

Theory and Practice of Burning Solid Biofuels in Low-Power Heating Devices

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Abstract: Combustion is the most advanced and proven method on the market for using agricultural by-product residues and waste from the agri-food industry. Currently, a wide range of combustion technologies is used to produce heat and electricity in low-power heating devices (> 50 kW) using various types of biofuels from biomass (woody biomass, herbaceous biomass, waste and residues from the agri-food industry). Combustion of biomass fuels, especially those of wood origin, causes lower carbon dioxide (CO₂) and sulfur oxides (SO_x) emissions into the atmosphere compared to coal combustion. The growing interest in solid biofuels has contributed to intensive activities on improving the combustion process and energy devices enabling effective and economic conversion of chemical energy contained in biomass into other usable forms such as heat, electricity. Having good quality fuel, it is necessary to ensure an appropriate, clean combustion technique, which allows to achieve the highest thermal efficiency of the heating device and at the same time the lowest emission of pollutants. The article presents issues related to the theory, characteristics of the combustion process and problems related to the formation of harmful chemical compounds nitrogen oxides (NO_x), SO_x, carbon monoxide (CO), particulate matter (PM) emitted to the atmosphere during the combustion process in low-power heating devices. The analysis indicates the possibility of minimizing undesirable phenomena during the combustion of these biofuels related to ash sintering, the formation of deposits, corrosion and improving the amount of condensable solid particles formed and therefore reducing the emission of gaseous products to the environment.

Keywords: plant biomass; combustion; low-power heating devices; emission

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1. Introduction

The current energy situation in the world is focused on increasing the production and use of green, ecological energy, which we also want to include biomass. The sustainable development of a given country is influenced by how it manages and to what extent renewable energy resources are used. For example, Poland produces about 23 million tons of biomass waste per year and 1.5 kg of straw can replace 1 kg of coal. It is currently estimated that biomass has the greatest potential for use in Poland, the technical potential of which as a biofuel is estimated at approximately 684.6 PJ per year, of which the largest 407.5 PJ falls on solid biofuels. Their resources consist of biomass surpluses obtained in

agriculture, 195 PJ; forestry, 101 PJ; horticulture, 57.6 PJ; and from wood industry waste, 53.9 PJ [1,2].

Due to the increase in power from renewable sources, there has been a decrease in demand for gas and coal used in power plants [3]. This trend will deepen in 2028, when a ban on the installation of gas furnaces will come into force, and from 2040, it will not be possible to use them. This is the effect of the so-called building directive adopted by the European Parliament. Currently, every fourth flat in Poland is heated with gas [4,5].

These activities are intended to contribute to a radical improvement in the quality of atmospheric air. Its constantly deteriorating quality is the result of many factors, including, among others, harmful substances emitted from household chimneys. In response to emerging challenges, legal regulations are being introduced in Europe and Poland to reduce emissions from such sources. Among them, the Ecodesign Directive and the previously existing EN 303-5 standard, which has been tightened several times since 2002, are important. Directive 2009/125/EC of the European Parliament (Ecodesign) introduces more restrictive requirements and establishes a European legal framework for energy and emission requirements for central heating boilers, fireplaces, and stoves [6,7]. This directive entered into force on 1 January 2020, introducing a single level of requirements for each newly sold heating device to meet the highest emission standards. It introduces classes regarding energy efficiency [8]. This regulation also concerns the obligation of boiler manufacturers to maintain appropriate levels of nitrogen oxides (NO_x) emissions. Currently, the PN-EN 303-5 standard has been in force since 2021, which is an update of the PN-EN 303-5:2012 standard. The above standard is replaced by the PN-EN 303-5:2021-09 standard [9], which was introduced from September 2021 and applies to heating boilers with a nominal thermal output of up to 500 kW. The latest applicable regulations are included in the PN-EN 303-5+A1:2023-05 standard, which introduces planned changes from May 2023 and is an update of the PN-EN 303-5:2021-09 standard [10].

Additionally, in reference to the requirements of the presented standards, there are legal acts concerning the monitoring and reduction of greenhouse gas emissions adopted by local government units. As of January 2021, anti-smog resolutions have been adopted by 14 voivodeships: Małopolskie (Resolution of 23 January 2017), Silesian (Resolution of 7 April 2017), Lower Silesian (Resolution of 30 November 2017), Mazowieckie (Resolution of 24 October 2017), Łódzkie (Resolution of 24 October 2017), Wielkopolskie (Resolution of 18 December 2017), Opolskie (Resolution of 26 September 2017), Podkarpackie (Resolution of 23 April 2018), Lubuskie (Resolution of 18 June 2018), West Pomeranian (Resolution of 26 September 2018), Kuyavian–Pomeranian Voivodeship (Resolution of 24 June 2019), Świętokrzyskie Voivodeship (Resolution of 29 June 2020), Pomeranian Voivodeship (Resolution of 28 September 2020), and Lublin Voivodeship (Resolution of 19 February 2021) [11]. In turn, for the Lublin Voivodeship, on the introduction of restrictions and prohibitions on the operation of installations in which biofuels are burned, is Resolution No. XXIII/388/2021 of the Lublin Voivodeship Assembly of 19 February 2021 [12]. This resolution entered into force on 1 May 2021 and assumes the gradual replacement of outdated installations with a capacity of less than 1 MW in which solid fuels are burned (coal, wood), in particular: boilers, stoves, coal-fired cookers, and fireplaces. Installations without a class and classified in class 1 and 2 are to be replaced by 2024. By 1 January 2030, all solid fuel boilers will have to meet the requirements for seasonal efficiency and pollutant emissions specified in EU Commission Regulation 2015/1189. In addition, it is prohibited to use solid fuel installations in newly constructed buildings with access to the heating or gas network (after 1 May 2021) and the use of the following fuels is prohibited:

- Coal fines and sludge, flotation concentrates, and mixtures produced using them;
- Brown coal and solid fuels produced using it;

- Hard coal that does not meet any of the requirements specified by law and solid fuels produced using it;
- Biomass with moisture content exceeding 20%.

The resolution also introduces intermediate deadlines for the faster elimination of non-class boilers, and the maximum time for replacing a boiler includes the following deadlines:

- 31 December 2023: non-class boilers and boilers of classes 1 and 2 according to the PN-EN 303-5:2002 standard;
- 31 December 2026 boilers of classes 3 and 4 according to the PN-EN 303-5:2012 standard;
- 31 December 2029 boilers of class 5 according to the above standard.

The implementation of the anti-smog resolution is intended to improve the air quality in the region, and at the same time contribute to improvements in health and greater comfort in the lives of residents [13].

Referring to these systems of EU requirements, standards, and local government resolutions, a significant challenge is to reduce the emission of harmful substances into the environment and to promote the topic of improving the thermal and emission parameters of modern heating devices in which plant biomass is burned in the form of piece wood, chips, briquettes, or pellets, constituting a real alternative to coal or crude oil [7,14–27].

However, despite the large investment in the development of solid fuel heating technology, air quality is still a major problem in Poland, where solid fuel heating boilers are considered the main source of harmful gaseous substances. The poor air quality in Poland is the basis for work on reducing exhaust emissions not only in professional power generation but also from low-power heating boilers. Therefore, biofuel-fired boilers should have an appropriate design to ensure the correct combustion process. In the case of low-power heating devices, it is necessary to comply with the regulations regarding the type of fuel and the method and conditions of its use.

One of the analyses that indicates the impact of energy generation through the combustion of various types of biomass on the environment and what environmental and economic benefits can be obtained as a result of increasing the share of biomass is the LCA (life cycle assessment) method. This method aims to identify and determine the amount of raw material, energy used, and pollutants and waste discharged, and therefore assess the impact of these elements on the environment. Thanks to this method, it is possible to determine threats and determine ways to improve the quality of the environment by examining the potential impacts of the technological process on the environment. LCA analysis has been described by the International Organization for Standardization (ISO) as a technique for assessing environmental factors and potential impacts related to the product, which includes four phases: defining the purpose and scope of research, inventorying the set of significant inputs and outputs in the product system, assessing the potential environmental impacts related to the system inputs and outputs, and interpreting the results of the set analysis and impact assessment phases regarding the research objectives [28].

In order for a heating device of a specific type to function properly, it must be supplied with fuel of appropriate quality—with standard physical and chemical properties. The literature on the subject indicates that on the biofuel market, woody biomass is a desired and dominant type of raw material in combustion processes [17,29–32]. However, in terms of increasing demand for biomass, this raw material has limited potential [33–35]. A promising alternative to cover the limited availability of high-quality woody biomass is herbaceous biomass, for which increasing importance is expected, especially in the aspect of using byproducts in accordance with the concept of sustainable development. However, despite the advantages of such biomass as an energy carrier, many problems arise due to variable fuel properties, including moisture content, calorific value, non-

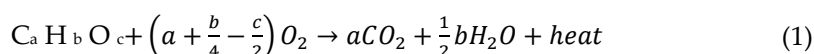
uniformity of particle size and shape, and carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) content [29,34,36].

In order to solve the above problems and improve the fuel properties of biomass, various thermochemical processes of biofuel oxidation are used, for example, the torrefaction process. Torrefaction is a thermochemical treatment process that increases the energy concentration and hydrophobicity of substrates, which contributes to improving the efficiency of the technology and the quality of the obtained product. Other technologies are also available, including combustion, pyrolysis, and gasification/Fischer–Tropsch synthesis [37].

Hence, the aim of this study is to analyze and synthesize the content of the theory and practice of solid biofuel combustion in low-power heating devices based on the current state of knowledge in the literature on the subject and to indicate important factors that determine the emission of harmful particles into the atmosphere. These issues are associated with a number of doubts related to the conditions of combustion of solid biofuels, the properties of biomass, and their mutual interactions. This study can help to systematize the course of the combustion process of solid biofuels in low-power heating devices and indicate solutions aimed at reducing the emission of harmful gaseous products into the atmosphere.

2. Theory of Combustion of Solid Biofuels

Combustion is a fast chemical reaction associated with the release of significant amounts of heat and light. Combustion is divided into statics and dynamics of fuel combustion. Combustion statics deals with the material and energy balance of the fuel combustion process and the analysis of the properties of substances burned and created in the combustion process. Dynamics, on the other hand, analyzes fuel combustion from the point of view of the time course of individual physical and chemical phenomena. The combustion process is presented according to the following equation:



There are four basic combustion phases:

- Phase I—evaporation of water contained in the fuel (drying by heating);
- Phase II—fuel gasification: at a temperature of about 270 °C, gases are released, resulting in the formation of carbon monoxide (CO), dihydrogen (H₂), methane (CH₄), and higher hydrocarbons;
- Phase III—combustion of gases (volatile parts): during complete combustion (appropriate amount of oxygen), CO₂ and water (H₂O) are formed, while in the case of oxygen deficiency CO, soot and tar are formed;
- Phase IV—combustion of coal (solid residue after pyrolysis): in the case of complete combustion, the product is CO₂ and in the case of oxygen deficiency, it is CO [38].

Characteristics of the Combustion Process

Combustion is a complex phenomenon, perceived mainly as physicochemical changes [20,39,40] in fuel, caused by thermal decomposition occurring at a given phase and time. The combustion process of solid biofuels, if carried out properly, depends on the amount of oxygen supplied, i.e., on the amount of air supplied. On the other hand, the type of pollutants generated in the combustion process depends on both the process factors and the type of biomass being burned. A smaller amount of air causes part of the fuel to not burn and the burnt fuel to not burn, which produces negative economic effects. On the other hand, too much air causes cooling of the combustion space of the furnace and a rapid increase in carbon monoxide emissions. Within these issues, the fuel combustion rate is also important, which is defined as the share of the mass of the burned fuel in a unit

of time in relation to the unit of the cross-section of the burned fuel. In addition to the external conditions of oxidation, the decisive influence on this parameter also has an impact on the following fuel properties:

- Density;
- Humidity;
- Surface roughness;
- Ratio of the fuel surface area (S) to its volume (V);
- Shape of the fuel particle.

Depending on the phase of the flammable substance, we distinguish homogeneous and heterogeneous fuel combustion [41–43]. A characteristic feature of heterogeneous fuel combustion is the luminescence of the non-volatile flammable substance and the absence of flame. The color shade of the glow of the non-volatile flammable substance depends on the temperature:

- At 400 °C, the color is pale (gray);
- At 700 °C, the color is dark red;
- At 900 °C, the color is light.

Higher-density fuels burn slower than lower-density fuels, which is related to the size of the surface absorbing the heat needed for thermal decomposition. The water contained in the fuel has an impact on the reduction of the combustion rate, which, as a result of evaporation, dilutes the flammable gases and lowers the flame temperature. In addition, an increase in the ratio of the fuel surface area to its volume causes the combustion rate to increase as well [44,45].

Characteristic parameters of the combustion process in relation to excess air [20] and exhaust gas temperature are exhaust gas losses and pyrotechnic efficiency. The excess air coefficient is one of the main combustion parameters ensuring high combustion efficiency. In turn, exhaust gas loss is the difference between exhaust gas temperature and the temperature of the combusted mixture in relation to the properties of the fuel and the amount of oxygen in the exhaust gas. The combustion process should be characterized by complete and total fuel combustion as well as low emissions of its combustion products into the environment. This has a beneficial effect on the efficient use of the energy contained in them. The combustion process of biomass fuels is difficult to control due to the high variability of parameters important from the point of view of the course of this process. An important parameter here is the combustion time, which is determined by the sum of the times needed for the combustion process and the physical and chemical phenomena occurring in it [44].

The combustion process of organic substances consisting mainly of carbon, hydrogen, oxygen, nitrogen, and sulfur can be presented in a very simplified way as the oxidation of carbon and hydrogen, which are of major importance in the energy balance [46,47]:



According to [7,30,48–60], the main primary air pollutants include CO₂, CO, NO_x, sulfur dioxide (SO₂), ammonium (NH₄), hydrogen chloride (HCl), and hydrogen fluoride (HF).

Complete and incomplete combustion are two conditions that can occur during combustion. Complete combustion results in the combustion of C, H, and S to CO₂, H₂O, and SO₂, respectively, without the participation of oxygen. Incomplete combustion, on the other hand, results in the formation of unburned carbon and gases such as H₂, CO, or hydroxide (OH) [61].

1. The products of complete combustion include the following:
 - CO_2 —The most important product of biomass fuel combustion. It is also an indicator of C content in biomass and is a major source of global warming (from biomass combustion, it is treated as a neutral gas in relation to the greenhouse effect). The amount of C released in the form of CO_2 is defined as combustion efficiency. The carbon content in biomass is about 45%, while coal contains 60% or more [62].
 - HCl —Part of the chlorine (Cl) contained in biomass, which is released during combustion. Higher amounts of Cl in biomass fuels can result in significant amounts of HCl . Chlorine content in wood is generally low, while higher amounts are found in herbaceous biomass, grain, and fruit residues. Problems with HCl emission are noticeable at concentrations above 0.1 wt.% [38,63].
 - NO_x — NO_x emission is one of the most important challenges in the field of emission reduction and minimization. This emission results mainly from the complete oxidation of nitrogen. Three forms of NO_x are thermal NO_x , fast NO_x , and fuel NO_x (Figure 1). Thermal NO_x is produced during combustion at high temperatures from N contained in the air. The fast chemical reaction between N, O, and hydrocarbons can cause the formation of fast NO_x at high temperatures. NO_x is produced as a result of direct oxidation of N contained in biomass. Additionally, nitrogen oxide (NO) is the dominant form of NO_x produced in combustion processes. More NO_x is produced when the amount of N in the fuel is higher. Another factor influencing NO_x emission is the exhaust temperature, where higher temperature causes the formation of more NO_x . Emission problems can be expected when the N content in the fuel exceeds 0.6% by weight (dry weight). This problem occurs especially during the combustion of cereal straw, grass, grains, and fruit residues [64–66]. Over 90% of NO_x emitted during combustion is NO, and the remaining part is nitrous oxide (N_2O) and nitrogen dioxide (NO_2). NO is the main source of NO_x emissions because when emitted to the atmosphere, it is oxidized to NO_2 under the influence of UV radiation. Of all nitrogen oxides, NO_2 is the most harmful. NO_x removal methods can be divided into two main groups, namely, primary and secondary measures. Primary measures include fuel staging (afterburning), air staging, and exhaust gas recirculation. Secondary measures include selective catalytic reduction (SCR; in NO_x reduction, it can reach even 60–90%) and non-selective catalytic reduction (NSCR) [67–70].

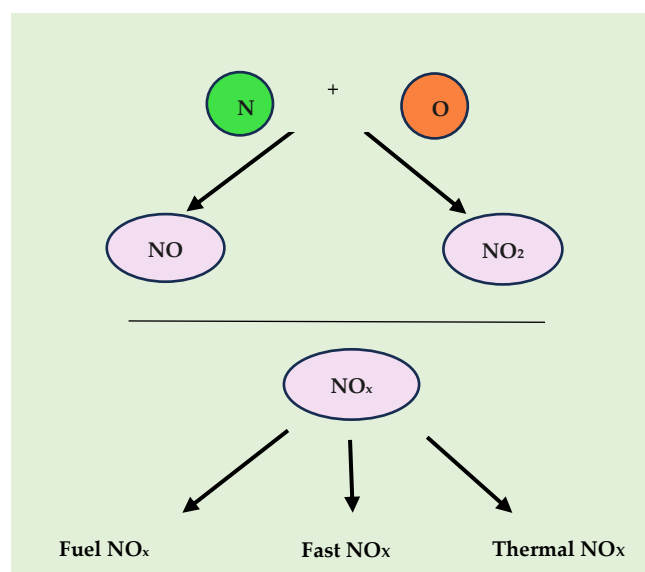


Figure 1. Formation mechanism of nitrogen oxides. Own study, based on [71].

Nitric oxide can be produced in the process of fuel combustion from atmospheric and fuel nitrogen as a result of a number of mechanisms. As a result of complex processes leading to the formation of NO, a number of radicals are formed, which, depending on thermodynamic and stoichiometric conditions, can be regulated. This allows for the modification of the entire process of NO production, leading, among other things, to a reduction in the rate of its formation. The reactions presented below describe the thermal mechanism of NO formation (Zeldovich reactions):



where N_2 —dinitrogen.

The mechanism of thermal dissociation of oxygen and nitrogen molecules in the air is the initiation of processes leading to the formation of NO. The energy contained in the nitrogen molecule makes the formation of NO by this mechanism possible only at high temperatures. Combustion of hydrocarbon fuels at temperatures $>1000^\circ\text{C}$ can cause the formation of relatively high concentrations of NO in exhaust gases:



where $\text{CH}^\cdot$ —methylidyne radical; HCN —hydrogen cyanide; CH_2 —methylene; $\text{NH}^\cdot$ —imide group radical; $\text{NCO}^\cdot$ —isocyanate acid residue radical.

NCO and NH radicals in reaction with NO are a source of N_2O . At temperatures $>1200^\circ\text{C}$ in the presence of the O radical, both N_2O and NO can be formed:



The formation of NO from nitrogen bound in the fuel is a process that requires less energy input. Nitrogen, which is usually bound in organic matter in cyclic or amine compounds, is more susceptible to reactions at elevated temperatures. It appears transiently in the combustion processes of hydrogen cyanide, CN (cyanide radical), HNO (azanone, HNO is a highly reactive triatomic molecule) and NH radicals. The reactions leading to the formation of NO are presented below:





The OH radical plays a very important role in the oxidation of carbon bonds in organic matter to CO as well as in the oxidation of nitrogen compounds formed during combustion to nitric oxide [72].

- SO_x —The result of complete oxidation of sulfur oxide (SO). Sulfur oxide is mainly SO_2 . However, some sulfur trioxide (SO_3) can be formed at lower temperatures, when more O is bound to S. Between 60 and 90% of sulfur contained in wood and bark is bound to ash during combustion. In the case of burning cereal straw, the ash contains between 40 and 55% sulfur [64,73]. Problems related to sulfur emissions should be expected at concentrations in the fuel above 0.2% by weight. It may be significant in the case of burning rape straw and grass.

2. The products of incomplete combustion include the following:

- CO—A product of incomplete combustion of coal fuel to CO_2 . Therefore, CO emission can be considered as a good indicator of incomplete combustion of biomass, and CO levels are minimal at an optimal air ratio (air ratio is 5.7 for typical biomass with HHV (higher heating value) 18.6 GJ/t). Increased CO emission can occur as a result of the large amount of combustion air used, which also cools the combustion chamber. The main sources of CO emission to the atmosphere are biofuels and industrial fuels [74],
- CH_4 —is a transition product formed during the conversion of C to CO_2 and H to H_2O during the combustion of biomass. Methane is a gas whose greenhouse potential, i.e., the impact it has on the greenhouse effect, is 28 times stronger than carbon dioxide (over a period of one hundred years). This makes methane emissions more dangerous to the Earth's climate than CO_2 [75].

The composition of exhaust gases is related to the combustion conditions and the heating devices in which solid biofuels are burned. In addition, the appropriate characteristics of the fuel are important due to the optimal course of the combustion process and the emission of its products. The use of appropriate techniques and technologies to protect the atmosphere from the impact of an additional stream of nitrogen oxides, sulfur, or carbon dioxide seem therefore inevitable.

Complete combustion is accompanied by the formation of ash, which also contains unburned organic matter compounds. Ash is a mineral (inorganic) substance that is formed as a result of combustion of elements contained in small amounts in biomass [36,38,41,43,45,61,76].

3. The Practice of Burning

3.1. Design Features of Low-Power Heating Devices

There are many biomass combustion and co-combustion installations. The choice of the appropriate combustion technology depends on the system power, fuel parameters, and its size. In order to obtain energy from biomass, it is burned in boilers/furnaces or processed into energy media. A boiler is a device used to burn solid fuels (wood, coal, pellets, or briquettes), liquid, and gaseous fuels in order to heat the heat carrier. It is one of the oldest and at the same time traditional and cheapest methods of heating buildings. A solid fuel boiler consists of a combustion chamber in which solid fuel is placed, and a heat exchanger that transfers heat to water or air, which circulates in the building's heating system. Solid fuel boilers are mainly used in single-family buildings, but they can also be used in larger facilities, such as production halls or warehouses. On the other hand, a furnace is a device that directly releases heat to the environment. This means that the furnace is also a source of heat, which is emitted to the immediate environment in which it is located. Heating is achieved by radiation and convection [77]. In turn, a fireplace is a type of heating device connected to a chimney flue, used to heat interiors. A wide range of possibilities allows for adapting the type and form of the fireplace to the purpose of the building, its architecture, and the needs and expectations of the user. The main classification of fireplaces is the division into fireplaces with an open and closed combustion chamber. This division determines the method of supplying air for combustion. Modern fireplaces with the Ecodesign certificate are ecological and economical devices, the use of which has a small impact on the environment [78].

Combustion technologies are divided into three groups: residential heating, industrial heating, and co-combustion [79]. In addition, large-scale boiler technologies are currently adapted to the combustion of wood and wood pellets. Pellet boilers for the residential heating sector are optimized for wood pellets only. However, greater problems arise with small-scale applications, because boilers need to be adapted, and national environmental regulations must take into account the emission threshold for pellets from herbaceous and mixed biomass.

Low-power solid fuel boilers are divided as follows:

1. Manually loaded boilers. In the group of these boilers, we distinguish the lower combustion technique (boilers with two or three flue gas passes) of the entire volume of the bed (countercurrent combustion), used in individual heating, and the upper combustion technique, which allows for a significant reduction in the emission of gases such as CO and SO₂ to the atmosphere. A properly used upper combustion boiler can achieve an efficiency of 50–60%. On the other hand, in chamber boilers (chamber grate boilers), the ember layer reaches the highest temperatures at the grate, in the zone of intensive aeration, where temperatures on the grate surface can reach <1000 °C, causing deformation of the grate and melting and sintering of ash. This problem is solved by using a grate composed of bar grates (moving grate) or using a water-cooled grate made of grate bars in the form of pipes, permanently built into the water space of the boiler (fixed grate).

2. Boilers with an automatic feeder. These boilers are divided as follows:

- Retort boilers (they can burn briquettes, pellets and peas, wood chips, cereal grains, shavings, sawdust, bark, energy plants, and coal) in which the advantage is a self-cleaning retort furnace and the comfort of operation in terms of fuel replenishment and ash removal. These boilers are fully automated, regulate and control the amount of air that is let into the combustion chamber, and automatically decide on the amount of fuel introduced. Therefore, they are ecologically and energetically efficient, because the emission of pollutants is reduced to the maximum,
- Boilers with a drawer burner. These boilers are characterized by fuel dosing from the tank, which slides by gravity into the feeder trough (cyclic operation) and gets into the grate space (slotted or hole), where it ignites.

- Boilers with a drop-in burner are equipped with an oblique screw feeder by means of which the fuel is fed to the central part of the boiler, where the burner is located. The fuel is burned and the automatic ash removal system with a rotating grate removes the ash. This solution improves the pellet combustion process.
- Boilers with a gutter burner (tubular or pipe) are characterized by the possibility of burning many types of fuel. They are equipped with a ceramic or cast iron deflector, which, by reflecting the flame front, improves the circulation of hot exhaust gases, increasing the efficiency of heat collection by the water jacket.

3. Wood gasification boilers are divided into three zones in the boiler, in which the basic processes take place. The disadvantage of the boiler design is the manual, single fuel loading and its operating cycle. A buffer (heat storage) is required, because the heat generation in the boiler operating cycle (up to several hours) does not coincide with the heat demand of the heated object.

Co-firing of solid fuels in power boilers can be divided into 1. direct co-firing, 2. indirect co-firing, and 3. parallel co-firing [77,80,81].

Low-power solid fuel boilers are divided according to the fuel feed method into boilers with manual loading (so-called batch) and boilers with an automatic fuel feed. The first type of boiler is the most common among users of multi-fuel coal boilers and boilers for lump wood. Boilers (Table 1) fueled by biomass can be divided according to the fuel feed method, combustion technique used, achieved dimensions (power), and type of fuel burned.

Table 1. Types of biomass heating devices and the scope of their power.

Fuel Feeding Method/Process	Type of Heating Device	Power Range	Fuel Type
Manually	Stoves	2–10 kW	Lump wood
	Boilers:		
	Bottom combustion boilers ^{2,4,13}	5–100 kW	Clearings, logs
	Top combustion boilers ^{2,4,13}		
	Chamber boilers, top-loaded ²		
	Universal boilers (upper–lower) ⁴		
Automatically	Stoves		Pellets
	Boilers:		Fuel from sawdust and wood shavings ⁴
	Retort boilers ^{2,4,9,10,13}	2–35 * kW	Pellets made of wheat bran, sunflower husks ⁴
	Boilers with drawer burner ^{2,9}		
	Boilers with a drop-in burner ^{2,10}		
	Boilers with a gutter burner (also known as a tube or pipe burner) ^{2,10,13}		
	Boilers with tube burner ¹⁰		Briquettes, sawdust, wood chips and cereal grains, seeds, nut shells ^{4,10,13}
	Feeder furnaces	20 kW–2.5 MW	Wood chips, wood waste
	Furnaces with a mechanical grate ¹	150 kW–15 MW	All types of biomass d 5–100 mm ³
	(step grate or retort burner) ^{3,5,6,7,8,11,12,13}	100 kW–50 MW ³	
	Forefire	20 kW–1.5 MW	Wood, sawdust
	Rotary under-feed furnace	2–5 MW	Wood chips
	Cigar hearth ^{1,11}	3–5 MW	Bales, straw bales ^{1,4,8}
	Batch boilers ^{4,8,11}		
	Hearth for burning straw ^{1,4,11}	100 kW–5 MW	Chopped straw ^{1,4,11}
		180 kW ⁸	Herbal waste ⁴
	Bubble combustion in the BFBC (bubbling fluidized bed combustion) fluidized bed ^{1,3,11,12}	5–15 MW	d < 80 mm ³
		20–100 MW ³	Different types of biomass

Co-combustion of biomass with coal	Circular combustion in a CFBC (circulating fluid- ized bed combustion) fluidized bed ^{1,3,11,12}	15–100 MW 20–100 MW ³	d < 10 mm d 40 mm ³
	Dust furnace ^{3,11}	5–10 MW 5–15 MW ¹¹ 500 kW–100 MW ³	Different types of biomass d < 5 mm d < 10–20 mm ³
	A furnace for burning whole cubes/bales	3–5 MW	Bales/straw cubes
	Direct co-combustion ^{2,3} Indirect co-combustion ^{2,3} Parallel co-firing ^{2,3}		Coal and biomass fuel mix- tures
	Bubble combustion in the BFBC (bubbling fluid- ized bed combustion) fluidized bed ^{1,3}	50–150 MW	Different types of biomass d < 10 mm with fine coal
	Circular combustion in a CFBC (circulating fluid- ized bed combustion) fluidized bed ^{1,3}	100–300 MW	
	Dust furnace ¹ With piston feeder ⁴ Stream ¹² Vortex ¹²	100 MW–1 GW	Different types of biomass d < 2–5 mm with coal dust (from mills)

Source: own study ¹ [82], ² [80], ³ [15], ⁴ [77], ⁵ [43], ⁶ [40], ⁷ [61], ⁸ [83], ⁹ [84], ¹⁰ [85], ¹¹ [80], ¹² [86], ¹³ [87].

* In 2016, boilers with variable combustion chamber geometry appeared, in which the thermal power range in the largest unit is 86–285 kW.

3.2. Combustion Problems and Reduction in Gaseous Pollutant Emissions in the Aspect of Heating Device Design

The most emission-intensive combustion technology is layer combustion, which is used in fireplaces, stoves, and boilers with a capacity of less than 50 MWth. To achieve better boiler efficiency, certain improvements should be made to reduce the emission of gaseous products into the atmosphere through better insulation inside the combustion chamber, more efficient techniques for supplying air to the combustion process, improved cooling of exhaust gases and optimization of the electronic air supply control unit or the use of fuel additives, high-efficiency, low-emission combustion. An important aspect is the promotion of research on the combustion technology of boilers with a capacity of >50 kW fired with plant and herbal biomass [6,79,88,89]. The combustion of solid biofuels is associated not only with the geometrical features of the fuel that affect the combustion process but also with the design of the furnace. The geometry of the combustion chamber and the regulation of the combustion process require more attention, because a much larger combustion chamber is required during biomass combustion [66,70,90–96]. Modern biomass combustion devices have an efficiency of about 95%, which is competitive with devices burning fossil fuels [97]. The group of traditional low-power heating devices >50 kW (stoves, boilers) is characterized by manual and periodic fuel feeding and thus high emission of pollutants into the natural environment.

Suspended dust has a significant share in the total load of air pollutant emissions from low-power boilers. Biomass with a higher N and S content leads to the production of toxic gases, i.e., NO_x and SO_x, during combustion, which is the main cause of acid rain and the release of PM (particulate matter) [91]. PM is considered one of the most important pollutants generated as a result of biomass combustion. Total suspended particles (TSP) and its fractions PM₁₀ and PM_{2.5} (the value of the PM index corresponds to the diameter in µm) have the ability to hang in the air, while the smaller ones PM_{2.5} can settle in the upper respiratory tract. It is estimated that about 90% of total particulate matter emissions come from individual heating (>90% of PM emissions from efficient combustion of wood fuel (with high moisture content) belong to the PM₁₀ fraction, and >75% to the PM_{2.5} fraction) [7,50,54,67,98–109].

More efficient combustion of biomass with simultaneous reduction in gas and particulate emissions can be ensured by using precise gradation of the amount of combustion air. Air gradation is a widely used basic parameter in NO_x reduction, and when used with precise control of residence time and primary air excess coefficient, significant NO_x reduction potential of up to 50–80% is observed. Significant NO_x emission reductions (20–56%) were noted when burning wood biomass (pellets) and some biomass fuel mixtures on a grate (fixed bed). The content of volatile substances has a significant effect on NO_x reduction. On the other hand, co-current combustion has been used in modern boilers fired with solid fuels characterized by automatic fuel dosing and rigorous fuel quality requirements, and at the same time high energy efficiency (over 87% and in the case of pellets over 92%), low pollutant emission, and high operating comfort (with periodic maintenance) [53,104,110]. Modern low-power boilers for solid fuels equipped with automatic systems for feeding fuel to the combustion chamber may be a solution that is becoming more and more commonly used. Precise dosing of the amount of supplied fuel guarantees both the economy of the combustion process and compliance with the emission criteria included in the PN-EN 303-5:2012 standard [85,111,112]. Another solution in this type of boilers is the use of filtration catalytic systems, which in the tests conducted [7] with the use of wood biomass pellets significantly reduced the emission of NO_x (88%), CO (94%), and particulate matter—PM (59%). Another method of feeding fuel to the boiler is the co-combustion of biomass with coal. Co-combustion of biomass or waste with the basic fuel is a suitable way to reduce the emission of some pollutants generated in the combustion process as well as replacing fossil fuels with biomass. Co-combustion means the simultaneous combustion of two or more fuels in the same installation in order to generate energy. Combining fuels can cause positive or negative synergistic effects (Figure 2), the most well-known of which are the interactions between S, chlorine (Cl), potassium (K), aluminum (Al), and silicon (Si), which can cause or prevent the formation of deposits on pipes or on catalyst surfaces and influence the formation of dioxins. A better understanding of these interactions can help avoid negative effects and use positive ones [113].

The influence that can be exerted on the combustion of biomass and the co-combustion process are the species of alkali and alkaline earth metals (AAEMs), which are the main components of biomass ash. Biomass ash can exert a positive influence on combustion because it contains a large amount of AAEMs, which can act as a catalyst in the combustion process. One of the important factors leading to the synergy effect is that the AAEMs contained in biomass ash can promote the combustion of biomass and coal. The four main components of biomass ash—potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg)—are essential integral nutrients in the process of plant growth. During the co-combustion process of biomass and coal, AAEMs can play a key role and affect combustion. Therefore, the order of the catalytic effect of AAEMs on NO reduction is as follows: Na > K > Ca > Mg. The migration and transformation of alkali metals and alkaline earth metals are not only related to ash problems but also directly affect the reaction behavior of binary particles during co-combustion. The influence of the type of feedstock on the migration and transformation of AAEM during co-combustion is mainly related to the composition categories, chemical species, and mineral content of binary feedstocks. The increase in combustion temperature enhances the release of AAEM in coal feedstocks, thus promoting the deactivation of AAEM. In the case of biomass with high K and Cl content, higher biomass content in the mixtures would result in a higher release of AAEM during the co-combustion process. On the other hand, the increase in the share of coal in the mixtures would promote the reduction in or inhibition of AAEM release. Moreover, AAEMs play a catalytic role in the pyrolysis, gasification, and combustion of coal and biomass. AAEM can significantly reduce the ignition temperature, burnout temperature, and apparent activation energy, thereby enhancing combustion [114–116].

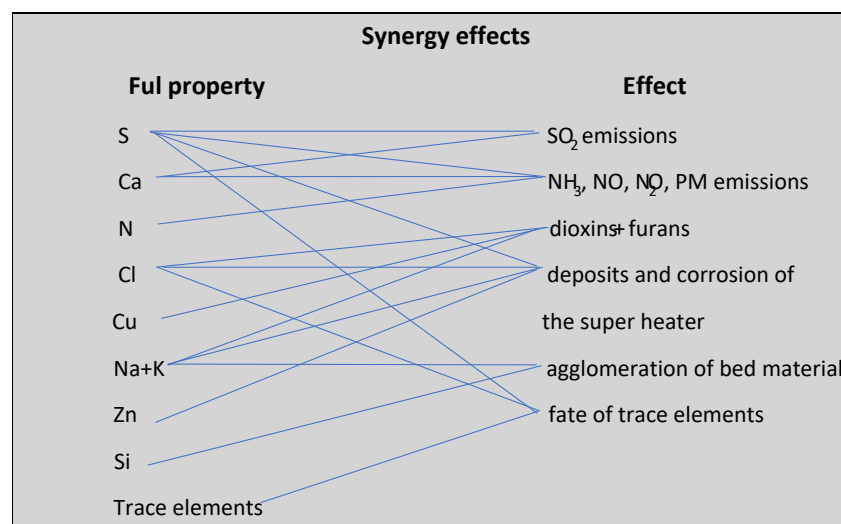


Figure 2. Synergy effects between co-burned fuels [117].

The analysis of the actual operation of heating boilers in Poland is based on the analysis of the power at which these devices operate during the year and the emission of pollutants into the environment during their operation. The operation of a heating boiler at nominal (maximum) power ensures its highest efficiency and the lowest possible emission of pollutants. One of the elements that can improve the air quality in Poland by influencing the operating conditions of low-power heating boilers are automatic combustion control systems. These systems manage the operation of the device based on data collected in real time. Some of the system components are state-of-the-art combustion quality analyzers, which, in combination with the heating boiler control systems, adjust the combustion process so that it is environmentally friendly and economical within the given power and temperature range. One of the methods of reducing CO₂ emissions may be the combustion of solid biomass in a chemical loop, which entails a small loss of energy compared to traditional combustion, which is lower compared to competitive CO₂ capture technologies [118].

The use of different forms of biofuels in a grate boiler and the change in ignition mode have a significant impact on gas emissions (NO_x and SO_x), which results from the size of particles and the penetration of flames through free spaces between fuel zones. This group of heating devices is characterized by manual, periodic fuel dosing to the grate and ignition from the bottom, which results in higher CO, NO_x, and SO₂ emissions [119].

On the one hand, the use of plant biomass as an energy carrier is crucial in reducing CO₂ emissions, being an alternative to fossil fuels and the approaching depletion of these resources, which cause CO₂ emissions and other greenhouse gases, contributing to global warming and climate change. On the other hand, the combustion of solid biofuels in low-power heating devices may pose a problem related to the possibility of emission of particulate matter (PM), NO_x, and SO_x as a result of the combustion of solid biofuels [17,21,33,42,43,57,59,93,103,120–129]. Power installations powered by solid fuels cause more than 75% of dust, NO_x, and SO₂ emissions; about 70% of CO emissions; and more than 90% of CO₂. Physical and chemical properties are an important reference in the application of biomass co-firing [18,130].

Both fossil fuels and solid biofuels contain various elements of carbon, hydrogen, nitrogen, sulfur, and a certain amount of chlorine and fluorine. They also contain calcium (Ca), magnesium (Mg), Al, sodium (Na), Si, phosphorus (P), and heavy metals (mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As), which after combustion constitute fly ash, i.e., dust emitted with exhaust gases, which leads to increased formation of deposits,

² Virginia mallow pellets	at 10% O ₂	118.85	248.31	–	0.120	–	–	
² Giant Miscanthus Pellets	at 10% O ₂	613.75	170.00	–	0.1978	–	–	
¹ Sewage sludge pellets		47.2 ± 23.3 g/kg	–	3.5 ± 0.6 g/kg	11.18 ± 0.48 g/kg	8.47 × 10 ^{−5} ± 1.03 × 10 ^{−4}	–	home pellet burner 13 kW
¹ Sunflower stalk pellets		32.8 ± 9.9 g/kg	–	2.1 ± 0.2 g/kg	0.02 ± 0.05 g/kg	2.71 × 10 ^{−2} ± 1.38 × 10 ^{−2}	–	
¹ Straw pellets		6.4 ± 5.0 g/kg	–	3.6 ± 0.8 g/kg	0.45 ± 0.20 g/kg	5.72 × 10 ^{−3} ± 3.70 × 10 ^{−2}	–	
² Rapeseed Straw Pellets	at 10% O ₂	447.50	151.02	–	0.7414	–	–	Boilers with automatic loading 10 kW
¹ Buckwheat husk pellets		48.7 ± 13.9 g/kg	–	2.2 ± 0.4 g/kg	0.01 ± 0.05 g/kg	1.09 × 10 ^{−4} ± 1.03 × 10 ^{−4}	–	Home pellet burner 13 kW
² Sunflower husk pellets	at 10% O ₂	983.75	122.65	–	0.2895	–	–	Boilers with automatic loading 10 kW
¹ Corn stalk pellets		5.2 ± 6.8 g/kg	–	2.4 ± 0.4 g/kg	0.61 ± 0.61 g/kg	1.03 × 10 ^{−5} ± 4.17 × 10 ^{−5}	–	Home pellet burner 13 kW
¹ Sifted wheat grain		9.6 ± 14.3 g/kg	–	4.6 ± 1.4 g/kg	0.12 ± 0.17 g/kg	6.89 × 10 ^{−5} ± 6.79 × 10 ^{−5}	–	
³ Apple tree wood		482.73	70.22	114.66	–	4.89%	280.36	Muffle furnace 3 kW
³ Spruce chips		334.72	96.45	157.17	–	6.02%	263.37	
³ Corn cobs		650.18	30.98	50.16	–	1.41%	149.29	
⁴ Straw and willow wood pellets (4:1)		285 ± 112.5	108.54 ± 24.12	170.648 ± 37	13.78 ± 9.26	–	141–162	Automatic pellet feed system 4–92 kW

Source: own study ¹ [137], ² [138], ³ [96], ⁴ [33]. ^a below detection limit

Pollutants generated during biofuel combustion, especially in low-power boilers and under unusual operating conditions (lower heat demand and therefore lower fuel consumption in the case of not-too-low outside temperatures) are usually products of incomplete combustion that should be controlled—CO, NO, organic compounds (polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds) and tar or total suspended particles. Solid particles are generated from aerosols created by NO_x (NO and NO₂) and SO_x (SO₂ and SO₃). It is estimated that about 90% of total solid particle emissions come from individual heating. In addition, many parameters of the furnace operation (independent of the user) affect the emission and thermal efficiency of the boiler. Therefore, gas emissions should be reduced as much as possible. SO₂ emissions from biomass combustion are due to the sulfur content of the fuel, while PM is a result of incomplete combustion, the presence of inert material in the fuel, and inappropriate air-to-fuel ratio [50,67,98,109,139,140].

One of the parameters influencing gas emissions are the geometrical features of the fuel such as density and particle size (length, diameter). The consequence of burning solid

biofuels with particles that are too small are CO, NO_x, particulate matter in exhaust gases, and total hydrocarbon emissions. In the case of burning biofuels with larger particles, a large surface area would increase the chance of complete combustion and reduce the formation of CO and NO_x.

The emission of pollutants is also influenced by combustion technology (boilers with reduced emission and increased thermal efficiency), combustion conditions, type of fuel burned, and its physicochemical parameters [140,141]. The composition and amount of generated flue gases and solid waste—ash or slag—depend on what and how we burn. Also, with good combustion, the emission of fly ash in flue gases leaving the device must be taken into account [53]. Usually, small combustion units (e.g., furnaces, small boilers) have higher emissions of unburned components than larger units, which are characterized by their greater possibility of controlling combustion. However, even in small combustion units, their efficiency can be increased and their emission of unburned products can be reduced by introducing appropriate technical solutions such as staged air supply, better insulation of the combustion chamber, preheating, and knowledge of fuel properties. Studies conducted by many authors indicate the influence of these dependencies during combustion of solid biofuels and on the amount of pollutant emission to the environment. Malafák et al. [142] assessed the elemental composition (C, H, N, and S) of selected species of herbaceous biomass (camelina (*Camelina sativa*), *Miscanthus giganteus*, reed canary (*Phalaris arundinacea*), and *Sorghum bicolor*)) and emission concentrations during combustion in a grate furnace using briquetted fuel. The studies showed that selected species of herbaceous biomass can be used for energy purposes. On the other hand, the produced briquettes from reed canary grass were characterized by high ash content (6.59%) and high N content (1.91%), which was associated with an increase in NO_x emissions (375.20 mg·m⁻³). Similar observations were made by other authors [15,61,83,143], stating that NO_x concentration in exhaust gases depends on the type of fuel burned. The conducted research [144] shows that increasing the secondary air flow (50 kW domestic furnace) increased the exhaust gas temperature during the combustion of pine chips, which had an impact on the reduction of the CO level. In a similar device, Lamberg et al. [145] found that the required amount of air is the main factor controlling gas emissions, which is also supported by the research by Carvalho et al. [146]. Similar research was conducted by Koniecznyński et al. [147] to assess the content of pollutants emitted by low-power domestic boilers. The emission factors were, respectively, for SO₂ from 0.16 (softwood pellets) to 2.49 kg/Mg (barley grain), and NO_x from 0.31 (miscanthus pellets) to 8.33 kg/Mg of fuel (conifer bark), while CO emissions for oat grain ranged from 9.64 to 140.88 kg/Mg for conifer bark. Ciupek et al. [112] compared emission values for three low-power heating boilers (20–25 kW) fired with wood pellets and hard coal. Emissions of CO, NO_x, SO_x, and PM pollutants were measured with the average annual emission of individual emission components in 2018–2019 in the following cities: Bydgoszcz, Lublin, Zielona Góra, and Warsaw. Analyses indicate a large share of CO (445.85 mg/m³) and PM (33.50 mg/m³) in emissions and a low NO_x (61.02 mg/m³) and SO_x (4.48 mg/m³) content. In other studies [148], two types of low-power boilers (an 18 kW boiler and a 5th class 14 kW boiler) were used, which burned hard coal, pine and spruce wood pellets, and cereal straw pellets. The results show differences in the amount of generated condensable particulate matter (CPM) depending on the fuel used and the type of low-power boiler. CPM emission determined in the class 5 boiler was lower (for hard coal, CPM emission was 1.3 times lower; for pine and spruce wood pellets and cereal straw pellets it was 9 and 2.06 times lower, respectively) than in the case of fuel combustion in an 18 kW boiler (CPM for hard coal was 0.46 g/h, for pine and spruce wood 0.54 g/h, and for cereal straw pellets 0.68 g/h). CPM emissions are relatively high and constitute a large part of the total suspended dust, so the impact of CPM on the environment should be noticeable. Therefore, we should pay special

attention to CPM research and control, especially taking into account low-power heating boilers for solid fuels. In studies conducted by other authors, it was noted that decreasing the amount of combustion air causes a lower amount of nitrogen oxides in the exhaust gases [142].

Staged combustion and intensive mixing of secondary air with combustible fuel components ensure very efficient boiler operation in conditions of low oxygen concentration from 4.0–6.0%. With an increase in oxygen concentration by more than 6%, the emission of harmful substances into the atmosphere increases. Therefore, in an automated control system, the threshold value of oxygen concentration should be reduced to 4% [149]. In turn, Najser et al. [59] in their research used a boiler (21.5 kW) with automatic fuel feeding using biomass from waste. In the process of combustion of biomass waste (wheat bran and beet pulp) and wood pellets, CO, NO_x, and SO_x emissions were 451 mg·m⁻³, 746 mg·m⁻³, and 252 mg·m⁻³; 559 mg·m⁻³, 341 mg·m⁻³, and 185 mg·m⁻³; and 13.4 mg·m⁻³ and 9.8 mg·m⁻³, respectively, and for wood pellets, no reduction in exhaust gas composition was observed. The authors in [69] examined the emission from combustion of wood biomass pellets (pine and beech) in a boiler with a nominal power of 21 kW and 6.3 kW with automatic fuel feeding at 10% O₂ in the exhaust gases. NO_x, PM, and CO emissions for pine pellets and beech wood pellets burned in a 21 kW and 6.3 kW boiler were, respectively, 313.30 mg/m³, 264.20 mg/m³, 294.50 mg/m³, and 265.70 mg/m³; 74.20 mg/m³, 64.80 mg/m³, 72.30 mg/m³, and 69.40 mg/m³; and 675.80 mg/m³, 635.20 mg/m³, 580.90 mg/m³, and 650.40 mg/m³.

Boilers burning wood and wood residues with a high moisture content may emit more PM than a boiler burning dry fuel, while a boiler burning 100% sludge has lower PM emissions than a boiler burning wood residues. Furthermore, manufacturers' experience indicates that a well-designed and appropriately sized boiler should be able to reduce NO_x emissions in the case of stoker-fired boilers. Therefore, when selecting the most appropriate emission factors for the boiler under evaluation, additional process parameters should be taken into account together with the feed composition and fuel properties such as moisture content [139].

During a study [150] of emissions from the combustion of pellets from the herbaceous perennial mallow *Sida hermaphrodita* (L.) Rusby, low CO emissions (40 mg·Nm⁻³), good combustion, and low slagging were observed. However, elevated NO_x and SO₂ levels were recorded. Furthermore, complete combustion showed high CO emissions (1300 mg·Nm⁻³) while SO₂ values were >100 mg·Nm⁻³. The HCl content in the flue gases ranged from 32 to 52 mg·Nm⁻³. In similar studies [151] using herbaceous biomass, i.e., peppermint (*Mentha piperita* L.), roundleaf mint (*Mentha rotundifolia* L.), spearmint (*Mentha spicata* L.), and curly mint (*Mentha crispa* L.), the emission of combustion products (CO, CO₂, NO_x, and SO₂) was determined, which, in comparison to hard coal, showed a reduction and amounted to 29–32%, 28–31%, 40–80%, and 92–98%, respectively. On the other hand, in another study [152], it was found that densification of herbaceous biomass (canary reed) with the addition of wood biomass (spruce sawdust) improves the combustion characteristics of herbaceous biomass through faster thermal decomposition of biomass pellets and ensures more complete combustion of volatile substances and reduces the average mass share of pollutant emissions (CO and NO_x). In another study [31], wood waste, straw, and hay were used for combustion. The lowest NO_x concentrations were recorded for wood waste (89 ppm) and hay (91 ppm), and the highest for straw (99 ppm). The observed differences in concentrations are mainly influenced by the content of volatile substances in the fuel used. Barmina et al. [153] showed that during the combustion of pellets from wheat straw, the emissions were CO (250 ppm), CO₂ (11.94%), and NO_x (250.7 ppm), respectively. In the case of pellets from spruce biomass, the data were 121 ppm, 13.21%, and 67.2 ppm, respectively. In turn, Petlickaite et al. [154] used herbaceous biomass (hemp, corn, and faba beans) and found that these plants can be used as an alternative to wood

biomass pellets. Hemp is a competitive energy plant with a huge potential to reduce greenhouse gas emissions and is one of the best plants that can be used in terms of physicochemical properties. Hemp biofuel has better properties compared to biofuel produced from cereal straw, reed, and miscanthus biomass. On the other hand, faba beans have the ability to fix atmospheric nitrogen and produce large amounts of waste biomass after harvest.

The lowest CO and hydrocarbon (C_xH_y) emissions were recorded during the combustion of corn and hemp pellets, and their values were 572 and 29 ppm. The lowest CO_2 content (3.5%) was observed during the combustion of corn pellets, and NO_x emission was 124 ppm. The study by Romanekas et al. [155] showed that the cultivation of hemp [156], corn, and faba bean in the same field can not only increase biomass yields but also stabilize the concentration of gaseous products in the environment and their emissions. In addition, energy plants such as giant miscanthus and hemp willow are interesting raw materials in terms of their use for energy purposes, which has been widely studied and described in research works [157,158] and in EU projects [159].

The results of the conducted elemental and stoichiometric analyses indicate higher concentrations of nitrogen, sulfur, and chlorine in the herbal biomass from agriculture compared to woody biomass. The influence on the selection of combustion devices is related to the increased content of sulfur and chlorine (corrosion). The selection of the appropriate fuel affects the efficiency of the furnace, and the size of this effect led to the creation of reliable furnace designs taking into account the properties of the fuel. The greater the amount of air supplied to the combustion chamber, the higher the gas emission [19,160].

One of the methods of reducing emissions was the development of [6] a new design of a low-emission heating boiler with a power of 10 kW fired with wood pellets. This boiler is to meet the requirements of the current Ecodesign directive. The innovative solution of the boiler design is the circular flow of exhaust gases around the centrally located combustion chamber. The use of such a solution ensures high-efficiency and low-emission combustion products. The test results show average gas emission values, i.e., CO (91 mg/Nm³) and NO_x (197 mg/Nm³).

Nitrogen oxides and other gaseous products generated during combustion processes in industrial, power, and household installations released into the atmosphere pose a serious threat to the environment and human health [161]. Solid biomass contains significant amounts of nitrogen in the form of organic bases and amino acids. Therefore, co-firing biomass with coal can significantly reduce NO_x and SO_x emissions, e.g., coke as a fuel with a very low nitrogen content can be effective in co-firing biomass rich in nitrogen [67]. Also, the synergy effect between different fuels, both in chemical and physical terms, can reduce problems related to ash deposition and corrosion in heating devices [117,162,163].

The sintering of bottom ash is particularly intensive in the case of herbaceous fuels compared to woody biomass, because the ash content is generally higher. Biomass containing a lot of silicon dioxide (SiO_2), alumina (Al_2O_3), and iron(III) oxide (Fe_2O_3) shows a much lower ability to settle. Ash generated from agricultural biomass sintering at low temperatures (below 850 °C) causes the formation of slags and corrosion [66,164–166]. The values of sintering temperatures (wheat straw 840 °C, rapeseed straw 640 °C, sunflower husk pellets 810 °C, rye straw 730 °C, oat straw 770 °C, mustard straw 630 °C, corn straw 650 °C, hemp straw 640 °C, sorghum stalks 760 °C, and tobacco stalks 570 °C) and softening temperatures (rye straw 1002 °C, wheat straw 998 °C, and barley straw 980 °C) may differ significantly for the same type of agricultural biomass, depending on the chemical composition of the ash, which is related to the plant species, cultivation method, and soil type [167–172].

NO_x emissions and other gaseous products can be reduced by using an appropriate additive. Among the additives used are ammonia, urea, and kaolin. Sulfur-based

additives during combustion of problematic biomass are a possible solution to minimize ash problems. Commonly used additives by injection into the combustion chamber or flue gas duct are ammonia or urea, in order to simultaneously reduce NO_x to nitrogen (N_2) and oxidize SO_2 to sulfuric acid (VI) (H_2SO_4) [67]. Another additive is kaolin, which increases the melting point of biomass ash and is considered the most effective additive. Example results of coal fuel combustion tests are presented in Table 4 using mono- and polycatalysts.

Table 4. The influence of additives on the reduction of gas emissions and boiler efficiency in the process of coal fuel combustion (metal cation and ammonia concentration—300 ppm) [173].

	NH_3	Na^+	Ca^{2+}	Mg^{2+}	E5
CO	−4.8	−2.9	−9.7	−3.1	−6.2
NO_x	−6.5	−0.5	−1.4	0.0	−11.7
SO_2	−1.6	2.2	−7.0	−3.4	−7.6
Boiler efficiency %	1.0	0.8	0.5	−1.1	2.9

The effect of the catalyst addition on the fuel combustion efficiency was determined in relation to the test sample without the catalyst, whereby the emission of pollutants and the boiler efficiency were assumed as 100%. On the one hand, the monometallic catalyst containing copper ion (Cu^{2+}) exerts the greatest influence on the reduction of the emission of gaseous pollutants, while on the other hand, a slight improvement in boiler efficiency was observed. On the other hand, when using the E5 polycatalyst, synergism of the interaction of its components was observed, as well as an increase in efficiency in relation to the tests using monocatalysts. This catalyst was an aqueous solution of a salt mixture containing 20% ammonia (NH_3), 30% sodium ion (Na^+), 40% copper ion (Cu^{2+}), and 10% magnesium ion (Mg^{2+}) [173].

4. Summary

Thermal use of solid biomass for heat production is constantly gaining importance and is expected to significantly contribute to reducing greenhouse gas emissions. Fossil fuels are limited resources and should be gradually replaced with resources such as plant biomass, including not only woody but also herbal biomass, also as byproducts or waste from the agri-food industry. The use of such biomass for energy production is a promising direction of development, as it is one of the options for its management, which contributes to reducing environmental pollution. Currently available combustion technologies are diverse and take into account the type of fuel used, fuel parameters, or system power. However, during their use, it is necessary to consider reducing the impact on the environment and climate change when using such types of biomass. Therefore, ecological messages are one of the main arguments justifying the validity of using biomass as a renewable and sustainable energy source. It is also important that the use of certain types of biomass enables efficient and economic conversion of chemical energy contained in biomass into other usable forms such as heat and electricity. However, the large variety of biomass raw materials with different properties, in terms of their effective use, makes it necessary to conduct research on the possibility of their use in the combustion or co-combustion process.

Hence, as a result of the presented literature studies, the following conclusions can be drawn:

1. The type of fuel and the quality of the solid biofuel used (N and S content in the fuel) have a significant impact on the concentration of pollutant emissions.
2. Optimization of combustion process parameters can be achieved through the following:

- Improving combustion conditions in the area of incomplete combustion, which leads to an increase in CO emissions (the lowest value for this indicator was observed during the combustion of rapeseed straw and the highest for wheat and rye straw).
- Increasing the secondary air flow, which increases the temperature of the exhaust gases during combustion and thus reduces the level of CO. In all conditions, the loss of efficiency caused by the exhaust gas temperature was much higher than the losses caused by unburned gases and solid residues. Ref. [65] found that effective CO reduction can be achieved in an optimized combustion process, as a result of which the fuel is well mixed with air. The required retention time is >1.5 s at high temperatures >850 °C and at a low excess air coefficient.
- Proper air circulation is the main factor controlling the gas concentration, e.g., reducing the combustion air causes a smaller amount of NO_x in the exhaust gases.
- Staged combustion and intensive mixing of secondary air with combustible components allows for efficient operation of the boiler at low oxygen concentrations from 4.0 to 6.0% (with an increase in oxygen concentration by more than 6%, the emission of harmful substances into the atmosphere increases).
- The degree of exhaust gas recirculation has a significant effect on the content of harmful substances (NO_x , CO, and PM), where the content of NO_x and CO gradually decreased with the increase in exhaust gas recirculation, and in the case of PM, higher values were observed.
- The efficiency of the heating device affects the values of emission parameters (CO_2 , NO, and NO_x).
- The higher the moisture content in the burned fuel, the higher the PM emission.

3. Some herbaceous plants (e.g., fibrous hemp, field beans, sunflower husks, plum pits, rice husks, cedar nut shells) can stabilize the concentration of gaseous products in the environment and their emissions and also constitute a promising alternative for covering the limited availability of wood biomass.

4. Technological problems (accumulation and melting of bottom ash on the grate) result in damage to the heating device.

5. Combustion of solid biofuels in modern heating devices and through certain design solutions of existing devices, e.g., an innovative solution of the design of a 13 kW boiler is the circular flow of exhaust gases around the centrally located combustion chamber, which ensures high efficiency and low-emission combustion products.

Based on the analysis of the state of knowledge based on the literature data, it can be stated that the emission of some gases from the use of different types of biomass in the combustion process and co-combustion of coal with biomass (synergism effect) may be lower than the emission from the combustion of coal alone. The combustion technology used, the design of the heating boiler, and the combustion conditions are also of great importance here. However, in the literature on the subject, no attention has been paid to the problem of improving the physical and chemical properties associated with the use of green biomass and the use of additives improving the combustion process in low-power heating devices, i.e., combining the reduction in gaseous product emissions (NO_x , SO_x , CO, CO_2 , and PM) with the reduction in ash sintering, corrosion, and the formation of deposits on the heat exchange surfaces of the heating device. Many works do not address this topic, which we can present in the conducted research. The authors did not pay attention to this aspect, so we solve the problem by the need to continue and expand research on the following:

- The course of the combustion process of biomass fuels, including green biomass;
- Factors including the implementation of new control concepts for biomass combustion devices (installation design);

- Parameters such as type, chemical properties of the biomass being burned, air, and fuel staging in the combustion chamber that affect the formation of solid and gaseous combustion products;
- Solving problems by improving the chemical and physical properties of solid biofuels and using additives that improve the combustion process, mainly in low-power heating devices, and at the same time reduce the emission of gaseous products into the atmosphere.

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