Marin Dujmović[1], Branimir Šafran[1], Matija Jug[1],
Kristijan Radmanović[1], Alan Antonović[1]

Biomass Pelletizing Process: A Review

Proces peletiranja biomase - pregled literature

REVIEW PAPER
Pregledni rad
Received – prispjelo: 14. 10. 2021.
Accepted – prihvaćeno: 13. 12. 2021.
UDK: 674.816; 662.638
https://doi.org/10.5552/drvind.2022.2139

ABSTRACT • *A review paper was designed as a lab-scale start-up guideline for general pelletizing process and technologies for biomass feedstock. The main body consists of summarized published research on the topic of all main parts of the biomass pelletizing process and technology, including machinery and their parts, optimal feedstock conditions as well as pellet forming processes and principles. This paper is more focused on the specific parameters necessary to obtain optimal pelletizing process that results in desired pellet quality, and less on feedstock preparation, final product post-treatment (e.g. cooling), handling (storage, transportation) or exact quality specifications. A summary of the suggested feedstock, technological and other parameters for the purpose of easier lab-scale start-up of biomass pellets production, which is based on the cited literature throughout this paper, is given in the last section.*

KEYWORDS: *biomass feedstock; pellets; pelletizing technology; pelletizing process; feedstock parameters*

SAŽETAK • *Pregledni rad pripremljen je kao laboratorijski priručni materijal za osnovne procese i tehnologije peletiranja biomase. U njemu su sistematizirane spoznaje iz dostupnih izvora literature o temi glavnih dijelova procesa i tehnologije peletiranja biomase, uključujući strojeve i njihove pripadajuće dijelove, optimalne ulazne parametre sirovine, kao i načela i procese izrade peleta. Ovaj je priručni materijal više usmjeren na specifične parametre nužne za optimalan proces peletiranja radi dobivanja peleta željene kvalitete, a manje na pripremu sirovine, tretiranje proizvedenog peleta (npr. hlađenje), rukovanje peletima (skladištenje, transport) ili na određena kvalitativna svojstva peleta. Sažetak preporučenih tehnoloških parametara i ulaznih parametara sirovine, koji se temelji na informacijama iz navedene i citirane literature, nalazi se na kraju ovoga preglednog rada.*

KLJUČNE RIJEČI: *biomasa/sirovina; pelet; tehnologija peletiranja; proces peletiranja; parametri sirovine*

1 INTRODUCTION
1. UVOD

In the past couple of decades, due to the urge to reduce greenhouse gas emissions and CO_2 footprint, utilization of so far underused biomass, which is considered a renewable energy source together with wind, solar, hydro, geothermal and marine (tidal) energy (Ellabban *et al*., 2014), has gained its popularity in replacing fossil fuels.

Biomass is defined as wood and agricultural residues from the wood industry, crop fields and forests. Even though there are obvious advantages of biomass in the form of clean heat and power generation, there

[1] Authors are researchers at University of Zagreb, Faculty of Forestry and Wood Technology, Department of Wood Technology, Institute of Processes Engineering, Zagreb, Croatia.

are also some disadvantages: ununiformed size and shape, low bulk and energy density as well as high moisture content, which can lead to degradation during storage and transportation (Demirbaş, 2001). All these properties negatively affect the supply chain management both economically and practically.

In order to overcome these obstacles, biomass is pelletized into cylindrical pellets used for both residential (diameter 6mm) and industrial (diameter ≥8mm) heat and power applications. Pelletized biomass has shown improved and more consistent properties over lose biomass, such as low moisture content, high energy content as well as homogenous shape and size (Mobini *et al*., 2014), all positively contributing to the supply chain management and logistics of biomass pellets.

Pelletizing process is described as compression of the feedstock (in this case biomass) that is pelletized. The friction between the biomass and the press channel generates a force which results in compression of biomass, causing the final product, pellets, maintain their shape and density due to bonding that occurs between the particles at high pressure inside press channels (Nielsen *et al*., 2009a; Holm *et al*., 2006).

This process is carried out by the pellet mill. Large scale producers usually use ring or flat die pellet mills, with ring die mills being the most common (Haslinger, 2005). The main parts of the mill are always the die and rollers, with rollers pushing the material through the bore-holes of the die, making an infinite string of pelletized material, breaking up into pieces randomly or getting cut into desired length by knives (Obernberger and Thek, 2010).

And finally, the goal of this paper was to summarize and organize available findings in the area of biomass pelletization in order to provide a pelletizing lab-scale start-up guidelines for the research project "INOPELET", held by Bjelin Ltd. in partnership with the University of Zagreb, Faculty of Forestry and Wood Technology.

2 PELLETIZING PROCESS
2. PROCES PELETIRANJA

Biomass is pelletized in order to achieve improved utilization performance as a solid biofuel, meaning reduced moisture content, increased calorific value and bulk density, and maybe most importantly, uniformed shape, size and density. These, in general more stable and consistent properties, offer lower usage cost in terms of transportation, storage and end use – feeding residential or industrial boilers and finally, burning.

There are multiple explanations and definitions of the pelletizing process available within the published research. In short, the pelletizing process is based on pushing the raw material through the openings of the die (Tica and Djurdjevic, 2007). It is also considered to be a kneading, compressing, heating and forming process where rheological transformations in the material take place (Salas-Bringas *et al*., 2008), as well as a high agglomeration process (Salas-Bringas *et al*., 2010). In general, this paper deals with biomass which can be compressed into pellets during the mechanical process in which pressure is applied to the biomass to crush its cellular structure, increasing its density. Key parameters affecting the cost, technique and dynamics of the process itself, as well as the quality of the final product (biomass pellets), are raw material species, exact plant parts/components used, moisture content and particle size. Additionally, temperature and pelletizing pressure play an important role in the pelletizing process (Stelte, 2011), together with the type of the pellet mill and specifications of the die (Holm *et al*., 2006), all affecting each other directly or indirectly to form a pellet of a certain quality.

2.1 Feedstock parameters
2.1. Parametri sirovine

2.1.1 Types and species
2.1.1. Tipovi i vrste sirovine

For the purpose of this paper, types of feedstocks are divided into two groups: forestry/woody and agricultural/herbaceous. Species refer to specific forest trees and agricultural crops within two feedstock groups. In general, types of forestry and wood industry feedstock species can be divided into hardwood and softwood. Different species have various energy requirements for pelletizing, directly impacting the cost and production capacities (Nielsen *et al*., 2009b). For example, a study showed that hardwood such as European beech required more energy to process than the softwood Scots pine, while producing the pellets of better mechanical properties (strongest) (Nielsen *et al.,* 2009b). This was also confirmed by Holm *et al*. (2006), who were not able to obtain a stable production of pure beech pellets, while pellets from pine shavings gave them a stable production, proving that beech dust is much more difficult to pelletize than pine. They also showed that pellets could be made by mixing pine and beech with the ratio of 60 % (wt) and 40 % (wt). On the other hand, another study done by Föhr and Ranta (2017) showed that pre-treated (torrefied) hardwood (without binders) pelletized better than the softwood. Mechanical durability of softwood pellets was lower than the hardwood ones, as shown in previous studies.

Pelletizing of agricultural type feedstock was investigated by Puig-Arnavat *et.al*. (2016), who studied pelletizing behavior of triticale, fescue, alfalfa and sorghum materials. When pelletized, all materials were of the same quality, except sorghum, which had poorer mechanical properties. Calorific value of these pellets was within 17.46 and 18.02 MJ/kg, which was similar to softwood (19.66 and 20.36 MJ/kg) and hardwood (17.63 and 20.81 MJ/kg) pellets (Telmo and Lousada, 2011). The research proved that investigated agricultural feedstock can have satisfactory pelletizing properties if other parameters, such as adequate moisture content, are met. Furthermore, the addition of softwood (pine) into the agricultural (straw) feedstock can result in improved mechanical properties of produced pellets (Theerarattananoon *et al*., 2011), which was also found by Harun and Afzal (2016), who investigated how particle size and other parameters impact the quality of agricultural pellets. They concluded that blending agricultural biomass with woody biomass to produce pellets can be one of the potential options for the pellet industry, not only because agricultural biomass is economically affordable and profusely available, but also because their research showed that blending agricultural biomass with existing woody biomass improved mechanical and physical properties of the pellet that can meet the quality standard. And finally, this was also confirmed in the study done by Šafran *et al*. (2017), who found a mixture of corn-stalk and fir to be a good option for agro-wood pellet production.

2.1.2 Moisture content
2.1.2. Sadržaj vode

In terms of moisture content (MC), feedstock can be divided into two stages: 1) raw, wet or pre-treated, when the material has not been dried to the desired MC yet and is not ready for pelletizing, and 2) dried to the optimal MC and ready for pelletizing, which is the one considered in this paper. Optimal MC can be described as the one that provides stable fiber compression and desired production performance, while producing the standard quality pellets.

Ungureanu *et al*. (2018) reported the MC of 10 to 15 % to be the most optimal for pelletizing the woody feedstock, while the MC above 20 % did not form any stable pellets. Furthermore, their research revealed that the increase of MC for both woody (beech and spruce) and agricultural (straw) feedstock resulted in a decrease of pelletizing pressure, while MC >14 % started to negatively affect pellets mechanical durability. Similar results were reported by numerous other studies: optimal MC for beech was found to be 6 to 10 % (wt), spruce around 10 % (wt) (Stelte *et al*., 2011a), and pine 6 to 8 % (wt) (Nielsen *et al*., 2009b).

Agricultural feedstock, on the other hand, has showed to require higher MC (barley straw 19-23 %; wheat straw ~15 %) in order to be properly pelletized (Serrano *et al*., 2011; Smith *et al*., 1977), while the increase of optimal MC values, as in woody feedstock, resulted in decreased mechanical durability of pellets produced (Theerarattananoon *et al*., 2011).

2.1.3 Particle size distribution
2.1.3. Distribucija čestica prema veličini

Particle size of biomass feedstock depends on the raw material characteristics as well as on pre-treatment methods of size reduction and equipment (hammers, knives, screens, etc.) specifications (Jensen *et al*., 2011). This paper, as in all other sections of feedstock parameters, deals only with already pre-treated feedstock (in case pre-treatment is necessary in terms of size reduction), meaning that its size is suitable for the pelletizing process.

Particle size, in synchronization with feedstock species and moisture content, plays an important role in the pelletizing process, impacting both production performance and pellet quality.

Research has shown that the decreasing particle size increases friction in the press channel of a pellet mill, while increasing pellet density (Stelte, 2011; Stelte *et al*., 2011a; Kaliyan and Morey, 2009; Mani *et al*., 2006). For example, the efficacy of the pressure agglomeration process directly depends on particle size – the smaller the particles are, the larger the contact surface is. Therefore, the bonds between the particles have higher energy per unit mass (Lisowski *et al*., 2020).

When it comes to the exact feedstock particle size that is adequate for pelletizing and for the production of good quality pellets, Lisowski *et al*. (2020) conducted a brief overview of already investigated size specifications, which were as follows: smaller than 3.2 mm (Mani *et al*., 2003), between 1 and 3 mm in diameter (Stelte *et al*., 2011b), below 5 mm in diameter (Stelte *et al*., 2012; Scatolino *et al*., 2018). Generally, a wide-ranging particle size is the most adequate with respect to the pellet quality; however, a too high amount of fine particles (smaller than 0.5 mm in diameter) has a negative impact on the friction and pellet quality (Stelte *et al*., 2012).

2.2 Pellet mill
2.2. Preša

2.2.1 Pellet mill design and main parts
2.2.1. Vrste preša i njihovi glavni konstrukcijski dijelovi

A typical pellet mill consists of two main parts: die and rollers, where the rollers force the biomass to flow into and through the die cylindrical press channels. These two main parts, which are wearing parts and need to be replaced periodically (Kytö and Äijälä, 1981), are manufactured from wear-resistant materials, mostly from hardened chromium steel (Alakangas and Paju, 2002). When wear and tear of these main parts of the pellet mill become significant, it might be necessary to substantially reduce the production rates (e.g. from 4.5 t/h to 3.5 t/h) in order to maintain the desired

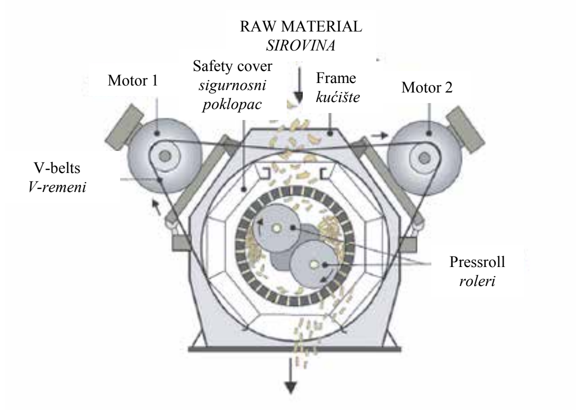

Figure 1 Pellet mill with ring die (source: www.smallpelletmills.net)
Slika 1. Preša s prstenastom matricom (izvor: www.smallpelletmills.net)

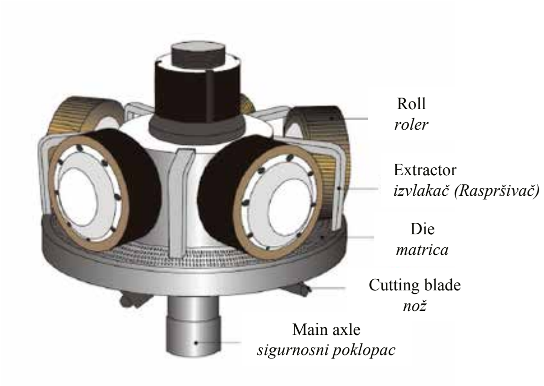

Figure 2 Pellet mill with flat die (source: ww.smallpelletmills.net)
Slika 2. Preša s ravnom matricom (izvor: www.smallpelletmills.net)

pellet quality properties (Sultana *et al*., 2010). This finding suggests that the worn out state of rollers and/or die can have a negative impact on pellet mechanical properties.

Pellet mills usually come in two different designs, which are dictated by the shape of the die. The die can either be in the shape of a ring (Figure 1) or a flat plate (Figure 2) (Alakangas and Paju, 2002). In case of the flat die, rollers are rotated, and in case of a ring die, motors power and rotate the die itself.

Ring dies are commonly used in commercial facilities due to their high throughput, while flat dies manifest more robustness with input biomass and generally require lower capital investment than ring dies (Jackson *et al*., 2016). Apart from the rollers and die, other fundamental parts of every pellet mill are the motor – powering the rollers or the die, usually by belt drive; cutting blades – cutting the infinite string of pelletized material into the desired length; and the axle – delivering the rotation from the motor, while being powered by belts through the gearbox.

2.2.2 Technological and constructional parameters
2.2.2. Tehnološki i konstrukcijski parametri

Tica and Djurdjevic (2007), as well as Tumuluru *et al*. (2010), have summarized some of the main technological and constructional parameters needed for an optimal pelletizing process:

- Temperature
- Circumferential speed of the rollers on the die
- Clearance between the rollers and the die
- Die parameters

Pelletizing process creates friction between the steel surface and feedstock in press channels, causing build-up of a high back pressure, consequently generating heat (Stelte, 2011). Numerous studies have been made on the subject of optimal pelletizing temperature. For example, Serrano *et al*. (2011) found that the temperature of the die under operation at stable conditions is around 90 °C. This was also confirmed in studies by Mostafa *et.al*. (2019) and Tumuluru (2014), who stated that the optimal die temperature for pelletizing biomass feedstock was close to 100 °C. However, Šafran (2015) found that increased temperature (170 to 220 °C) of pelletizing can increase pellet density, consequently increasing calorific value.

As for the circumferential speed of the rollers on the die, Amandus-Kahl Group recommended it to be 2.2 to 2.6 m/s for a flat die, while for a ring die, where the die is turned around the fixed rollers, the speed of the rollers is equal to the speed of the edge of the die, and can be determined by the number of spins of the shaft (Tica and Djurdjevic, 2007).

The distance between the rollers and the die needs to be adjusted before starting the pelletizing process, and it might need to be re-adjusted after certain production time, due to wear and tear of the die and rollers. The distance depends on multiple factors such as type, moisture and particle size of the feedstock, but the general "rule-of-thumb" would be to adjust it to 0.1 to 0.5 mm. One roller, however, which is always lower than the others, by design, in order to push the material through the die, is adjusted to 0.1 to 0.2 mm. Clearance between the rollers and the die greatly affects the mechanical properties of pellets.

Die specifications and dimensions depend on the type of the pellet mill (already discussed in chapter 3.2.1. Pellet Mill Design and Main Parts) and the desired shape and size of the pellet.

Šafran (2015) has summarized some of the key parameters of the die:

- conically recessed opening of the press channel (Figure 3) for easier entry of the material into the die
- inlet angle of indentation (30 ° to 60 °)
- indentation compression ratio (1 to 1.56 for smaller diameter pellets; 1 to 4 for bigger diameter pellets)

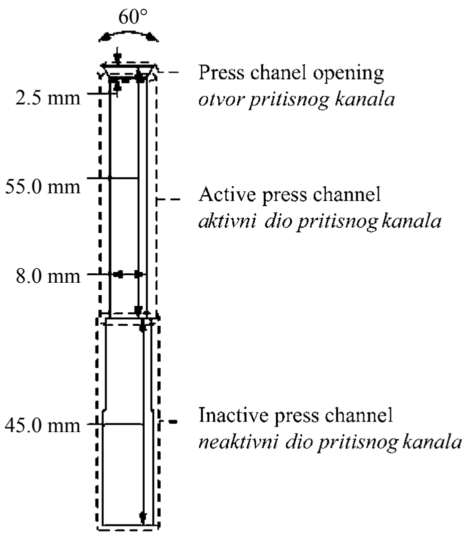

Figure 3 Example of a press channel (source: Nielsen et al., 2009b)
Slika 3. Primjer kanala u matrici (izvor: Nielsen et al., 2009b)

- compression ratio, which is the ratio between length (usually between 6 and 25 mm (Stelte, 2011) and diameter of the press channel (Stelte, 2011) (e.g. softwoods demand 4 to 5 for flat die and 8 to 10 for ring die, while agricultural biomass demands higher ratios) disposition and number of holes (it is necessary to achieve the highest number of holes as possible, without affecting the mechanical integrity of the die itself).

2.3 Pellet forming
2.3. Formiranje peleta

As it can be seen in Figure 4, pellets are formed from the crushed biomass that is compressed inside the press channels.

Mani *et al*. (2004) investigated pellet forming principles for various feedstock and described the forming process in terms of the applied pressure. The initial stage, also called particle rearrangement, of pellet forming happened at low pressures, when particles were moved around and rearranged, while pore spaces were being eliminated. In the second stage, as compressive force progressed, densification was indicated by elastic, plastic deformation and interlocking of particles, where these particles were bound by the cohesion of inner surfaces and their fibrous parts (Alakangas and Paju, 2002). As stated in previous sections, this process creates friction between biomass particles and die channel, generating heat that softens some biomass components, such as natural binding material lignin, due to its relatively low melting point of 140 °C (Mani *et al*., 2004.). Softened and/or melted lignin causes adhesion of biomass particles, forming pellets (Alakangas and Paju, 2002). After the pellets are formed, they are discharged through the die, cut by knives to desired length and, as the last stage, cooled in the cooler in order for pellet particles to form very strong solid bridges (Ghebre-Sellassie, 1989). The pellet particles now being fully interlocked, pellets achieved their final shape and other mechanical properties.

3 DISCUSSION AND CONCLUSIONS
3. RASPRAVA I ZAKLJUČAK

A brief overview of specific feedstock, technological and constructional parameters necessary for optimal pelletizing process was conducted in order to help with lab-scale start-ups designed for scientific research in the area of biomass pellets. Summarized findings and parameters are as follows:

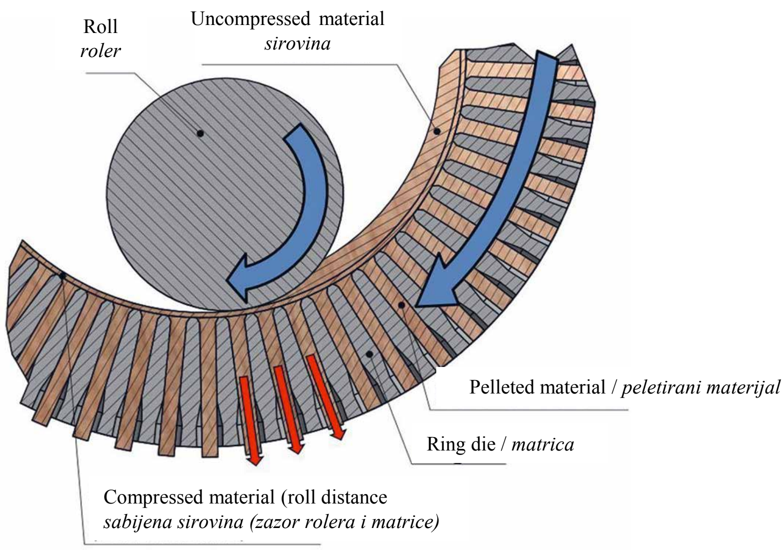

Figure 4 Close-up pelletizing process (source: Nielsen *et al.*, 2020)
Slika 4. Prikaz procesa peletiranja (izvor: Nielsen *et al.*, 2020.)

All key parameters need to be in harmony in order to obtain optimal pelletizing process and pellets of desired quality.

Hardwoods require more energy to be pelletized than softwoods.

Pellets made of hardwood feedstock are often more durable than those made of softwood.

Thermal pre-treatment (e.g. torrefaction, steam explosion) of feedstock can improve pelletizing properties as well as durability and end quality of pellets in general.

Pelletizing agricultural feedstock, as well as mixing different feedstock (hardwood/softwood; wood/agricultural) in various ratios, is possible and can even improve pelletizing properties and pellet quality.

Woody feedstock requires the moisture content of between 10 and 15 % in order to be properly pelletized. The increase of moisture content reduces pellet mechanical durability, while the decrease can amplify energy consumption needed for pelletizing, simultaneously reducing production capacity and increasing the risk of die blockage.

Agricultural feedstock requires the moisture content of around 20 %, which is substantially higher than that of woody feedstock.

The optimal particle size of the feedstock was found to be between 1 and maximum 5 mm, with a not too high amount of particles below 0.5 mm in diameter, due to the negative impact of fines on the mechanical durability of pellets.

The temperature of the die required for biomass pelletizing was found to be around 100 °C. Increased pelletizing temperature can increase pellet density and calorific value.

Roller velocity is recommended to be between 2.2 and 2.6 m/s.

Clearance between the rollers and the die should be between 0.1 and 0.5 mm. One roller that is always closest to the die should be adjusted to 0.1 to 0.2 mm.

Preferable blends of feedstock (woody/agricultural) for achieving optimal parameters (e.g. moisture content and particle size) for the desired pelletizing process and pellet quality is yet to be investigated. However, this paper would suggest to lean towards setting both feedstock and pressing parameters closer to woody feedstock requirements for the purpose of lab-scale research. With the idea of agricultural feedstock being a minority share, gradual introduction and increase of agricultural feedstock into the blend during the process will allow for "real time" adjustments of pelletizing parameters, if necessary.

Replacement of the die and rollers is necessary due to their wear and tear. Frequency of replacement mostly depends on the quality of the die and rollers, type of feedstock, production rates, etc. Lower quality of pellets, in the first place mechanical durability, is usually the first indicator of die and/or rollers wear out (in case all other parameters are in optimal state).

Die parameters depend on the type of the pellet mill as well as on the type of the feedstock. Summarized parameters of the die can be found in the last paragraph of the section 2.2.2. (Technological and Constructional Parameters).

The optimal pelletizing pressure was found to be around 100 MPa. Increased pressure increases pellet density.

After they are discharged from the die and cut to desired length, pellets need to be cooled in order to achieve their final shape and other mechanical properties.

All parameters and findings listed above are solely projected to be a general guideline providing a framework for setting up a lab-scale production for research purposes, and are not intended to represent any definitive claims. Optimal parameters can greatly vary depending on the type of the feedstock and many other factors.

4 REFERENCES
4. LITERATURA

1. Alakangas, E.; Paju, P., 2002: Wood pellets in Finland – technology, economy, and market. OPET Report 5: 85.
2. Demirbaş, A., 2001: Relationship between lignin contents and heating values of biomass. Energy conversion and management, 42 (2): 183-188. https://doi.org/10.1016/S0196-8904(00)00050-9
3. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F., 2014: Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews, 39: 748-764. https://doi.org/10.1016/j.rser.2014.07.113
4. Föhr, J.; Ranta, T., 2017: Manufacturing of torrefied pellets without a binder from different raw wood materials in the pilot plant. Wood Research, 62 (3): 481-494. (online). www.woodresearch.sk/wr/201703/13.pdf (Accessed Oct. 4, 2021).
5. Ghebre-Sellassie, I., 1989: Mechanism of pellet formation and growth. Pharmaceutical Pelletization Technology, 37: 123-145. (online). http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=19388220 (Accessed Oct. 5, 2021).
6. Harun, N. Y.; Afzal, M., 2016: Effect on particle size on mechanical properties of pellets made from biomass. Procedia Engineering, 148: 93-99. https://doi.org/10.1016/j.proeng.2016.06.445
7. Haslinger, W., 2005: Pellets – Technologien – ein Überlick. In: Proceedings of the World Sustainable Energy days 2005. (online). https://www.researchgate.net/profile/Walter-Haslinger/publication/292995024_Pellets-Technologien_ _ein_Uberblick/links/56b4e10408ae5ad36057670b/Pellets-Technologien-ein-Ueberblick.pdf (Accessed Oct. 5, 2021).
8. Holm, J. K.; Henriksen, U. B.; Hustad, J. E.; Sørensen, L. H., 2006: Toward an understanding of controlling parameters in softwood and hardwood pellets production. Energy & Fuels, 20: 2686-2694. https://doi.org/10.1021/ef0503360

9. Jackson, J.; Turner, A.; Mark, T.; Montross, M., 2016: Densification of biomass using a pilot scale flat ring roller pellet mill. Fuel Processing Technology, 148: 43-49. https://doi.org/10.1016/j.fuproc.2016.02.024
10. Jensen, P. D.; Temmerman, M.; Westborg, S., 2011: Internal particle size distribution of biofuel pellets. Fuel, 90: 980-986. https://doi.org/10.1016/j.fuel.2010.11.029
11. Kaliyan, N.; Morey, R. V., 2009: Factors affecting strength and durability of densified biomass products. Biomass & Bioenergy, 33: 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005
12. Kytö, M.; Äijälä, M., 1981: Utilization and processing of forest energy – 3. Equipment techniques of biomass pelletization. Tied.-Valt. Tek. Tutkimuskeskus, Poltto-Voitelunelab. (Finland), 38: 5. (online). https://www.osti.gov/etdeweb/biblio/5164968 (Accessed Oct. 5, 2021).
13. Lisowski, A.; Matkowski, P.; Dąbrowska, M.; Piątek, M.; Świętochowski, A.; Klonowski, J.; Mieszkalski, L.; Reshetiuk, V., 2020: Particle size distribution and physicochemical properties of pellets made of straw, hay, and their blends. Waste and Biomass Valorization, 11: 63-75. https://doi.org/10.1007/s12649-018-0458-8
14. Mani, S.; Tabil, L. G.; Sokhansanj, S., 2003: An overview of compaction of biomass grinds: Powder Handling and Processing. The International Journal of Storing, Handling, and Processing Powder, 15 (3): 160-168.
15. Mani, S.; Tabil, L. G.; Sokhansanj, S., 2004: Evaluation of compaction equations applied to four biomass species. Canadian Biosystems Egineering, 46 (3): 55-61. (online). https:// www.researchgate.net/profile/Lope-Tabil/publication/230704492_Evaluation_of_compaction_equations_applied_to_four_biomass_species/links/02bfe50d07c233151c000000/Evaluation-of-compaction-equations-applied-to-four-biomass-species.pdf (Accessed Oct. 1, 2021).
16. Mani, S.; Tabil, L. G.; Sokhansanj, S., 2006: Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass and Bioenergy, 30: 648-654. https://doi.org/10.1016/j.biombioe.2005.01.004
17. Mobini, M.; Meyer, J. C.; Trippe, F.; Sowlati, T.; Fröhling, M.; Schultman, F., 2014: Assessing the integration of torrefaction into wood pellet production. Journal of Cleaner Production, 78: 216-225. https://doi.org/10.1016/j.jclepro.2014.04.071
18. Mostafa, M. E.; Hu, S.; Wang, Y.; Su S.; Fu, X.; Elsayed, S. A.; Xiang, J., 2019: The significance of pelletization operating conditions: An analysis of physical and mechanical characteristics as well as energy consumption of biomass pellets. Renewable and Sustainable Energy Reviews, 105: 332-348. https://doi.org/10.1016/j.rser.2019.01.053
19. Nielsen, N. P. K.; Holm, J. K.; Felby, C., 2009a: Effect of fiber orientation on compression and frictional properties of sawdust particles in fuel pellet production. Energy & Fuels, 23: 3211-3216. https://doi.org/10.1021/ef800923v
20. Nielsen, N. P. K.; Gardner, D. J.; Poulsen, T.; Felby, C., 2009b: Importance of temperature, moisture content, and species for the conversion process of wood residues into fuel pellets. Wood and Fiber Science, 41 (4): 414-425. (online). https://wfs.swst.org/index.php/wfs/article/view/469/469 (Accessed Oct. 1., 2021).
21. Nielsen, S. K.; Mandø, M.; Rosenørn, A. B., 2020: Review of die design and process parameters in the biomass pelleting process. Powder Technology, 364: 971-985. https://doi.org/10.1016/j.powtec.2019.10.051
22. Obernberger, I.; Thek, G., 2010: The Pellet Handbook: The Production and Thermal Utilization of Pellets. Graz: University of Technology, 549. (online). https://books.google.hr/books?hl=hr&lr=&id=597yh15Q6kEC&oi=fnd&pg=PP5&dq=obernberger+thek+2010&ots=XCwZZtdHJW&sig=YnRNJ09zR4j_7wjMxLScp_9sjM0&redir_esc=y#v=onepage&q=obernberger%20thek%202010&f=false (Accessed Sep. 23, 2021).
23. Odogherty, M. J.; Wheeler, J. A., 1984: Compression of straw to high-densities in closed cylindrical dies. Journal of Agricultural Engineering Research, 29: 61-71. https://doi.org/10.1016/0021-8634(84)90061-1
24. Puig-Arnavat, M.; Shang, L.; Sárossy, Z.; Ahrenfeldt, J.; Henriksen, U. B., 2016: From a single pellet press to a bench scale pellet mill – pelletizing six different biomass feedstocks. Fuel Processing Technology, 142: 27-33. https://doi.org/10.1016/j.fuproc.2015.09.022
25. Šafran, B., 2015: Dependence of mechanical properties of pellets on input variables of raw material. PhD Thesis. University of Zagreb, Faculty of Forestry and Wood Technology: 152.
26. Šafran, B.; Radmanović, K.; Jug, M.; Lučić Beljo, R.; Lojen, T.; Risović, S., 2017: Influence of pressing temperature and additive on mechanical properties of wood pellets. Natural Resources, Green Technology & Sustainable Development, 3: 8.
27. Salas-Bringas, C.; Lekand, O. I.; Schüller, R. B., 2008: Rheology in feed production. Annual Transactions of the Nordic Rheology Society, 16: 229-237. (online). nordicrheologysociety.org/Content/Transactions/2008/Posters/Salas-Bringas%20et%20al.pdf (Accessed Oct. 1, 2021).
28. Salas-Bringas, C.; Filbakk, T.; Skjevrak, G.; Lekang, O. I.; Høibø, O.; Schüller, R. B., 2010: Compression rheology and physical quality of wood pellets pre-handled with four different conditions. Annual Transactions of the Nordic Rheology Society, 18: 87-94. (online). https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.661.9350&rep=rep1&type=pdf (Accessed Oct 1, 2021).
29. Scatolino, M. V.; Neto, L. F. C.; Protásio, T. P.; de Cássia, A.; Carneiro, O.; Andrade, C. R.; Guimarães, J. B.; Mendes, L. M., 2018: Options for generation of sustainable energy: Production of pellets based on combinations between lignocellulosic biomasses. Waste and Biomass Valorization, 9: 479-489. https://doi.org/10.1007/s12649-017-0010-2
30. Serrano, C.; Monedero, E.; Lapuerta, M.; Portero, H., 2011: Effect of moisture content, particle size and pine addition on quality parameters of barley straw pellets. Fuel Processing Technology, 92 (3): 699-706. https://doi.org/10.1016/j.fuproc.2010.11.031
31. Smith, I. E.; Probert, S. D.; Stokes, R. E.; Hansford, R. J., 1977: The briquetting of wheat straw. Journal of Agricultural Engineering Research, 22(2): 105-111. https://doi.org/10.1016/0021-8634(77)90054-3
32. Stelte, W., 2011: Fuel pellets from biomass: Processing, bonding, raw materials. PhD Thesis Report. Danish National Laboratory for Sustainable Energy, Technical University of Denmark: 47.
33. Stelte, W.; Holm, J. K.; Sanadi, A. R.; Ahrenfeldt, J.; Henriksen, U. B., 2011a: Fuel pellets from biomass: the importance of the pelletizing pressure and its dependency on the processing conditions. Fuel, 90: 3285-3290. https://doi.org/10.1016/j.fuel.2011.05.011
34. Stelte, W.; Holm, J. K.; Sanadi, A. R.; Barsberg, S.; Ahrenfeldt, J.; Henriksen, U. B., 2011b: A study of bonding and failure mechanisms in fuel pellets from different bio-

mass resources. Biomass Bioenergy, 35 (2): 910-918. https://doi.org/10.1016/j.biombioe.2010.11.003
35. Stelte, W.; Sanadi, A. R.; Shang, L.; Holm, J. K.; Ahrenfeldt, J.; Henriksen, U. B., 2012: Recent developments in biomass pelletization – A review. BioResources, 7 (3): 4451-4490. (online). https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_07_3_4451_Stelte_Developments_Biomass_Pelletization_Review/1690 (Accessed Oct. 1, 2021).
36. Sultana, A.; Kumar, A.; Harfield, D., 2010: Development of agri-pellet production cost and optimum size. Bioresource Technology, 101: 5609-5621. https://doi.org/10.1016/j.biortech.2010.02.011
37. Telmo, C.; Lousada, J., 2011: Heating values of wood pellets from different species. Biomass and Bioenergy, 35 (7): 2634-2639. https://doi.org/10.1016/j.biombioe.2011.02.043
38. Theerarattananoon, K.; Xu, F.; Wilson, J.; Ballard, R.; McKinney, L.; Staggenborg, S.; Vadlani, P.; Pei, Z. J.; Wang, D., 2011: Physical properties of pellets made from sorghum stalk, corn stover, wheat straw, and big bluestem. Industrial Crops and Products, 33 (2): 325-332. https://doi.org/10.1016/j.indcrop.2010.11.014
39. Tica, M.; Djurdjevic, M., 2007: Theoretical analysis of the dominant construction-technological parameters of the lumber scrap pelleting systems from the aspect of the optimal main function of the system. Faculty of Technical Sciences, Novi Sad, 435-438.
40. Tumuluru, J. S., 2014: Effect of process variables on the density and durability of the pellets made from high moisture corn stover. Biosystems Engineering, 119: 44-57. https://doi.org/10.1016/j.biosystemseng.2013.11.012
41. Tumuluru, J. S.; Wright, C. T.; Keneny, K. L.; Hess, R., 2010: A technical review on biomass processing: densification, preprocessing, modeling and optimization. 2010 ASABE Annual International Meeting: 33. (online). www.researchgate.net/profile/Jaya-Shankar-Tumuluru/publication/236898167_A_Technical_Review_on_Biomass_Processing_Densification_Preprocessing_Modeling_and_Optimization/links/00463521Žbbf9411ebe00-0000/A-Technical-Review-on-Biomass-Processing-Densification-Preprocessing-Modeling-and-Optimization.pdf (Accessed Oct 1, 2021).
42. Ungureanu, N.; Vladut, V.; Voicu, G.; Dinca, M. N.; Zabava, B. S., 2018: Influence of biomass moisture content on pellet properties – Review. Engineering for rural development: 1876-1883. https://doi.org/10.22616/ERDev2018.17.N449
43. ***www.smallpelletmills.net/improve-the-production-of-wood-pellet-mill/ (Accessed Oct. 4, 2021).

Corresponding address:

MARIN DUJMOVIĆ, M.Sc.

University of Zagreb, Faculty of Forestry and Wood Technology, Department of Wood Technology, Institute of Processes Engineering, Svetošimunska 23, 10000 Zagreb, CROATIA, e-mail: mdujmovi@sumfak.hr