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Combustion of Granulated Solid Fuels and Wood and Domestic Waste Processing: A Comprehensive Review

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ABSTRACT

Biomass, as a separate type of granulated solid fuel, ranks third in terms of the share of generated electricity and in a number of countries is the main type of fuel in the production of thermal energy. Made for home heating systems, but might work in commercial and industrial settings as well. Fuels such as sawdust, wood chips, and wood mill waste, as well as recycled wood from disassembled pallets or furniture, often have a high energy density (16-19 MJ/kg), and their ash level varies depending on the kind of fuel. However, burning these fuels poses environmental challenges such as air pollution and greenhouse gas emissions. This work focuses on the state of production of granular solid fuels, including their types and potential applications. To understand the underlying phenomena and chemistry of combustion, as well as to design and run different combustion devices to enhance the conversion efficiency of these fuels into energy. The main study area centered on a granulation process, whereas fines are agglomerated into larger granules for better handling and combustion characteristics. It evaluates the current technology approaches employed in producing and utilizing these fuels as a granulator for domestic waste. The evidence also points to the importance of understanding the combustion processes desired for optimization, lessening environmental impacts, and the importance of pyrolytic processes in transforming solid particles that determine total combustion efficiency.

1. INTRODUCTION

Granular solid fuels contain renewable and non-renewable energy. For better combustion and handling, these fuels are refined into tiny, homogenous particles. Granular solid fuels are broadly characterized as biomass-based, waste-derived, and fossil-based. Each category impacts the energy mix differently due to its characteristics and usage [1]. In developing countries, wood and coal are the main energy sources; hence, they have long been used for lighting and cooking. Green energy from wood pellets was developed in the 1980s to reduce wood-burning air pollution [2]. Regulations on wood burner emissions in Oregon and Washington have reduced "brown cloud" effects from wood smoke, driving global demand for wood pellets, which affects the environment and regulations. In the 1980s, Idaho established the first US wood pellet factory. The 1970s oil crisis revived wood heating, prompting Oregon and Washington to regulate wood stoves, culminating in EPA guidelines in 1988 [2]. Despite these challenges, improved technology and methods are used to mitigate the consequences [3, 4]. Thus, since 2016, energy businesses, including Danish ones, have signed a voluntary industrial agreement with biomass sustainability objectives. Even wood pellets. Thus, sustainability standards compliance rose from 57% in 2016 to 70% in 2017, reducing environmental damage [5]. Today, garbage disposal and related issues are crucial to sustainable growth and environmental preservation. They say it requires government, science, and society to constantly process environmental, economic, and social obligations [6]. By reducing the greenhouse gas emissions from traditional energy sources, biomass fuels are ideal for current heating and power plants [7, 8]. Broken into granulated solid fuels, this fuel is conveniently transported and stored. In power plants and furnaces, this fuel creates energy and heat [9].

The CL categorization lists biomass, forest slag wood waste, tobacco conversion process waste, agricultural waste and fast-growing energy crops as renewable energy wastes. Biomass energy is a viable answer to future energy needs [10].

A review of pelletized solid fuel combustion studies from wood and household trash was conducted. We examined these questions:

(1) What makes wood pellets a solid fuel?

(2) How do pelletized solid fuel particle sizes affect combustion efficiency?

(3) How does biomass thermodecompose?

(4) What pellet fuel combustion systems are employed and modeled?

(5) What are solid fuel combustion's hazardous emissions?
(6) Pellets' solid fuels' life cycle?
(7) What are your thoughts on wood pellet combustion issues and pelletized solid fuels?

Methodology: keywords from previous queries were used to search “Google Scholar” and “Science Direct” for peer-reviewed scientific literature. Found article bibliographies were examined. Thus, 135 sources were chosen, comprising 29 from 2022-2024, 79 from 2015-2021, and 27 from before 2015.

2. WOOD AS A SOLID GRANULAR FUEL

2.1 Classification of pelletized biomass fuel

Biomass-based, waste-derived, and fossil fuels are granular solid fuels. Each variety has unique features and uses, contributing to the energy mix.

(1) Biomass-Based Granular Fuels

Sawdust, straw, and stems are used to make this fuel. Calcium bicarbonate and vegetable oil increase combustion and reduce impurities in these compounds [11].

(2) High-Combustion Biomass Fuel

This fuel for excellent combustion efficiency contains pine, China fir, and bagasse. It boosts combustion rate and heat value with ammonium bicarbonate and calcium peroxide [12].

(3) Compound Biomass Granular Fuel

This fuel includes sawdust, crop straws, anthracite powder, and rice husk powder. It improves combustion efficiency and reduces emissions, resolving slag bonding [13].

(4) New Biomass Granular Fuels

To increase combustion and prevent ash deposition and slag bonding, calcium oxide is added to sawdust and rice hulls [14].

Granular solid fuels provide energy production alternatives, but also pose problems. Biomass fuels are renewable and minimize net CO_2 emissions; however, slag bonding and combustion optimization are difficult [15]. Coal is abundant and dependable, but it emits greenhouse gases and pollutes the environment [16]. Developing a sustainable energy strategy requires balancing these elements.

2.2 Methods of preparation of fuel from pelletized biomass

Granulated fuel technology has advanced during the past decade. Fuel blocks and granules can be compressed under high pressure to be readily stored and handled. Wood pieces and straw are bulk fuels [17]. Palletized gasoline provides higher durability and delivery management benefits than bulk solid fuel [18]. A technical complex for manufacturing composite combinations of materials with varied physical and mechanical properties, including wood and man-made polymeric materials, was proposed in the study [19]. Granulated wood fuels may be marketed by maintaining and increasing forests, lowering greenhouse emissions like Cox, adopting green technology, and achieving fuel combustion standards [20]. Pellets created from various materials and methods are depicted in Figure 1. Understanding these disparities is critical to developing energy solutions. To reflect their purposes, wood pellets come in pre-selected forms and sizes. Most are one to 1.5 inches long and one-fourth to five-sixteenths of an inch wide. They are straightforward to maintain and utilize like regular gasoline [21]. Milled sawdust, wood chips, planer shavings, repurposed wood, and pure wood can be utilized [22]. Wheat and agricultural wastes may be used in refining procedures. To avoid collecting and dehydrating agricultural waste, small-scale furnaces consume rice husks, pistachio shells, coffee husks, and coconut debris. Figure 2 illustrates palletiser-friendly biomasses [23].

Figure 1. Illustration of granules produced from a variety of materials and procedures [24]

Figure 2. Illustration of the biomass sources that are utilized for palletization [25]

2.3 Energy value of pelletized biomass fuel

Energy from wood is 4800-5800 kcal/ton. Pulp wood has 8-9 kcal/ton of energy. About 18–21 gigajoules per ton and 4.8-5.8 per cubic meter come from dry wood. Wood boards have an estimated energy density of 8.2 GJ/m³, averaging 1200 kg/m³ due to major components and filled holes. Accordingly, wood is the best fuel with a density of 500-700 kg/m³ [26]. Table 1 lists biomass feedstock bulk density and mean energy [27]. The calorific value of wood is:

- Higher heating value at constant volume (on a dry basis);
- Lower heating value at constant pressure (on a dry basis);
- Lower heating value at constant pressure (on a wet or received basis) [28].

Table 1. Bulk density and average energy content of biomass feedstocks [29]

Biomass	Biomass Bulk Density (kg/m³)	Average Heat Value (MJ/kg)	Ref.
Pine	510	19.1	[30]
	420–670	30.20	[29]
Wheat straw	24-121	17.4	[24]
Rice straw	50-120	15.17	[31]
	154.9	13.23	[32]
Sugarcane bagasse	112-160	18	[33]
Rice husk	850	13.50 – 17.80	[34]

Birch, spruce, pine, alder, aspen, and willow bark and stems were used to make pellet fuel in Finland. Experiments created marketable biofuel from stem material. Measurements utilized 11 pellet fuel types. Pellets were 8 mm in diameter and 1-9 cm long, averaging 3 cm [35]. Each fuel was measured for calorific value, moisture, and 550°C combustion residues.

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Sawdust briquettes and particleboard are known for their high burning. Briquettes have 4800 kcal/kg, far more than typical firewood's 1800–2000. Solid wood pellet fuel, like sawdust, burns well. Particleboard also burns with significant energy, making it good for starting fires at high temperatures. Solid wood pellets emit fewer pollutants than traditional fuel, improving air quality. Agricultural residues may create 50% ash after burning; however, wood granule board briquettes yield just 1.5% [6, 36]. To use wood for fuel and other purposes, one must understand its properties and combustibility. The cost and efficiency of wood depend on the heat of combustion, moisture content and chemical composition. Combustible waste streams include wood rubbish from construction, furniture, forest, and municipal sources. Wood rubbish reduces waste and generates green energy. It may be used to incinerate and turn wood waste into thermal energy if properly sorted and processed. Used for heat or electricity, with careful management of the burning of treated or contaminated wood, including painted or chemically protected wood, to limit heavy metal and dioxin emissions [37].

3. EFFECT OF PARTICLE SIZE ON THE COMBUSTION EFFICIENCY OF GRANULAR SOLID FUELS

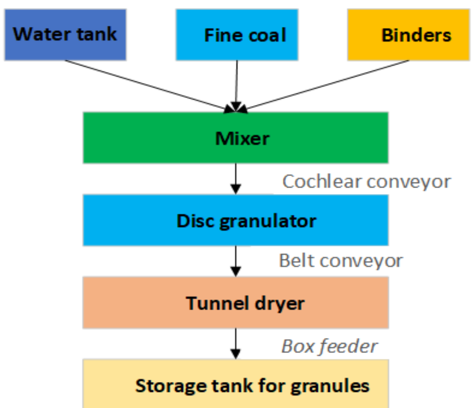
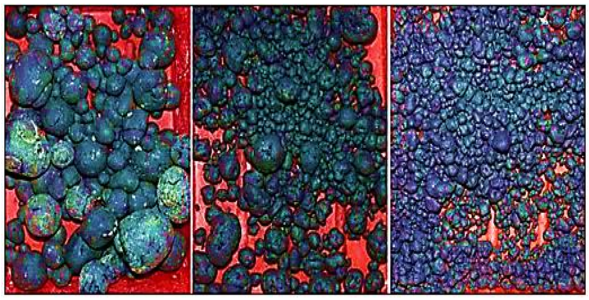


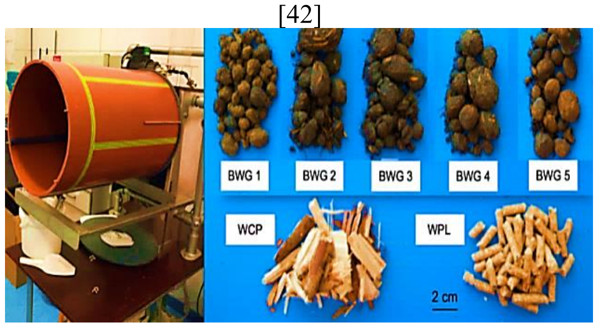
Figure 3. Block diagram of the technique for fine coal granulation [36]

The size and form of woody solid fuel particles affect combustion efficiency. However, study effects and variability differ. The increased surface area of smaller particles improves combustion performance, although this connection is complex and context-dependent. This granular fuel is commercially practical and technologically pure, increasing density and combustion efficiency [38]. Many poor nations burn wood chippings and agricultural waste as fuel due to perceived conservation [39, 40]. General inquiry encompasses theoretical and experimental investigations of solid fuel combustion [9, 41]. Furthermore, solids and household wastes are recycled to make recalcitrant granules like granulated coal and biomass pellets, which generate granular fuels by forming larger lumps from fine powder-like conditions like coal dust. Pellets of all these wastes can be used for energy production. Pulverized fine coal may be used better without harming the environment or economics. Figure 3 of the block diagram shows the fine coal cutting system for granulation technology [42]. KAHL waste granulation machines and systems compress mechanical/biological and mechanical waste after treatment for domestic trash. The invention can produce a granular product of a specified fraction size, mechanical strength, and calorific value suited for industrial fuel if scaled up industrially.

Many types of existing equipment can be used to create granular products for specific primary particles regardless of their size and shape (Figure 4). For example, the drum utilizes agricultural biowaste to blend it with further materials into pellets. These materials move and mix inside the drum to form small spherical pellets ranging from BWG1 to BWG5. The pellets comprise the following agricultural inputs: cow dung, fodder, grass-feeding, and chicken dropping.



(A) Illustration of the various fractions of granulated coal [42]



(B) Bio-waste granules (BWG 1–5) and wood fuels (WCP and WPL) [36]

Figure 4. Fractions of granulated fuel

Moreover, WCP stands for wood chip bio-pellets, and WPL stands for wood pellet bio-pellet material; it comprises small wood chips and compressed wood fibers. In its natural form or processed into charcoal or briquettes, wood fuel is normally used for heating or power generation because it is easily available and its combustion properties are fairly predictable [8, 41]. Some examples of relatively simple shapes of granulated solid fuel are presented in Figure 4(A), which includes several different shapes and types of fuel.

Figure 4(B) illustrates the diverse fractions of granulated coal, including bio-waste granules (BWG 1–5) and wood fuels (WCP and WPL).

Particle size significantly affects the combustion efficiency of granular solid fuels due to its effect on surface area, heat transfer, and reaction kinetics [43]. Fernandez-Anez et al. [44] found that smaller particles have a larger surface area relative to their size to allow this surface area to come into better contact with oxygen because oxygen is critical in promoting the ignition and combustion of small woody granular materials as well as larger particles. It increases the temperature of the material to ignite more easily than larger particles and this enhances the efficiency of combustion. The layer thickness effect also plays an important role in smaller thin layers that can be more easily ignited and thus lead to better combustion. Physical properties such as density and surface strength affect combustion efficiency as shown in Figure 5. Harder and denser materials such as coke and sewage sludge have higher ignition temperatures due to their stronger surfaces, which can limit oxygen access and reduce combustion efficiency [45]. On the other hand, small particles release volatiles faster and uniformly, which also enhances combustion efficiency, as well as large particles, which release gases more slowly or unevenly, leading to the formation of undiluted hydrocarbons or carbon monoxide, as shown in Figure 6 [46].

Figure 5. Influence of particle size and dust layer thickness on the igniting properties of PMMA dust on a heated surface [47]

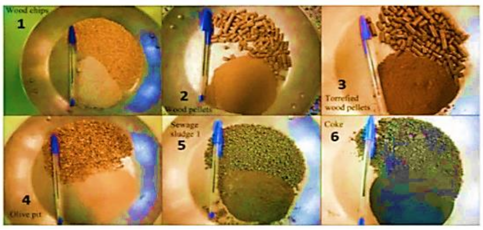


Figure 6. Different types of bulk materials and dust to study the effect of particle size [44]

4. MECHANISMS OF THERMAL DECOMPOSITION OF BIOMASS

4.1 Thermal decomposition processes of fuel from pelletized biomass

Thermal breakdown has several steps [48]:

- The biomass material is pyrolyzed at a high temperature (300°C and 700°C) during the heating step. Heat decomposes solids.
- The solid biomass decomposes when the feed temperature rises during the decomposition stage. It segments. Destruction is the goal. This step produces gaseous, liquid, and solid byproducts [49].
- Product formation: Decomposition produces various products. Carbon dioxide, methane, and other volatile gases are gases. Hydrolytic oil is liquid-based. Renewable fuel from this oil is possible. Coal: The solid pyrolysis residue can be utilized to improve soil or generate electricity [50].

One of the possible BSCC decomposition reactions related to solid waste derived from biomass is shown in Figure 7.

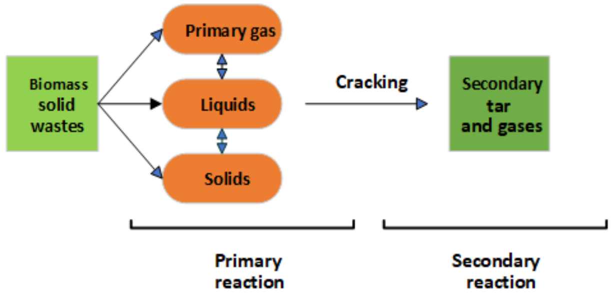


Figure 7. A potential reaction route for the pyrolysis process of biomass solid waste [48]

On the other hand, concerning Wood-granular solid fuels, Gómez et al. [51] focused on solid-granular biomass and the properties of domestic fuels. Where they discussed only the parameters necessary for proper combustion: e.g., condensation, processing, and fuel feeding; ash melting; and trends of contamination of granular fuel ash.

The main solid conversion mechanisms include drying, volatilization, and oxidation of coal. The process of thermal conversion of solid fuel is described by the simplified diagram presented in Figure 8. Trends in the pollution of granular fuel ash greatly affect the overall efficiency of the thermal conversion process.

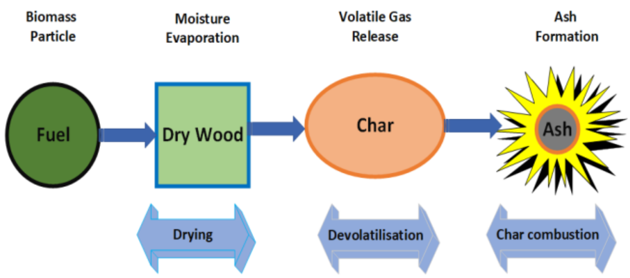


Figure 8. Solid fuel thermal conversion process schematic diagram [52]

Pollutants can lead to a decrease in thermal conversion efficiency, which not only increases energy costs but also increases environmental emissions [8]. The characterization of fuel ash is crucial, as it helps to understand how these pollutants affect the conversion process [53]. Moreover, effective fuel quality control measures are necessary to minimize pollution and ensure optimal efficiency [54]. In addition, the deposition of ash on heat transfer surfaces can exacerbate efficiency losses by necessitating more frequent maintenance and leading to unscheduled downtime [55]. Therefore, addressing pollution through improved strategies and understanding of these mechanisms and continuous monitoring and control. This is extremely important to improve the efficiency of the boiler, combustion in general, monitoring, and control. It is vital to enhance the efficiency of thermal conversion and promote sustainable energy production [56, 57].

4.2 Biomass composition

It is very important to characterize solid fuels. This should be done before combustion, to understand the possible association between the fuel's chemical and physical properties and the emission of pollutants [58]. Proximate analysis is a great tool to determine the concentration of volatile chemicals, fixed carbon, or moisture in ash and solid fuels [59]. This information is very necessary to predict the behavior of fuel combustion and the resulting energy output. Furthermore, contaminants and impurities present in granulated solid fuel that may affect its efficiency and emissions in thermal boilers can be identified using proximate analysis. One of the first things to do before using solid fuel for anything is to collect the necessary data for efficient and safe burning. Since it shows all the many changes that occur during combustion, a rough analysis is useful here. It is possible to comprehensively evaluate the fuel composition using proximate analysis, which works according to a fairly clear principle: it identifies air pollutants generated during combustion, which constitute 40-90% of combustion products by weight [60].

Ultimate analysis is another significant approach for assessing solid fuels since it offers carbon, hydrogen, nitrogen, sulfur, and oxygen information [61].

As shown in Table 2, proximal and ultimate investigations can help researchers and engineers understand fuel qualities and make informed energy production decisions [62].

Table 2. Compositions and fuel properties data

Fuel	Corncob [63]	Coal [64]	Wood [65]	Fuel as Received [66]
Proximate Analysis, wt.%				
Moisture	7.96	62.0	9.68-14.97	52.9
Volatile	85.08	50.5	75.97	37.4
Fixed carbon	13.43	47.8	21.54	9.3
Ash	1.49	1.70	2.49	0.4
Ultimate Analysis, wt.%				
C	48.1	67.7	48.45	52.4
H	6.02	4.63	6.37	5.9
O	43.96	24.9	44.11	40.6
N	0.36	0.52	1.06	0.19
S	0.05	0.30	0.02	0.0022

4.3 Combustion of fuel from pelletized biomass

Numerous investigations and tests have been conducted to develop mathematical models that faithfully simulate the combustion of biomass [67].

Since hydrogen, carbon, and oxygen constitute the majority of biomass fuel, carbon dioxide and water are the main by-products of biomass combustion. Depending on the calorific value of the fuel, the moisture content, the amount of air used to burn the fuel, and the design of the furnace, the flame temperature can rise above 2000°C [68].

The following basic steps must be in place to complete the combustion process: The first stage of fuel combustion is called ignition. For ignition, it requires a heat source or spark. Once ignited, the flame grows through the fuel, consuming it and releasing heat. As the fuel burns, the heat is then released to create thermal energy, which can be used for various tasks such as heating water or generating electricity [8]. Finally, the exhaust gases produced after combustion include carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O), oxygen (O_2), and nitrogen (N_2). These are the actual compositions of the products of complete combustion, as shown in Figure 9, which shows how often some of the gases released from combustion are released into the atmosphere [6].

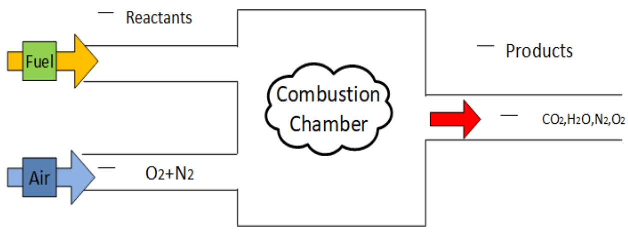


Figure 9. Diagram showing the fuel combustion process

Numerical and computational models for precise and detailed combustion product temperature and concentration fields in granulated fuel layers are the major focus of the evaluated research. Models that account for the fuel burning's complicated porous structure and heterogeneity simulate combustion more accurately [69]. These models also take into consideration airflow and diffusion in the oxidizing media. Calorimetric investigations of solid granule fuel combustion and wood and household waste treatment might improve energy production technologies more effectively and sustainably [70]. These models can help us understand combustion processes and build more efficient and sustainable energy production methods [71]. Mathematical and computational models can transform energy production and environmental effects [72]. These models enable combustion process optimization and environmental protection by exactly calculating combustion product temperature and concentration fields [73].

Char burns during fuel-oxidizer contact. Therefore, special attention was paid to the study of the role of gas-phase combustion and pyrolysis in particle conversion. During char combustion, particle temperature peaks at 1800 K and stays there until char burns out. Thermal balance is restored [74]. The porous nature of granulated solid fuel combustion must be considered [38]. During combustion, it studies oxidizing medium mass transfer and granule structure destruction.

Figure 10 displays typical simulation results for a reactor burning a 10 mm spherical beech wood particle in air at 1223 K.

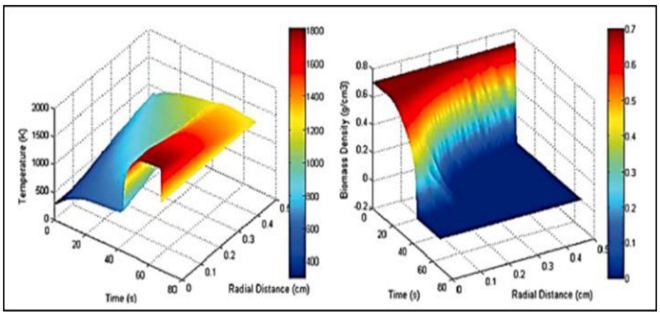


Figure 10. The typical simulation results for the combustion of a 10 mm spherical beech wood particle burned in the air at a temperature of 1223 K in the reactor

Notes: Copyright 2011, Elsevier; adapted with permission from the study [75]

4.4 Chemical reactions in combustion from pelletized biomass

Combustion heat measures fuel heating value. Heat energy is released by the enthalpy shift in the chemical reaction, which usually involves oxygen [76].

This reaction generates heat. The biomass combustion stoichiometric Eq. (1) is [77]:

$$\textit{Biomass} + \textit{Air} \rightarrow \textit{Carbon dioxide} + \textit{Water vapor} + \textit{Nitrogen} + \textit{Heat} \quad (1)$$

Nitrogen oxides (NO, NO_2), ammonia (NH_3), oxygen (O_2), carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and water vapor (H_2O) are the most critical components of the gaseous biofuel [78]. Solid residues comprise ashes, calcium, iron, silicon, and aluminum oxides. In various combustion processes, such as those employed in industrial, transportation, and residential applications, the heat of combustion is a critical parameter for determining the energy content and performance of fuels. It is also essential to create energy-efficient and ecologically friendly fuel production and use [79]. The analysis of heat of combustion provides useful insights into the environmental effect, emissions, and combustion efficiency of various fuel sources, aiding future efforts to produce sustainable and clean energy solutions [80].

The discharge of energy from a material because of exposure to oxygen is known as combustion, a rapid chemical reaction. The fuel in thermal boilers reaches its autoignition temperature when appropriately pressured and heated. The chemical reaction rate sets combustion apart from other types of rapid oxidation [81].

The primary chain of chemical reactions in the combustion of carbon compounds is the combustion of carbon:

$$CO + OH; CO_2 + H$$

The equation describes how carbon monoxide is depleted from the gas phase in response to hydroxyl. It is regarded as the primary combustion reaction, as it involves the oxidation of CO with hydroxyl. At elevated temperatures, CO_2 can undergo dissociation by reacting with hydroxyl:

$$CO_2 + H \rightarrow CO + OH$$

A mono-molecular mechanism is responsible for the oxidation of hydrogen and hydrocarbons. This reaction optimally leads to the formation of CO_2 and H_2O in the case of hydrocarbons. Oxygen is consumed, and CO_2 is reduced to monoxide in the presence of solid particulates [82]. As a result, the concentration of CO_2 in the vicinity of the particles increases, resulting in a concurrent CO_2 gradient between the gas phase and the particles. The temperatures of the tube walls in furnaces exceed those characteristics of the typical flue-gas environment, characterized by the combustion of a homogeneous mixture of gases and particles [83]. Layer combustion of granulated solid fuels involves complex physicochemical and fluid-dynamic processes. Always start with ignition. Hot solid fuel decomposes, emits flammable gases, and loses moisture. Released gases and volatiles ignite when the fuel combustion air is hot enough. It starts with granulated solid fuel combustion [84]. The main combustion research areas involving chemical reactions include:

- Basic chemical kinetic experiments to quantify biomass coal secondary friability under gasification conditions (Figure 11).
- Development of detailed or skeletal chemical kinetic mechanisms. Combustion of charged or radical-type species.
- The creation and use of combustion diagnostics in experiments.
- Numerical simulations and models for combustion research.

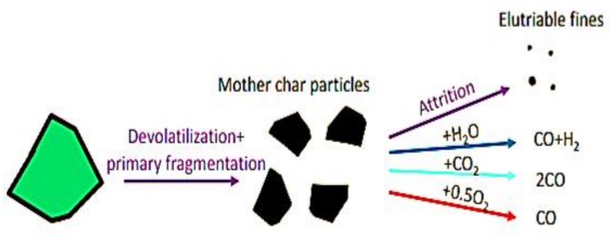


Figure 11. Schematic of primary combustion and chemical kinetics in the coal conversion model [85]

4.5 Pyrolysis

Watching this untreated substance turn into combustion gases is interesting, which leads to the power generation system [8, 86, 87]. Verissimo et al. [88] also found that the use of new simulations involves the use of pyrolysis models that predict smaller amounts of coal. Therefore, the basic kinetic mechanisms of the model of pyrolysis and combustion of granular solid fuels involve complex chemical reactions and physical processes. These mechanisms are influenced by the model and composition of the wood granular slab, the conditions under which this decomposition occurs, and the mathematical modeling that is used to describe these processes. Pyrolysis is considered a key step in the combustion of solid fuels in the absence of oxygen, leading to the formation of coal, gases, and liquids. This process is considered solved to improve the combustion of wood granular solid fuel.

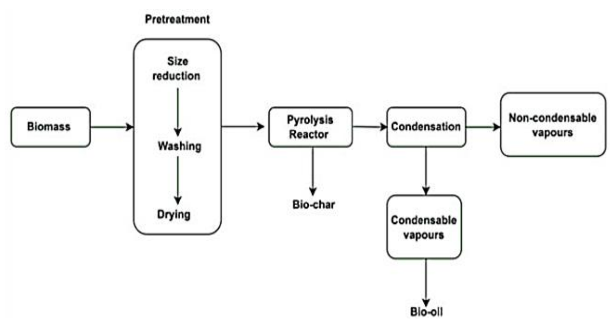


Figure 12. A comprehensive process flow diagram for the pyrolysis procedure [86]

Among the models, techniques and kinematic methods are:

(1) Pyrolysis has two stages: primary and secondary. Secondary pyrolysis decomposes byproducts after the first pyrolysis crushes biomass. Various kinetic models have been devised to represent these stages, although biomass complexity makes general models problematic [89].

(2) Kinetic analysis techniques

The Kissinger-Akahira-Sonose and Flynn-Wall-Ozawa (FWO) techniques are used to investigate pyrolysis kinetics. For pyrolysis system design, these approaches determine activation energy and reaction processes. A single reaction model with activation energies of 180 kJ/mol was developed for the pyrolysis of particleboard manufacturing fine-particle Emery wood waste (FPSW) [90, 91]. According to Chen et al. [92], materials impact solid fuel pyrolysis and combustion, with the cellulose, hemicellulose, and lignin contents of particleboard affecting its pyrolysis. Various components' pyrolysis reactions impact kinetics and product distribution. Lautenberger and Fernandez-Pello [93] stated that conduction, convection, and radiation affect solid fuel pyrolysis. Increasing pyrolysis and combustion efficiency depends on these mechanisms. Pyrolysis, which breaks chemical bonds in solid fuels to produce gaseous products at high temperatures, directly affects combustion efficiency, heat transfer, electrical charges, and NO_x generation and destruction in combustion systems [94]. Heat transfers electrical charges, combustion efficiency, and NO_x generation and destruction are affected [95]. Knowledge of pyrolysis also guides other clean and efficient combustion methods. The pyrolysis process flow diagram is shown in Figure 12.

5. DESIGN AND OPERATION OF COMBUSTION SYSTEMS

5.1 Methods of combustion of pelletized biomass fuel

When planning, building, and running a combustion-based system that processes any granulated solid fuel, key design factors must be considered [96]. Analysis of fuel characteristics, combustion system compatibility, and fuel preparation. Designs for granulated solid fuel combustion systems are complicated. The qualities of solid fuel particles and the procedure to be utilized have a big impact on proximal and final data for each fuel.

Numerical studies have also simulated biomass combustion in a fixed/moving bed kiln that burns granular solid fuels to see how circumstances and factors affect combustion [97].

The most energy- and environmentally-efficient way to burn granulated solid fuel is via fluidized bed and stationary bed combustion [98, 99]. Industrial applications and power production benefit from these methods' high combustion efficiency and low emissions. Fluidised and stationary bed combustion involves. Solid fuel particles are suspended in mobile layers or organized horizontally on a filamentary grid for permanent layers into an upward airflow to improve fuel-air mixing and combustion efficiency [100]. These systems manage biomass and coal efficiently and are adaptable across deployment levels. They alter the fuel-air mixture to burn fuel particles fully to improve combustion efficiency. Regulating fuel combustion temperatures in mobile and fixed layer systems improves combustion, maintains reaction conditions, reduces energy loss, and reduces NO_x, SO_x, and CO_2. Solid fuel combustion with ash management recycles ash, reducing waste and environmental effect (Figure 13) [101].

Burning biomass (pelleted solid fuels) depends on particle size, oxidizer residence time, and other parameters. The main combustion equipment is fixed bed (grids) and fluidized bed. In fixed-bed equipment, the solid stays still while the oxidizer reacts through the solid particles' spaces. Pressure from the oxidizer moves the fluidized bed [102].

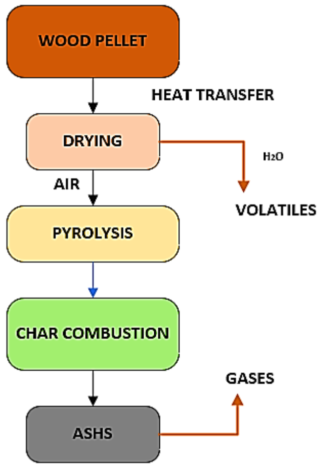
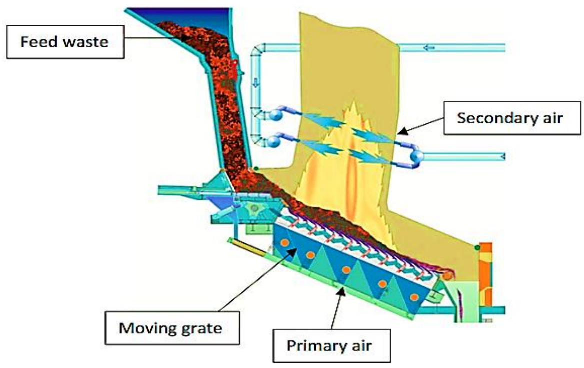
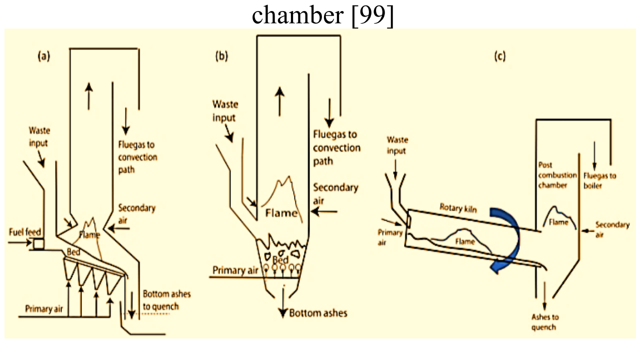


Figure 13. Methodology for combustion of wood pellet solid fuels [87, 103]

5.2 Models for a fluidized bed for granulated solid fuel combustion



(A) Schematic diagram of a moving grate combustion chamber [99]



(B) The most prevalent waste conversion devices, depicted in the form of combustors: (a) grate (moving bed), (b) fluidized bed, and (c) directly heated rotary kiln with post combustor [99]

Figure 14. Biofuel combustion scheme in the bed

Due to excellent heat transmission, compact infrastructure, and self-cleaning, fluidized bed furnaces seem promising for granulated solid fuel combustion [38]. Fluidized bed reactors have a higher heat transfer coefficient and more even bed temperature than moving grate reactors, improving efficiency and minimizing maintenance [73]. Fluidized bed combustion of mixed fuel grains is feasible for small-scale power engineering because ignition delay times decrease with wood component size [74, 104]. Because it burns low-quality fuels with various properties, fluidized bed combustion is effective for waste-to-energy applications [104, 105].

Most combustion methods use grate and fluidized bed furnaces. The moving grate kiln is the most typical for burning coal and rubbish [99]. The grid kilns burnt livestock feed and waste. The moveable grate combustion chamber burns MSW to generate power [99, 106]. Figure 14 illustrates adding MSW to a moving network. High temperatures incinerate garbage over the net. The high temperatures incinerate waste as it goes over the net [8]. Turbines create electricity from combustion steam. Animated matrix helps. Keeping garbage supplies steady promotes municipal solid waste burning [107]. This method uses municipal solid waste to create power while reducing pollution [99].

A solid fuel bed is ignited against airflow in an indirect-fired fixed-bed combustion system. Heat ignites oxygen-oxidized solid fuel [100]. Figure 15 illustrates how biomass, particle size, and air-fuel ratio affect fixed-bed combustion furnace evaluation.

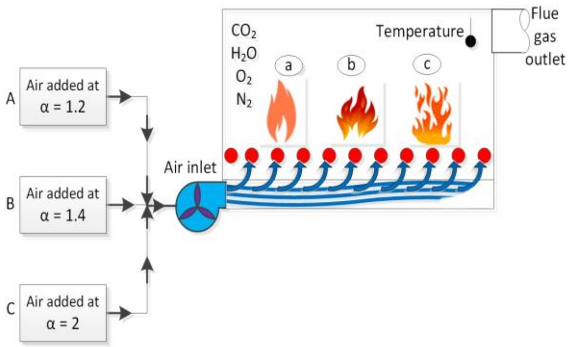


Figure 15. Biomass combustion at different excess air ratios [108]

5.3 Models for fixed-bed combustion systems for granulated solid fuels

To complete fuel combustion in the stoichiometric ratio, the surplus air coefficient (α) represents the extra volume of air (V_B) delivered at the required rate (V_B^0).

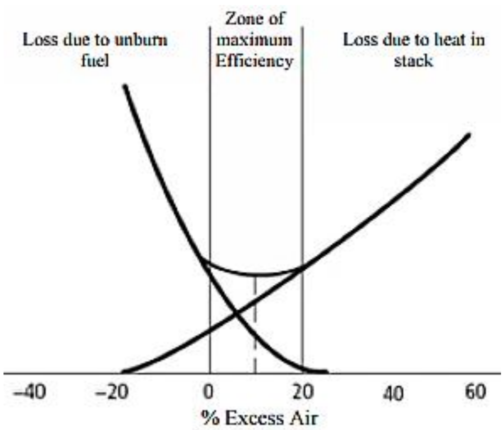


Figure 16. The effect of excess air on boiler efficiency [109]

According to Eq. (2), this coefficient determines the ratio of supplied air (oxygen) to stoichiometric or theoretical air (oxygen) needed to burn wastes and solid combustible on the grate boiler. Combustion requires fuel, air, and heat [109, 110]. When any of the three is eliminated, combustion stops. Since heat brings additional fuel into the combustion process, all three will burn independently if they are present in sufficient quantities. As shown in Figure 16, joining extra air as a fixed or movable grille affects boiler efficiency [109]:

$$\alpha = \frac{V_B}{V_B^0} \approx \frac{21}{21 - (O_2 - 0.5CO)} \qquad (2)$$

where, V_B is the actual volume of air supplied to the boiler furnace per 1 kg of fuel, V_B^0 is the stoichiometric volume of air required for combustion, O_2, and CO is the content in combustion products, volume%.

5.4 Governing equations

In pellet stoves and boilers, chemical, thermodynamic, and fluid dynamics equations control the burning of wood pellets or biomass briquettes. During operation, equations define fuel, air, and combustion byproduct dynamics [111].

The subsequent are the principal mathematical frameworks:

(1) Chemical reaction equation

The generalized combustion reaction for a biomass-based solid fuel (approximated as CH_xO_yNz) is:

$$\mathit{Fuel} + O_2 \rightarrow CO_2 + H_2O + N_2 + \mathit{Other\ species} \qquad (3)$$

Example simplified reaction (stoichiometric combustion):

$$CH_xO_y + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 \qquad (4)$$

where, *a*, *b*, *c*, and *d* are the coefficients that are determined by elemental balancing of C, H, O, and N.

(2) Mass conservation (continuity equation**)**

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = m_{source} \qquad (5)$$

where, ρ is density, t is time, u is velocity vector, m_{source} is mass source term (e.g., devolatilization).

(3) Energy conservation equation

$$\rho c_p\left(\frac{\partial T}{\partial t} + u\nabla T\right) = \nabla(k\nabla T) + Q_{reaction} + Q_{\mathrm{radiation}} \qquad (6)$$

where, c_p is specific heat, T is temperature, k is thermal conductivity, $Q_{reaction}$ is heat release from combustion, $Q_{\mathrm{radiation}}$ is radiative heat transfer (important in stoves and boilers).

(4) Species conservation equation

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla(\rho u Y_i) = \nabla(D_i \nabla Y_i) + \omega_i \qquad (7)$$

where, Y_i is mass fraction of species i, D_i is diffusion coefficient, ω_i is reaction source term for species i.

(5) Momentum conservation (Navier-Stokes equations)

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u) = -\nabla p + \mu\nabla 2u + \rho g \qquad (8)$$

Equations govern the movement of gases (air and combustion products) within the system.

(6) Devolatilization and char combustion kinetics

$$\frac{dm_v}{dt} k_v e^{-\frac{Ev}{RT}}(m_{v,0} - m_v) \qquad (9)$$

where, m_v is mass of volatiles, k_v is pre-exponential factors, Ev is activation energies, R is gas constant.

(7) Char oxidation

$$\frac{dm_c}{dt} = k_c e^{-\frac{E_c}{RT}} (O_2)^n \qquad (10)$$

where m_c is the mass of char, k_c is the pre-exponential factors, E_c is the activation energies.

(8) Radiative Heat Transfer (for enclosed systems)

$$Q_{radiation} = \epsilon\sigma\left(T^4 - T^4_{surroundings}\right) \qquad (11)$$

where, ϵ is emissivity, σ is the Stefan-Boltzmann constant.

Microcomputer simulations and CFD modeling of boiler biomass combustion facility (Figure 17). The findings support the combustion hypothesis. Excess air coefficient α is the only factor affecting combustion efficiency. Trash burning and boiler outlet environmental gas temperatures require this time.

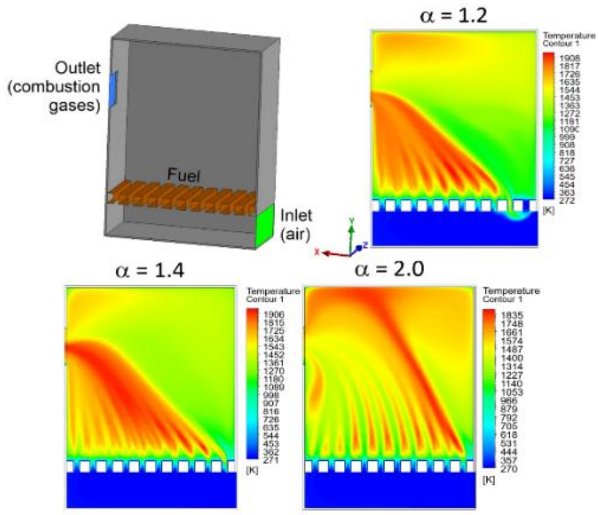


Figure 17. Example CFD model of a furnace for biomass combustion and the effect of excess air on combustion [112]

6. EMISSION REDUCTIONS AND EFFICIENCY PELLET COMBUSTION

National competition for sustainable energy sources demands reducing emissions and pollution. For international competitiveness, governments must preserve the environment and energy. Supporting solid fuel burning, developing technology, and discovering new fuels is vital [113].

Yang et al. [114] used a stationary combustion machine to test MSW and other materials. Circle-shaped, its main vertical cylinder is horizontal on support pieces. Researchers can burn enough material by balancing [115]. The apparatus chamber is insulated to maintain combustion temperatures. Combusted material fits fine through the base's perforated mesh. A probe samples fuel combustion gases like nitrogen (N_2), carbon monoxide (CO), oxygen (O_2), and carbon dioxide (CO_2) [116]. The type of material burnt, temperature, and airflow may be monitored and adjusted by researchers to improve fuel combustion and decrease hazardous emissions. Device shown in Figure 18 [117, 118].

A comprehensive study entitled "Evaluation of the efficiency and emissions of a pellet boiler burning multiple types of pellets" provides detailed experimental data on the combustion efficiency and environmental impacts of various pellet fuels, including wood pellets. The research was carried out using a 20kW pellet boiler with a movable grate burner, complying with PN-EN 303-5:2012 as shown in Figure 19 [119, 120].

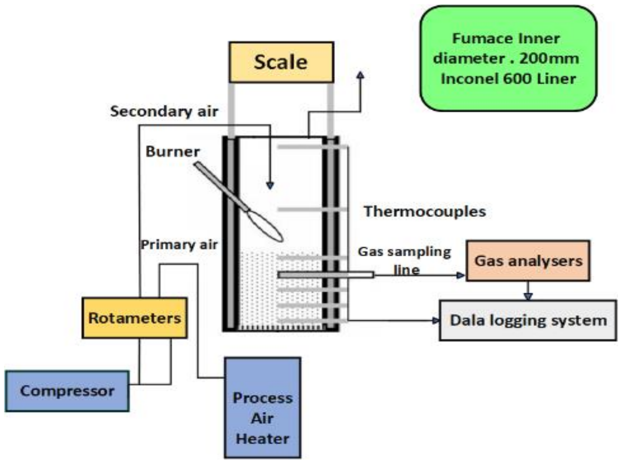


Figure 18. Schematic of testing arrangement

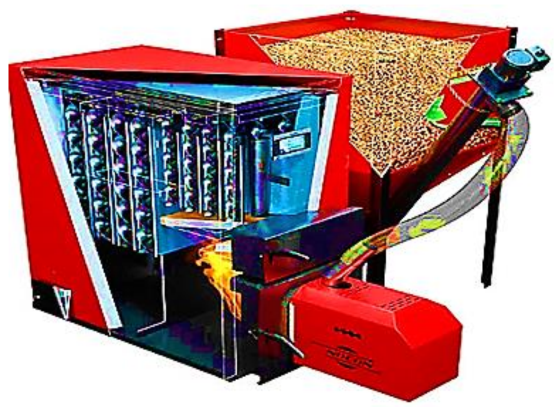


Figure 19. Cross-section of tested solid fuel boiler [119]

7. GRANULATED SOLID FUEL LIFE CYCLE, ENVIRONMENTAL EFFECT, AND ASH DISPOSAL

(1) Stage of production

Understanding the production, transportation, combustion, and waste treatment phases of granulated solid fuels is crucial to assessing their environmental impact and finding ways to reduce greenhouse gas emissions, air pollution, and resource depletion.

(2) Raw materials processing and sourcing

Biomass or waste granules require agricultural or municipal waste. Here, energy-intensive drying, crushing, and pelletizing may affect the environment Li et al. [121]. Show that Canadian Prairies wheat straw pellet dehydration and pelletization lead to global warming and other environmental challenges. Bioprocessing biowaste is significant now [122].

(3) Process energy consumption

Compression molding is energy-intensive. The straw briquette fuel's life cycle consumes a lot of energy in this phase [123].

(4) Transportation

The transfer of solid fuels from production to usage may affect carbon emissions. Substituting Coke in cement kilns reduces emissions from transporting recovered solid fuel, which is 35.6 kg of 2-ton equivalent [124].

(5) Combustion

Burning releases pollutants and energy. Granulated solid fuel burning emits CO_2, SO_2, NO_x, and PM. Fuel type and combustion technology affect emissions. Coal and wood pellets emit CO_2 and other pollutants, Rajkumar et al. [125]. Hydrocar granules replace coal in combined heat and power plants, improving health, ecosystems, and climate change.

(6) Waste management

To prevent environmental damage, solid fuel ash must be managed. The disposal of coal combustion waste poses health and environmental risks [126]. Using municipal solid trash and agricultural leftovers for fuel can enhance resource efficiency and reduce dependency on virgin materials [6].

8. ADDRESSING GAPS IN WOOD PELLET COMBUSTION

Air management and flue gas recirculation improve wood pellet fuel combustion. Kokkali et al. [127] showed that air circulation and flue gas recirculation in small boilers can reduce CO_2 and NO_x emissions, suggesting future research. Mack et al. [128] stressed the need to improve fuel design to address pellet quality and combustion efficiency. Zhang et al. [129] and Hamza et al. [130] showed that pelletized biomass may significantly lower emissions, but they stressed the need to better understand particular pollutants such as PAHs. Hamza et al. [130] found that roasting and pelletizing wood pellets reduces greenhouse gas emissions compared to coal. Table 3 outlines the study's subjects, methods, and key limitations.

Table 3. Summary of key studies, key methods, and limitations used that address gaps in wood pellet combustion

Topics Covered	Methods Used	Key Limitations	Ref.
Optimizing stove design for energy efficiency and CO reduction	Experimental tests and computational modeling	Design limitations like poor air supply and fume extraction	[131]
Comparison of wood pellets and torrefied pellets with coal	TGA, Bomb Calorimetry	Solely covers combustion and exhaust basics, not field conditions	[130]
Emission analysis of pelletized biomass combustion	Laboratory emission measurements	Issues with NO_x and SO_2 persist; inadequate emission profiles	[129]
HTC pellets burn more efficiently than softwood pellets.	Kinetic modeling, combustion tests	Focused on efficiency benefits, not all pollutants	[132]
Impact of fuel variability on combustion emissions	Comparative analysis across different pellet compositions	Accounting for emission changes due to fuel heterogeneity	[133]

9. CONCLUSIONS AND PROSPECTS FOR GRANULAR SOLID FUELS

This study briefly explores solid fuel granule combustion using household waste and biomass. The article emphasizes biomass, the third greatest source of electrical and thermal energy. Granular solid fuels are becoming more important in energy. Energy self-sufficiency and rising fossil fuel prices demonstrate this. Solid fuel burning regenerates energy but emits greenhouse gases and air pollution. The research recommends fixing these issues to improve energy practices.

Combustion process improvement, or combustion system design and management, remains complex. Fuel consumption efficiency and combustion chemistry are covered.

Alternative drying methods research: Improved biomass drying can increase combustion energy.

Integrating Analytical Models: Understanding solid granular fuel behavior under diverse conditions can assist combustion system operations analysis models in maximizing energy production.

In conclusion, solid granular fuel burning reduces greenhouse gas emissions and improves combustion efficiency. New technology and approaches will boost biomass and waste energy generation.

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