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Thermal Pre-treatments of Woody Biomass: A High-Level Overview

Toplinski predtretmani drvne biomase: opći pregled

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ABSTRACT • *The global demand to reduce CO_2 emissions has led large industrial pollutants, particularly power generation and metallurgical sectors, to search for alternatives to traditional fossil fuels like coal. Wood pellets have emerged as a recognized cleaner alternative. Yet, pellets fall short of coal key properties, notably in calorific value and storage stability. By subjecting the feedstock for wood pellet production, namely woody biomass, to thermal pre-treatments like torrefaction or steam explosion, these limitations can be mitigated. These treatments reduce moisture content, increase energy density, and enhance storage stability, making the wood pellets produced from thermally treated feedstock more similar to coal and compatible with existing coal infrastructure. While these pre-treatments offer potential energy savings and other benefits along the process of pellet production and supply chain, they might also necessitate significant capital investments. This review provides a concise overview of thermal pre-treatment technologies, necessary parameters, their impact on treated woody biomass, as well as final characteristics of treated woody biomass.*

KEYWORDS: *torrefaction; steam explosion; biofuel; industrial application; renewable energy*

SAŽETAK • *Globalna težnja za smanjenjem emisije CO_2 potaknula je velike industrijske onečišćivače, posebice iz sektora proizvodnje energije i metalurgije, da potraže alternative tradicionalnim fosilnim gorivima poput ugljena. Drvni pelet nameće se kao prepoznata čišća alternativa. Ipak, svojstva peleta zaostaju za ključnim svojstvima ugljena, posebice po kalorijskoj vrijednosti i stabilnosti pri skladištenju. Podvrgavanjem sirovine za proizvodnju drvnog peleta, prije svega drvne biomase, toplinskim predtretmanima poput torefakcije ili parne eksplozije, ti se nedostatci mogu smanjiti. Toplinskim predtretmanima smanjuje se sadržaj vode, povećava energetska gustoća te poboljšava stabilnost tijekom skladištenja, što drvni pelet proizveden od toplinski predtretirane sirovine čini sličnijim ugljenu i kompatibilnijim s postojećom infrastrukturom za upotrebu ugljena. Iako spomenuti predtretmani nude potencijalne energetske uštede i neke prednosti u procesu proizvodnje peleta i lanca opskrbe, oni ujedno zahtijevaju i znatna kapitalna ulaganja. Ovaj pregledni rad donosi sažeti pregled tehnologija toplinskih predtretmana, potrebnih parametara, njihova utjecaja na obrađivanu drvnu biomasu, kao i konačnih svojstava obrađene drvne biomase.*

KLJUČNE RIJEČI: *torefakcija; parna eksplozija; biogorivo; industrijska primjena; obnovljiva energija*

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1 INTRODUCTION
1. UVOD

Global demand to reduce CO_2 footprint and harmful emissions into the atmosphere has most recently become an imperative. This situation has led us to search for alternative fuel solutions for heat and energy generation, which will provide similar utilization properties (storage, transportation, handling, and energy outputs) as fossil fuels, while releasing less harmful gasses into the atmosphere and being economically feasible. Solid biomass has imposed itself as one of the main alternative options for these applications. Solid biomass is considered as residuals from the forestry and wood industry operations, as well as agricultural and municipal wastes (Malico *et al*., 2019). Currently, the most commonly used type of solid biomass is woody biomass, in the form of residuals from the wood processing industry, namely, sawdust, shavings, and wood chips (García *et al*., 2019; Nielsen *et al*., 2009). Other types of woody biomass, such as harvest residues and pulpwood can also be used. However, woody biomass in its original form has certain limitations as fuel when compared to fossil fuels. Specifically, biomass high moisture content and low bulk density make it less efficient when being handled and combusted (García *et al*., 2019). For these reasons, woody biomass is compressed/pelletized into wood pellets, in order to improve its energy density and handling characteristics, which consequently improve biomass performance along the supply chain (Dujmović *et al*., 2022; Abelha and Cieplik, 2021).

As a result of various policies and incentives to reduce harmful emissions, as well as to tackle increased prices of mainstream energy sources such as gas and power, wood pellets have been widely used by both residential and industry sectors (Eurostat, 2017) in Europe for the last couple of decades.

Most recently, even more intense global push to reduce emissions of harmful gasses has been implemented in the countries worldwide in the form of various laws and policies that primarily target larger industrial pollutants, such as power plants, iron and steel producers, and other heavy industries that still mainly rely on coal as their fuel. Consequently, the need for cleaner fuel solutions has further increased, mainly driven by these heavy industries complying with the newest demands for the reduction of emissions. Heavy industries were required to partially supplement or even completely replace their current fossil fuel needs with some form of cleaner alternative, such as wood pellets (McKechnie *et al*., 2016).

However, despite these benefits, wood pellets still fall short of coal properties. Heavy industry users specifically seek even higher energy density and superior mechanical properties to achieve greater similarity in transportation, storage, and combustion characteristics between wood pellets and coal.

Therefore, woody biomass requires additional treatment, in order to turn it into more desirable feedstock for the production of wood pellets, which could then replace fossil fuels in industrial applications such as steel and iron industries. These additional pre-treatments are typically of a thermal nature, where biomass is treated under various controlled conditions and raised temperature, all in order to upgrade biomass characteristics to make it more susceptible for further processing and utilization by the industry (Abelha and Cieplik, 2021; Cahyanti *et al.*, 2020).

This high-level overview intends to summarize and condense process technologies and necessary parameters of thermal pre-treatments of woody biomass. It also provides their chemical and physical impact on treated woody biomass, as well as final characteristics of the treated biomass, which is typically intended to be further pelletized and used as a biofuel by industrial users.

2 TYPES OF THERMAL TREATMENTS
2. VRSTE TOPLINSKIH POSTUPAKA

Thermal pre-treatments change chemical and physical characteristic of treated raw woody biomass. Changed physical properties and chemical composition of the processed feedstock has a positive impact on the whole biofuel supply chain, from production to final energy utilization (Christoforou and Fokaides, 2018; Christoforou and Fokaides, 2016). In particular, thermal treatments of feedstock prior or after pelletization, can decrease its moisture content while increasing its calorific value, improve chipping/milling and bonding/pelletization properties, as well as increase its final bulk density, hydrophobicity (Abelha and Cieplik, 2021), and even grindability, which becomes an important parameter if treated biofuels, as substitutes for coal, are to be pulverized prior to co-firing (Chen *et al*., 2015). Currently, torrefaction and steam explosion are among the most known thermal pre-treatments of woody biomass.

Torrefaction involves heating the feedstock at moderate temperatures, typically between 200 °C and 300 °C, to enhance its energy density and other fuel properties. In contrast, steam explosion employs high-temperature, high-pressure steam followed by rapid depressurization to disrupt the cell structure of the treated feedstock, thereby improving its suitability for subsequent processing and use as a fuel.

In addition to torrefaction and steam explosion, pyrolysis is another significant thermal treatment that should be acknowledged. Pyrolysis occurs at higher temperatures (>300 °C) than the two above-mentioned treatments, in the absence of oxygen. This treatment leads to the decomposition of the feedstock, producing biochar, bio-oil, and syngas, all of which can be further utilized as biofuels for energy generation (Mohan *et al*., 2006).

Even though pyrolysis is an effective thermal treatment for enhancing the properties of woody biomass, this review will specifically concentrate on torrefaction and steam explosion, for which high-level overviews are provided in the following sections.

3 TORREFACTION
3. TOREFAKCIJA

3.1 Torrefaction technologies and parameters
3.1. Torefakcijske tehnologije i parametri

Torrefaction is a thermo-chemical biomass treatment, also considered as mild pyrolysis (Christoforou and Fokaides, 2018), as it is done inside an inert atmosphere under similar conditions to those of pyrolysis. It is carried out in the controlled non-oxygen environment, which is typically attained through flowing nitrogen gas inside the stainless steel-reactor (Kizuka *et al*., 2019).

Christoforou and Fokaides (2018) have summarized the existing torrefaction technologies, based on Cremers *et al*. (2015) study. They have listed the following types of reactors: rotary drum, screw conveyor, multiple heat furnace (MHF) or Herreshoff oven, fluidized bed reactor (torbed reactor), moving bed reactor, and microwave reactor. Each of the above reactors has their specific features, such as size and capacity, sensitivity to feedstock quality, maximum allowed temperature, energy consumption, and overall efficacy, all providing options for different torrefaction applications.

Torrefaction is considered mild pyrolysis as it takes place at temperatures between 190 °C and 320 °C (Tran *et al*., 2013; Cahyanti *et al*., 2020; Rousset *et al*., 2013; Föhr and Ranta, 2017; Kizuka *et al*., 2019), as opposed to regular pyrolysis, which takes place at higher temperatures, between 350 °C and 650 °C (Chen *et al*., 2015; Tran *et al*., 2013). Apart from the temperature, residence/duration time plays an important role in the torrefaction process. As reported by a number of studies (Shang *et al*., 2014; Föhr and Ranta, 2017; Kizuka *et al.*, 2019), the typical duration of the torrefaction process is between a couple of minutes to up to two to three hours.

The level of torrefaction severity depends on two above-mentioned main parameters of the process: residence time and process temperature. Therefore, depending on the combination of these two said parameters, torrefaction can be classified into light, medium, and severe levels. However, within the typical range of torrefaction parameters (1-2 h, 200-300 °C), temperature has a prevailing influence on the properties of treated biomass (Chen *et al*., 2015), making it the crucial parameter that determines the level of severity. With that said, each temperature range of the process has a certain impact on the components of the treated woody biomass. Generally, lower process temperatures have lower impact on the material, while increased temperatures result in higher levels of degradation and weight loss.

3.2 Torrefaction process and its impact on treated woody biomass
3.2. Proces torefakcije i utjecaj na tretiranu drvnu biomasu

Woody biomass is mainly comprised of hemicellulose, cellulose, and lignin (Chen *et al*., 2018). The severity of the biomass torrefaction is then characterized by the level of degradation of these three components during the process. Specifically, the direct quantifier of the level of torrefaction is the weight loss of the treated biomass. The weight loss is mainly caused by decomposition of hemicellulose and cellulose during the process. Lignin, on the other hand, is the most difficult component to be thermally degraded, hence torrefaction impact on it is very low (Chen *et al*., 2015). Furthermore, the weight loss is also coming from the reduction of the moisture content of the treated biomass during the process, as well as due to the partial loss of the volatile matter (Kizuka *et al*., 2019; Acharya *et al*., 2015).

To summarize, Christoforou and Fokaides (2018) have provided five main stages of the torrefaction process, as described by Bergman (2015). The initial stage was described as the heating of the treated biomass, where the increase in feedstock temperature is observed. This stage is followed by the pre-drying stage, at around 100 °C, in which free water is evaporated from the biomass. Further increase of the temperature to up to 200 °C continues to increase feedstock temperature, starting to release some of the bound water. This is followed by the fourth stage, where the temperature rises above 200 °C, and the torrefaction itself begins. In this stage, treated feedstock is depolymerized, partially devolatilized, and carbonized (Christoforou and Fokaides, 2016). And finally, after the intense torrefaction stage, now torrefied feedstock is cooled down to desired temperature.

The impact of each temperature range classified into the level of torrefaction severity can be found in Table 1, derived from Chen *et al*. (2015), and Chen and Kuo (2011) studies.

Torrefied biomass, depending on the process severity, typically becomes darker in color, when compared to the initial biomass before treatment. As per Chen *at al*. (2015), light torrefaction results in brown

Table 1 Impact of toreffaction on main components of woody biomass
Tablica 1. Utjecaj torefakcije na glavne komponente drvne biomase

Severity level *Intenzitet*		**Light** *lagani*	**Medium** *srednji*	**Severe** *jaki*
Temperature, °C / *Temperatura,* °C		200-235	235-275	275-300
Impact on component *Utjecaj na komponentu*	Hemicellulose *hemiceluloza*	medium / *srednji*	medium to severe *srednji do jaki*	severe / *jaki*
	Cellulose / *celuloza*	slight / *blagi*	medium to severe *srednji do jaki*	medium to severe *srednji do jaki*
	Lignin / *lignin*	slight / *blagi*	slight / *blagi*	slight / *blagi*

Table 2 Impact of toreffaction on main chemical parameters of woody biomass
Tablica 2. Utjecaj torefakcije na glavne kemijske parametre drvne biomase

Torrefaction temperature, °C *Temperatura torefakcije,* °C	**Moisture content, %** *Sadržaj vode,* %	**Ash content, %** *Sadržaj pepela,* %	**Volatile matter, %** *Hlapljive tvari,* %	**Carbon content, %** *Sadržaj ugljika,* %	**Gross calorific value, MJ/kg** *Bruto kalorijska vrijednost,* MJ/kg
increase *povećava se*	decrease *smanjuje se*	increase *povećava se*	decrease *smanjuje se*	increase *povećava se*	increase *povećava se*

color, medium in darker brown, while severe torrefaction results in almost black color. Also, moisture content of the treated material is reduced approximately in half during the torrefaction process. For example, Shang *et al*. (2014) have torrefied wood chip samples and reduced their moisture content from initial 10 % down to final 5 %. Phanphanich and Mani (2011) have done a similar study, where they torrefied pine chip and logging residue samples, and tested them for numerous chemical properties. In summary, moisture content of the treated samples reduced from initial 6.69-7.94 %, down to between 3.30 and 1.57 %. Reduction in moisture content was directly correlated with the severity of the treatment, where higher temperatures resulted in lower moisture content. Ash content, on the other hand, increased with higher temperatures, from initial 0.27 % to up to 0.43 % for pine chips, and from 1.77 % to up to 6.52 % for logging residue samples. Furthermore, volatile matter was reduced approximately in half, while carbon content followed an upward trend with the severity of the treatment, from initial 47 % to up to > 60 %. Finally, reported gross calorific value has substantially increased with the torrefaction treatment, from around 18 MJ/kg to more than 25 MJ/kg. A very similar pattern in the results was reported by Park *et al*. (2012) as well, where torrefaction resulted in reduced moisture content and volatile matter, and increased ash content, carbon content, and gross calorific value. In both studies, the increase in the level of severity resulted in more distinct increases/decreases in the above-mentioned chemical parameters. Table 2 offers a simplified visual representation, derived from the research of Phanphanic and Mani (2011) and Park *et al*. (2012), showcasing the impact of torrefaction treatment on the fundamental chemical characteristics of woody biomass.

Even though torrefaction is considered a chemical treatment, it also changes some of the physical properties of the treated material. Impact on particle and bulk density of the treated woody biomass can also vary depending on the treatment temperature, with temperatures to up to 250 °C reducing the densities of the treated material, while further increase of the temperatures (300 °C) increases the densities of treated wood chips (Phanphanic and Mani, 2011). Torrefaction also has an effect on the grindability of treated materials. Grindability, quantified as a total energy (kWh/ton) required to grind the material, has been reported to improve after torrefaction treatment (Wang *et al*., 2017). This means that the total energy needed to grind torrefied woody biomass is lower than that of raw woody biomass, which directly translates into significant cost savings associated with size reduction of biomass intended to be utilized as a fuel. Again, higher torrefaction temperatures result in higher grindability, and consequently lower energy consumption needed for the size reduction of treated materials.

4 STEAM EXPLOSION
4. PARNA EKSPLOZIJA

4.1 Steam explosion technologies and parameters
4.1. Tehnologije i parametri parne eksplozije

Steam explosion, as a thermal pre-treatment that has both chemical and mechanical impact on treated woody biomass, was first described and patented by Mason in 1926. After a long period of stagnation of this technology, scientists and the wood industry have started to further explore capabilities and opportunities of steam explosion only 20 to 30 years ago. Since then, numerous studies have been done on this specific topic.

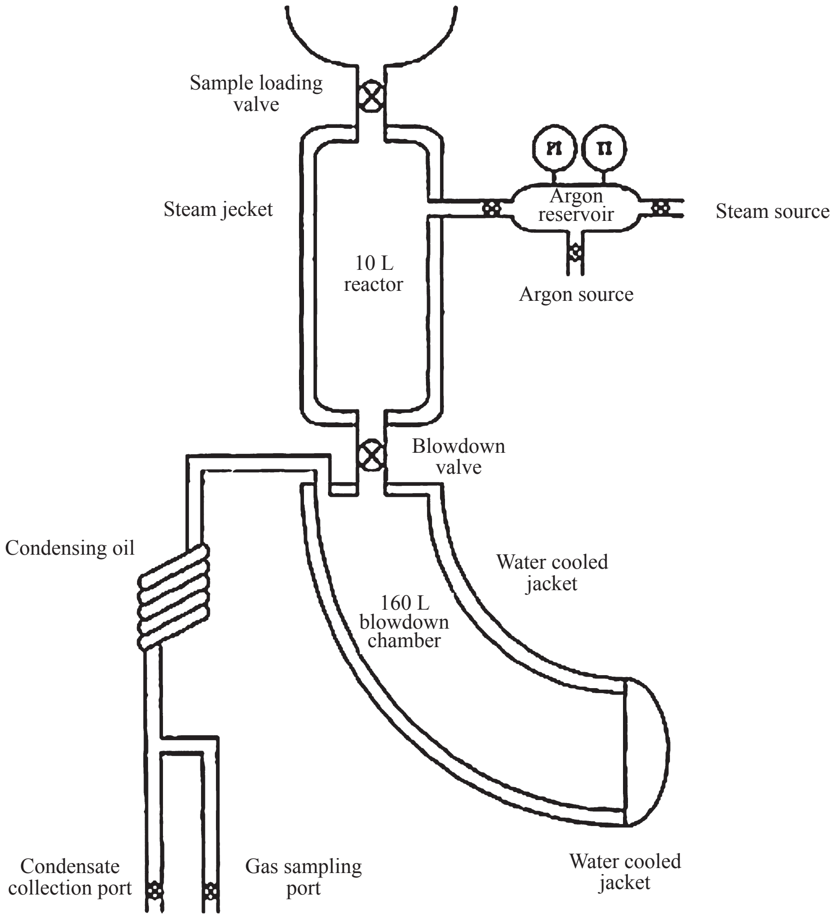

Figure 1 Steam explosion equipment line up (Turn *et al*., 1998)
Slika 1. Oprema za parnu eksploziju (Turn *et al*., 1998.)

As described by Mason (1926), Stelte (2013), and Turn *et al*. (1998), steam explosion of biomass has to be carried out in a steam explosion reactor that can provide controlled conditions for a successful treatment process. It usually consists of a steam generator, high pressure reactor/tank, discharge tank, and accompanying set of valves and piping (Figure 1).

Woody biomass, chipped into smaller pieces, is placed into a high-pressure chamber (reactor), which is sized on mass of treated material per the volume of the reactor basis (1 kg/10 L) (Stelte, 2013; Turn *et al*., 1998). Then, hot steam is forced into the reactor, until the target pressure and temperature are reached. After the certain retention time at a set pressure and temperature, biomass is released through a valve at the bottom of the reactor. According to the literature (Yu *et al*. 2012), the size and the opening speed of the release valve are crucial for a successful process, as the explosion happens at the moment when the valve is opened and when the biomass, forced by the pressure from inside the reactor, is pushed through the valve into the atmospheric conditions. Treated biomass is typically released into a discharge chamber, that according to the literature (Turn *et al*., 1998), needs to be 16 times larger in volume than the reactor itself, in order to capture both exploded material and released pressure.

Three crucial parameters for steam explosion process are temperature, pressure, and residence time. Numerous studies have provided different combinations of these three parameters that must be achieved inside a reactor in order to obtain steam explosion of treated biomass.

Steam explosion process can be done at a wide range of temperatures, ranging between 140 ºC and 280 ºC (Ziegler-Devin *et al*., 2021; Iroba *et al*., 2014; Jacquet *et al*., 2015). However, it seems that several studies that have done steam explosion on woody biomass opt for a narrower temperature range, from 180 ºC to 230 ºC (Tooyserkani *et al*., 2013; Jacquet *et al*., 2015). When compared to higher temperatures, the ~200 ºC process has proved to be more cost effective from the perspective of energy consumption, while yielding optimized quality of the treated material.

Furthermore, a relatively wide range of optimal pressures for achieving successful steam explosion was reported. Reported pressures range from 15 bar inside the reactor to up to 35 bar, while most studies have found the most optimal pressures to be in the range of 16 bar to 24 bar (Asada *et al*., 2012; Yu *et al*., 2012; Lam *et al*., 2013).

And finally, a duration/residence time that the treated material has to spend under the above-mentioned pressure and temperature has also been investigated by numerous studies, including the ones mentioned above as well as some additional ones, such as Jedvert *et al*. (2012), Stelte (2013), and Shimizu *et al*. (1998). As is the case with temperature and pressure, provided ranges of residence times are relatively wide, from 1 to up to 35 minutes. However, most steam explosion treatments last from 5 to 20 minutes.

Typically, the upper ends of the reported ranges of all of the parameters can be associated with experimenting with extreme levels of steam explosion, which often requires more energy consumption, thus being less economically viable for wider industrial applications.

4.2 Steam explosion process and its impact on treated woody biomass
4.2. Proces parne eksplozije i utjecaj na tretiranu drvnu biomasu

As per Ziegler-Devin *et al.* (2021), steam explosion treatment of woody biomass consists of two distinctive stages – chemical and mechanical. The initial stage involves conditions of elevated temperature and pressure caused by injecting hot steam into the reactor. This results in hydrolytic destabilization and breakdown of the lignocellulosic structure of the treated woody biomass and can be considered as a chemical stage. This stage, also known as cooking stage, generally leads to degradation of the cell wall, making treated biomass more susceptible to further treatment.

The chemical stage is then followed by a second stage with physical disruptions of the treated biomass particles and can be considered as a mechanical stage. The second stage occurs at the moment when the treated biomass is released from high temperature and high pressure conditions inside the reactor into the atmospheric conditions. At his moment of explosion, water vapor trapped inside the biomass structure is rapidly expanded, causing ruptures in the once rigid structure of the woody biomass particles.

To summarize, all main components of wood are impacted by the steam explosion. Hemicellulose and cellulose are deconstructed and thermally degraded (Stelte, 2013), while usually stable lignin is modified and relocated within the cells (Auxenfans *et al*., 2017) (Figure 2).

The severity of the steam explosion process, and its impact on the treated biomass, depends on the main parameters of the process: temperature, pressure, retention time, and decompression speed. Generally, the higher the temperature and pressure, coupled with longer retention times and faster decompression, the more severe the impact on the biomass and its structure.

The initial and most noticeable alteration in the characteristics of steam exploded woody biomass, compared to untreated biomass, occurs with the reloca-

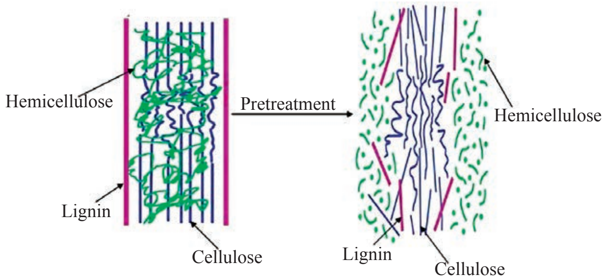

Figure 2 Impact of steam explosion on woody biomass structure (Wang *et al*., 2015; Harmsen *et al*., 2010)
Slika 2. Utjecaj parne eksplozije na strukturu drvne biomase (Wang *et al*., 2015.; Harmsen *et al*., 2010.)

tion of lignin, a naturally dark substance. This relocation results in a darker brown color of the treated biomass. Another physical change happens to particle size distribution, where studies have shown that the size reduction of the steam treated material is by around 25 % (Tooyserkani *et al*., 2013; Boussaid *et al*., 2000), which is due to rapid breakdown of the material into finer particles at the moment of explosion/decompression. Reduction in particle size is followed by the substantial increase in bulk density. It was reported that the bulk density increased from around 600 kg/m^3 for untreated material, to up to > 700 kg/m^3 for material after steam explosion, which consequently increased the energy density as well (Joronen *et al*., 2017). Ash content in steam exploded biomass is increased when compared to initial biomass before treatment (Joronen *et al*., 2017). Furthermore, increase in calorific value is directly related to a decrease in moisture content, as well as to thermal degradation of hemicellulose and an increase in carbon content (Stelte, 2013). Steam exploded biomass becomes more hydrophobic and generally more resistant to external influences. This is also due to the restructuring of the main woody biomass components, including lignin, which in this case acts as a repellent against water. Finally, as is the case with torrefaction, the grindability of steam exploded material improves (Stelte, 2013), and less energy is required to grind the steam exploded woody biomass, when compared to untreated raw biomass.

5 COMPARISON OF QUALITY PROPERTIES OF WOOD PELLETS AND COAL
5. USPOREDBA KVALITATIVNIH SVOJSTAVA DRVNOG PELETA I UGLJENA

Here, an indicative and brief overview is provided of approximately typical final quality properties of different types of wood pellets, compared to those of coal (Table 3) based on papers of Kamperidou (2022), Gorzelany *et al.* (2020), Tumuluru *et al.* (2011), Joronen *et al.* (2017), Wolbers *et al.* (2018), Graham *et al.*

Table 3 Comparison of quality properties of different types of wood pellets and coal
Tablica 3. Usporedba kvalitativnih svojstava različitih vrsta drvnog peleta i ugljena

Quality property *Kvalitativno svojstvo*	**Wood pellet type** / *Vrsta drvnog peleta*				**Coal** *Ugljen*
	Conventional *Konvencionalni*	**Torrefied** *Torefakcionirani*	**Steam exploded** *Tretiran parnom eksplozijom*	**Pyrolyzed** *Pirolizirani*	
Moisture content, % *sadržaj vode, %*	5.0 – 10.0	1.0 – 5.0	8.0 – 10.0	4.8 – 5.5	10.0 – 15.0
Calorific value, MJ/kg *kalorijska vrijednost,* MJ/kg	17.0 – 19.0	20.0 – 24.0	19.0 – 21.0	21.0 – 30.0	23.0 – 28.0
Mechanical durability, % *mehanička izdržljivost, %*	96.0 – 99.4	50. 0 – 65.0	>92.0	45.0 – 57.0	Not applicable as testing methods for coal differ from methods for wood pellets. *Nije primjenjivo jer se metode ispitivanja ugljena razlikuju od metoda za drvene pelete.*
Ash content, % *sadržaj pepela, %*	0.3 – 1.9	Substantially increased compared to conventional. *Znatno povećan u usporedbi s konvencionalnim peletom.*	0.5 – 3.0	1.5 – 7.0	<8.0 – >16.0
Bulk density, kg/m^3 *nasipna gustoća,* kg/m^3	600 – 650	750 – 850	650 – 780	Increased compared to conventional. *Povećana u usporedbi s konvencionalnim peletom.*	800 – 850

(2017), Dyjakon *et al.* (2021), Phanphanich and Mani (2011), Park *et al.* (2012), Hashan *et al.* (2013), Saletnik *et al.* (2022) and Arous et al. (2021). Even though not covered in this high-level overview in detail, some data are also provided on pyrolyzed wood pellets for informative purposes.

6 CONCLUSIONS
6. ZAKLJUČAK

Thermal pre-treatments of woody biomass feedstock, through torrefaction or steam explosion, present substantial advantages for the production of industrial-grade wood pellets to be used as coal replacement in various industrial applications. Both pre-treatments result in feedstock with lower moisture content, higher calorific value and increased energy density, aligning more closely with coal properties. While torrefaction focuses more on enhancing calorific value of the treated feedstock, steam explosion provides feedstock resistant to environmental factors, making pellets produced from steam exploded feedstock more suitable for utilization at coal power plants and the like, due to its coal-like storage and handling properties. Apart from obvious improvements of quality properties of the treated feedstock, these thermal pre-treatments potentially offer energy savings and other benefits along the wood pellet supply chain. Higher energy density of pellets results in certain energy savings and reduced costs in the transportation of treated wood pellets (Wolber *et al*., 2018). Furthermore, the grindability/pulverization properties of torrefied and steam exploded pellets, as opposed to untreated pellets, have shown to be substantially improved (Wang *et al*., 2020; Wolber *et al*., 2018). For example, the studies have shown that up to 50 % less energy is needed for grinding/pulverizing torrefied pellets, relative to untreated pellets (Wang *et al*., 2020). Energy savings, as well as capital cost of installation of steam explosion and torrefaction equipment need to be further explored.

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