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Sustainable Management of Wood Residues: Challenges of Recycling, Combustion and Environmental Impact

Održivo gospodarenje drvnim ostatcima: izazovi recikliranja, spaljivanja i utjecaja na okoliš

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ABSTRACT • *In the quest for climate neutrality, the importance of sustainability and the reuse of wood waste are becoming crucial. To determine how wood waste is managed by wood and wood-based panel plants, the research aimed to focus particularly on energy recovery contribution. The research was based on quantitative data analysis obtained through computer-assisted telephone interviews. The results showed that over 57 % of respondents declared that they combusted waste to recover energy, which causes immediate CO_2 emissions, instead of enabling long-term storage in wood-based products. Further research analyzed the emissions produced by combustion of the selected products: MDF boards and softwood and hardwood pellets. Laboratory tests showed that the incineration of MDF boards resulted in the emission of a number of harmful substances, which pose a threat to health and the environment. In contrast, burning pellets does not generate toxic compounds, but it still leads to the release of CO_2. Research findings indicate the need for further research into the cascading wood utilization strategy, focusing on the use of wood waste in the material cycle instead of the energy cycle in order to understand and promote the EU's sustainable development goals throughout the wood industry.*

KEYWORDS: *wood waste; toxic substances; medium-density fiberboard; pellet; biomass; supply chain*

SAŽETAK • *U postizanju klimatske neutralnosti ključnu važnost ima održivost i ponovna uporaba drvnog otpada. Kako bi se utvrdilo na koji način tvornice za proizvodnju drvnih ploča gospodare drvnim otpadom, istraživanje je bilo posebno usredotočeno na proizvodnju energije od drvnog otpada te se temeljilo na kvantitativnoj analizi podataka dobivenih putem računalno potpomognutih telefonskih intervjua. Rezultati su pokazali da je više od 57 % ispitanika izjavilo da otpad spaljuju radi proizvodnje energije, posljedica čega su neposredne emisije CO_2, umjesto da ga dugoročno skladište u drvnim proizvodima. U daljnjim istraživanjima analizirane su emisije nastale spaljivanjem odabranih proizvoda: MDF ploča te peleta od mekoga i tvrdog drva. Laboratorijska ispitivanja pokazala su da spaljivanje MDF ploča rezultira emisijom niza štetnih tvari koje su prijetnja za zdravlje i okoliš. Nasuprot tome, izgaranjem peleta ne nastaju otrovni spojevi, ali se ipak oslobađa CO_2. Rezultati upućuju na potre-*

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bu daljnjeg istraživanja kaskadne strategije iskorištavanja drva, posebice drvnog otpada u materijalnom umjesto u energetskom ciklusu kako bi se razumjeli i promovirali ciljevi održivog razvoja EU-a u cijeloj drvnoj industriji.

KLJUČNE RIJEČI: *drvni otpad; otrovni spojevi; MDF; peleti; biomasa; opskrbni lanac*

1 INTRODUCTION
1. UVOD

Wood is one of the most suitable renewable raw materials. Its key value is recognized from both an economic and environmental point of view. Based on FAO reports, the trend of increasing global timber supply has been observed (FAO, 2020). Within the past two decades, the global timber supply increased by over 20 %. This growth is estimated to continue in the following decades of the 21st century. The main factor that influences the growth in demand for raw wood material is the increase in the world's population. As the world's population grows, there is an increase in the demand for wood in various areas of the timber industry as well as in households.

One of the most popular wood utilizations is fuelwood (sometimes firewood). Among the earliest applications of wood were its uses in building and as a fuel source (Rhodes, 2018). According to Eurostat (Eurostat, 2023), in 2022 approximately 25 % of total wood production in the European Union was used as fuelwood. In some countries fuelwood production is a major direction of wood production, i.e. Netherlands – 78.5 %, France – 50.7 % or Lichtenstein – 50 %. This phenomenon is due to the great heating value of wood. In general, the heating value depends mainly on wood species and moisture content, but it is commonly well-known that burning wood is a good source of heat or power. In Poland, 21 % of households use wood for any heating purpose, while 11 % use it as a primary commodity for dwelling heating (GUS, 2023). Unfortunately, the side effect of energy/heat production from burning wood is wood smoke, which consists of particulates and gases that negatively affect human health. The effect of wood smoke on people and the environment was widely studied (Heibati *et al*., 2025; Naeher *et al*., 2007; Ward and Lange, 2010). However, this problem is gradually being minimized by the introduction of clean air programs in both cities and villages throughout the World to improve air pollution control (Wang *et al*., 2024).

Another argument in the discussion of the legitimacy of wood combustion is the question of what wood should be used for energy production, so as not to compete with its use in other wood industries. Wood biomass, such as forest residues, wood processing residues or construction and municipal waste, can be recycled and reused. The work has proven that forest residues from Scots pine (*Pinus sylvestris* L.), which are usually burned after shredding, can be used as a raw material for particleboard manufacturing with increased mechanical strength (Pędzik *et al*., 2022).

Pellet production should be based on the use of wood waste that cannot be reintroduced into the material cycle, rather than full-grade wood. The production of pellets from forest residues from thinning stands of Mediterranean pine (*Pinus halepensis* Mill. and *Pinus pinaster* Aiton) is uneconomical, and pellets produced from debarked logs of larger diameter show the highest quality, while pellets produced from branches have lower quality (Lerma-Arce *et al*., 2017). Therefore, the priority should be to use wood waste that is no longer suitable for further processing for pellet production. Such reasonable wood management is called wood cascading, a concept that allows for maximum use of wood in material applications, with an indication of energy use at the end of utilization. This concept becomes more and more popular both in research and industry (Jarre *et al*., 2020). Cascading wood and a reverse supply chain would allow the long-term use of wood, which, despite being a renewable resource, has a long renewal cycle. In addition, it would allow carbon dioxide to be sequestered rather than, as in the case of incineration, immediately released into the atmosphere along with other harmful substances.

In this context, it is worth highlighting the measures taken by the European Union to reduce carbon emissions by promoting the alternative, more sustainable use of wood. The climate package is based on two key objectives: reducing greenhouse gas emissions in the EU by 55 % by 2030 compared to 1990 levels and achieving climate neutrality for the climate and the environment by 2050 (European Commission, 2018; Köhl *et al*., 2021). One of the priority areas of action remains the reduction of carbon dioxide emissions, including those resulting from the energy use of wood through combustion (Brodny and Tutak, 2020). One of the key elements of the European Green Deal is the promotion of timber construction. The use of wood in the construction and fitting out of buildings promotes long-term carbon storage, which contributes to the reduction of greenhouse gas emissions (Mazur and Winkler, 2025). The strategic implementation of technologies focused on the use of wood waste in sustainable production processes is becoming crucial for promoting responsible environmental management (Pelyukh *et al*., 2025). Therefore, the effective management of wood waste, its recycling and reuse in the construction sector is a key element in reducing the carbon footprint and promoting a circular economy (European Commission, 2021). At the same time, this emphasizes the need for optimized logistics and transportation strategies that enable an efficient management of wood raw materials at every stage of the supply chain.

In Poland, around 15 % of total round wood production is used for fuelwood (Eurostat, 2023). In an era of growing demand for wood, which is necessary to produce building materials, wood-based panels and other industrial products, efficient wood waste management is becoming a key challenge. Burning full-value wood solely for its high energy value leads to an irretrievable loss of raw material that could be used in further production. Therefore, the purpose of the article was to determine how wood waste and residues are managed by wood plants, what part of it goes to recycling and what part is used for energy recovery. In addition, emissions from the combustion of wood products and pellets were analyzed, which is important for assessing the environmental impact of the process. The second aim of this study was to understand what substances may be emitted when material such as MDF is ignited, e.g. in the event of a building or furniture fire.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research was carried out based on a multi-step study on wood biomass supply chain, which consists of literature review with the focus on group interviews (Kawa, 2023) and originally published methods (Dubisz and Kawa, 2023). The study was based on a dataset provided by a specialized research agency, which conducted computer-assisted telephone interviews based on a questionnaire and interview script prepared by the research team. The main topic of investigation consisted of wood waste management in the wood and furniture industries – what types of residues are generated and how they are processed in practice.

The sample was selected through stratified random sampling, with the population limited to companies involved in processing or transporting wood waste, producing wooden products, and recycling wood materials. Out of 12,000 potential participants, 3,800 were contacted, but only 300 companies agreed to take part in the study, resulting in a success rate of 8 %. The sample is representative of a population of up to 50,000 entities with a margin of error of 5.64 % (Raosoft, 2025). Participation in the interview was restricted to respondents with experience in the wood industry, particularly biomass. Two screening questions were used to ensure this. Respondents were asked whether the company they worked for dealt with wood waste, wood materials or post-consumer wood (waste from used wood products) and whether they had any knowledge of such waste, including its generation, processing, collection or transport. Positive answers to both questions were required for the respondent to qualify for the study.

Given the survey data obtained, in a further step, it was decided to test the presence of toxic substances in two combusted wood wastes – medium-density fiberboards (MDF) and pellets. MDF boards are commonly used in many branches of economy, including the furniture and building industry. In general, this material is commonly known as hard to recycle and burn due to its structure and presence of toxic substances. Pellets are made from the sawdust of softwood and hardwood and are one of the most common ways of utilization in the wood industry. Measurements using a cone calorimeter from Fire Testing Technology Ltd. were conducted in accordance with ISO 5660-1, 2015. This calorimeter enables accurate measurements of relevant flammability parameters, which are essential for understanding the fire risks associated with different materials. Samples were placed horizontally against the cone heat sink and exposed to a 35 kW/m^2 heat flux. At least three measurements were taken for each material. To investigate the formation of gaseous combustion products, the tube furnace (Purser furnace) method was employed to simulate fire conditions, following ISO/TS 19700, 2016. Samples of the test materials were placed in a quartz mold and inserted into a furnace. The samples were then heated to 350 °C with an airflow of 2 dm^3/min (poor ventilation) and to 650 °C with an airflow of 10 dm^3/min (good ventilation). The test run was considered valid only if the initial air velocities were correct according to the ISO standard and the selected steady-state conditions were maintained for at least 5 minutes during the test. The sampling procedure for the chromatograph coupled with a mass spectrometer was described in an earlier publication (Mizera *et al*., 2024).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In the context of wood waste management in the wood and furniture industry, it is crucial to determine what types of residues are generated in production processes and to define their uses. The research carried out included the following waste groups: wood residues from agriculture and forestry (e.g., wood chips), post-production residues (e.g., particles, wood-based panel residues) and post-consumer wood. Such categorization of waste utilization is part of the wood cascading concept (Besserer *et al*., 2021; Jarre *et al*., 2020), especially in terms of size of the wood waste production in

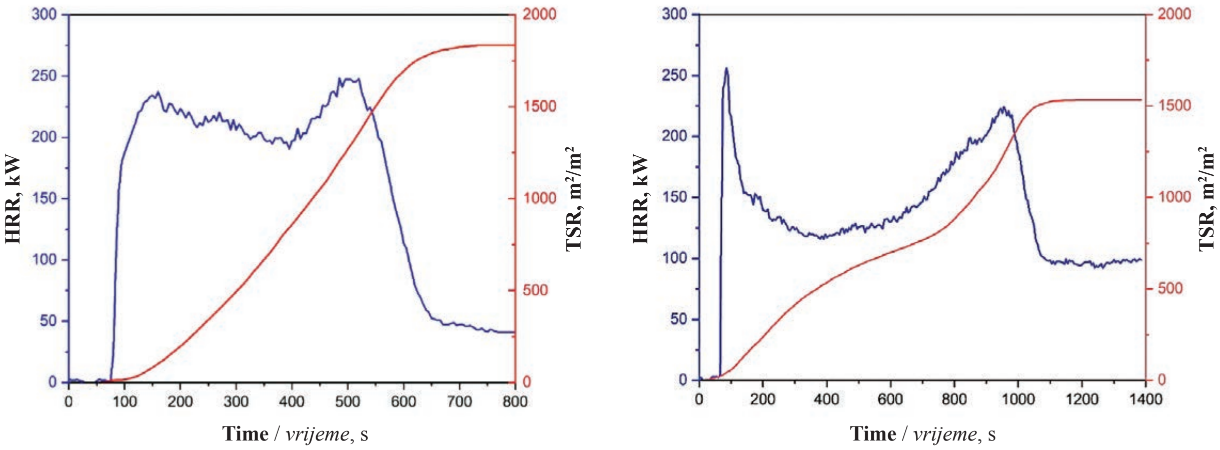

Figure 1 Representative heat release rate (*HRR*) and total smoke release (*TSR*) curves of a) pellet and b) medium-density fiberboard

Slika 1. Reprezentativne krivulje brzine oslobađanja topline (*HRR*) i ukupnog oslobađanja dima (*TSR*): a) spaljivanjem peleta, b) spaljivanjem MDF ploča

Europe (Garcia and Hora, 2017), i.e., Germany produces around 11 million tons of wood waste (Burnard *et al*., 2015; Sommerhuber *et al*., 2015) and is the biggest wood waste producer in the whole Europe, followed by France, United Kingdom, Italy and Finland (Garcia and Hora, 2017). In the first part of the study, we conducted and analyzed a survey on wood waste management of wood and furniture industries in volunteer companies. In general, the utilization of the wood waste is a combination of recycling, energy recovery, and disposal processes (de Souza Pinho *et al*., 2023; Hossain and Poon, 2018). An analysis of the answers regarding waste management methods indicates that most waste ends in combustion with energy recovery or is transferred to external companies for energy production, which confirms the worldwide trends described in the literature (Elginoz *et al*., 2024; Farjana *et al*., 2023). The three most numerous groups participating in the research, namely sawmills, furniture manufacturers and manufacturers of joinery, declare that 52 %, 65 % and 55 %, respectively, combust waste or transfer it for energy recovery. Although this approach allows for effective biomass management and a reduction in landfill waste, from a wood cascading concept point of view, incineration should be considered a last resort in the context of environmental strategies. Wood plays an important role as a carbon (CO_2) store, and its rapid combustion contributes to the accelerated emission of stored carbon dioxide into the atmosphere. To further investigate the environmental impact of burning different wood products, a laboratory study simulating fire conditions was conducted.

Testing the flammability of materials using a cone calorimeter is a crucial method for assessing their behavior under combustion conditions. The heat release rate (*HRR*) is a key parameter that indicates the amount of heat released by a material over a specific period. A higher heat release rate correlates with an increased risk of fire spreading (Mizera *et al*., 2023). Another significant phenomenon during combustion is the emission of smoke, which consists of the gaseous phase of liquid or solid products resulting from incomplete combustion. Smoke emission is an extremely important parameter due to its toxicity and the reduced visibility it causes (Hu and Wang, 2020). Increased emissions of toxic substances in the air are harmful on many levels, both to humans, animals and the environment as a whole (Lelieveld *et al*., 2015; Ram Mahala, 2024). Figure 1 summarizes the representative *HRR* and total smoke release (*TSR*) curves for the tested pellet and MDF.

The nature of the *HRR* curves indicates the presence of two distinct peaks. During wood combustion tests, two peaks typically occur: one at the initial stage of combustion and the second just before the flame extinguishes. The initial peak is primarily caused by the formation of a char layer, which reduces heat output and gas emissions. Following this first peak, the heat release rate stabilizes. As combustion continues, a second increase in the heat release rate occurs due to heat accumulation within the sample (Xu *et al*., 2015). The combustion of the MDF lasted longer than that of the tested pellet. The maximum peak heat release rate (*pHRR*) for the MDF was 244 kW/m^2, occurring 85 seconds into the measurement. For the pellet, the *pHRR* value was slightly lower at 242 kW/m^2, but this peak appeared later, at 485 seconds into measurement. In contrast, the TSR values were 1542 m^2/m^2 for the MDF and 1834 m^2/m^2 for the pellet.

Volatile gas-phase products emitted during the combustion of the test materials were identified using a Purser furnace in conjunction with a gas chromato-

Table 1 List of products identified in fire effluents released during ~5 min steady-state periods during different fire stages
Tablica 1. Popis proizvoda identificiranih u otpadnim vodama ispuštenim tijekom ~5 minuta stabilnog stanja u različitim fazama gorenja

Detected products (products exceeding 1 %) *Utvrđeni spojevi (spojevi kojih je više od 1 %)*	**CAS No.**	**Amounts** / *Količina*, %			
		Pellet		**MDF**	
		350 °C	**650 °C**	**350 °C**	**650 °C**
COx. NOx. H_2O	-	5.11	100.00	7.02	66.29
Oxalic acid	64-19-7	2.84		2.25	
Glycolaldehyde	141-46-8	1.16			
Acetic acid	64-19-7	2.84		2.25	
Benzene	71-43-2				1.18
Furfural	98-01-1	2.55		1.75	
2-Furanmethanol	98-00-0	2.56		2.57	
2(5H)-Furanone	497-23-4	1.26		2.40	
2-Hydroxy-2-Cyclopenten-1-one	10493-98-8	1.52			
5-Methyl-2-Furancarboxaldehyde	620-02-0	2.09			
3-Methoxy-Pyridine	7295-76-3			1.13	
Benzoniltrile	100-47-0				1.88
Phenol	108-95-2			1.11	3.00
Hexanoic acid	142-62-1	1.19			
3-Methyl-1.2-Cyclopentanedione	765-70-8	1.25		3.13	
2.5-Furandicarboxaldehyde	823-82-5	1.21			
2-Methoxy-Phenol	90-05-1	6.64		10.79	
Maltol	118-71-8	1.19			
Naphthalene	91-20-3				10.87
Creosol	93-51-6	9.66		9.36	
5-Hydroxymethylfurfural	67-47-0	1.21			
4-Ethyl-2-methoxy-Phenol	2785-89-9	3.80		6.21	
2-Methoxy-4-vinylphenol	7786-61-0	3.43		3.47	
2-Methoxy-4-propyl-Phenol	2785-87-7			1.34	
Biphenyl	92-52-4				1.08
Acenaphthylene	208-96-8				5.18
Dibenzofuran	132-64-9				1.74
1-Isocyan-naphthalene	1984-04-9				1.12
(2H)-Acenaphthylene	2235-15-6				1.44

graph coupled with a mass spectrometer. Table 1 summarizes the products obtained during the combustion and thermal decomposition of both pellet and MDF.

The pyrolysis and combustion of the studied materials produce products similar to those from wood decomposition. At 350 °C, the main substances in the emitted gases and vapors included creosol, 2-methoxyphenol, 4-ethyl-2-methoxyphenol, and 2-methoxy-4-vinylphenol. Creosol, a phenolic aromatic compound found in wood creosote, is known to irritate the eyes and skin. Other compounds present in smaller amounts were oxalic acid, acetic acid, furfural, 2-furanomethanol, and several others. Furfural, derived from biomass through xylose hydrolysis and dehydration in lignocellulose, contains an aldehyde group and a conjugated double-bond system within its furan ring (Sun *et al.*, 2024). It is toxic to the respiratory tract and irritates the eyes and respiratory system. Maltol vapor, a natural substance found in pine tree bark and needles, was also detected during pellet combustion (Cai *et al.*, 2023). In contrast, phenol was released during the flameless decomposition of wood-based panels.

In the case of complete combustion, the number of identified products was significantly lower. For the pellet, no products other than carbon and nitrogen oxides were detected. MDF characteristically has a high calorific value, which makes it well-suited for energy generation (Ali *et al.*, 2024). However, in the case of MDF, several compounds were identified, including benzene, benzonitrile, phenol, naphthalene, biphenyl, acenaphthylene, dibenzofuran, 1-isocyan-naphthalene and (2H)-acenaphthylene. These compounds can irritate the respiratory system and eyes, as well as lead to skin lesions. Additionally, naphthalene and its derivatives, biphenyl and dibenzofuran, are highly toxic to aquatic environments. Furthermore, benzene is a known carcinogen, and naphthalene is also suspected of having carcinogenic properties.

The combustion of pellets mainly emits nitrogen compounds and carbon dioxide, making it relatively clean in terms of chemical composition. In contrast, the combustion of MDF boards generates many harmful and irritating substances due to the presence of adhesives, resins and other additives used in their production. The emission of toxic gases in the event of a building fire poses a significant risk to health and the environment, which emphasizes the importance of research into the safety of materials used in the furniture and construction industries. Although pellets are much less harmful than MDF in terms of toxic emissions, burning them still releases CO_2 into the atmosphere. Carbon dioxide, which could remain locked in wood-based products during the natural cycle, is immediately released during the combustion process. Despite the fact that wood pellets are still considered carbon-neutral due to the equilibrium between carbon dioxide released upon combustion and carbon dioxide absorbed during biomass cultivation, their net carbon footprint is notably lower than that of fossil fuels (Mortadha *et al*., 2025; Pradhan *et al*., 2018). In terms of MDF, advanced incineration technologies and strict emission controls are needed to address the specific challenges of MDF waste (Ali *et al*., 2024). Ongoing research focuses on optimizing processes and minimizing environmental impacts. Therefore, it is crucial to promote methods that use wood more efficiently, extending the time of carbon sequestration rather than its immediate emission.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of the survey and laboratory tests clearly confirm the need for well-planned wood waste management and emphasize the importance of choosing methods of wood waste management that minimize the negative impact on the environment. The analysis showed that 57 % of respondents declared that wood and wood-based waste generated in their plants is combusted or used for energy recovery, which contributes to the rapid emission of CO_2 into the atmosphere, instead of allowing for its longer sequestration by producing wood-based products.

Additional laboratory tests of two selected wood wastes have shown that burning pellets made from hardwood and softwood results in relatively low nitrogen oxide and carbon emissions but still contributes to the release of CO_2 that could be retained in the material cycle. Despite the common perception of wood pellets as a clean bioenergy source owing to their low toxic emissions, the findings suggest that their climate impact from CO_2 release requires consideration when assessing their contribution to EU climate neutrality.

On the other hand, MDF boards, which contain adhesives, varnishes and other chemicals used in their production, lead to the emission of toxic compounds such as benzene, benzonitrile, phenol, naphthalene, biphenyl, acenaphthylene, dibenzofuran, 1-isocyannaphthalene and (2H)-acenaphthylene. These substances can pose a serious threat to human health, i.e. cause cancer, and to the environment by pollution of water, air and soil, especially in the event of a fire in buildings or furniture containing MDF.

Therefore, it is crucial to find more sustainable methods of waste wood management. Waste MDF boards and other composite materials should be recycled or processed in alternative ways instead of being incinerated. At the same time, the production of pellets should be based exclusively on clean wood waste that is no longer suitable for reuse, for example, in the production of particleboard or as a filler in thermoplastics. At the same time, research findings indicate the need for further research into the use of pure wood waste in the material cycle instead of the energy cycle, as long as the quality of the material allows for reuse. The research results also emphasize the importance of using safe building and furniture materials that will not generate toxic substances that pose a threat to human health and the environment in the event of a fire.

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5 REFERENCES
5. LITERATURA

1. Ali, L.; Alam, A.; Kuttiyathil, M. S.; Alalabi, A.; Al-Kwradi, M.; Altarawneh, M., 2024: Exploring the potential of chemical recycling of waste medium-density fiberboards (MDF) under oxidative and pyrolytic conditions. Sustainable Chemistry and Pharmacy, 41: 101685. https://doi.org/10.1016/j.scp.2024.101685
2. Besserer, A.; Troilo, S.; Girods, P.; Rogaume, Y.; Brosse, N.; 2021: Cascading recycling of wood waste: A Review. Polymers, 13: 1752. https://doi.org/10.3390/polym13111752
3. Brodny, J.; Tutak, M., 2020: Analyzing similarities between the European Union countries in terms of the structure and volume of energy production from renewable energy sources. Energies, 13: 913. https://doi.org/https://doi.org/10.3390/en13040913

4. Burnard, M.; Tavzes, C.; Tosic, A.; Brodnik, A.; Kutnar, A., 2015: Environmental implications of recycling and recycled products. In: Environmental Implications of Recycling and Recycled Products. Springer Science + Business Media, Singapore. https://doi.org/10.1007/978-981-287-643-0
5. Cai, Z.; Guo, H.; Zhou, Q.; Zhao, S.; Ding, L., 2023: Simultaneous determination of maltol and maltol glucuronide in human plasma and urine by HPLC – MS/MS: Application in clinical study in patients with iron deficiency. Journal of Chromatography B, 1225: 123760. https://doi.org/10.1016/j.jchromb.2023.123760
6. de Souza Pinho, G. C.; Calmon, J. L.; Medeiros, D. L.; Vieira, D.; Bravo, A., 2023: Wood waste management from the furniture industry: The environmental performances of recycling, energy recovery and landfill treatments. Sustainability, 15: 14944. https://doi.org/10.3390/su152014944
7. Dubisz, D. K.; Kawa, A., 2023: Adaptation of supply chain management methods within reverse supply chains of wood biomass. Logforum, 19: 669-681. https://doi.org/10.17270/J.LOG.2023.828
8. Elginoz, N.; van Blokland, J.; Safarian, S.; Movahedisaveji, Z.; Yadeta Wedajo, D.; Adamopoulos, S., 2024: Wood Waste recycling in Sweden – Industrial, environmental, social and economic challenges and benefits. Sustainability, 16: 5933. https://doi.org/10.3390/su16145933
9. Farjana, S. H.; Tokede, O.; Ashraf, M., 2023: Environmental impact assessment of waste wood-to-energy recovery in Australia. Energies, 16: 4182. https://doi.org/10.3390/en16104182
10. Garcia, C. A.; Hora, G., 2017: State-of-the-art of waste wood supply chain in Germany and selected European countries. Waste Management, 70: 189-197. https://doi.org/10.1016/j.wasman.2017.09.025
11. Heibati, B.; Renz, H.; Lacy, P., 2025: Wildfire and wood smoke effects on human airway epithelial cells: A scoping review. Environmental Research, 272: 121153. https://doi.org/10.1016/j.envres.2025.121153
12. Hossain, Md. U.; Poon, C. S., 2018: Comparative LCA of wood waste management strategies generated from building construction activities. Journal of Cleaner Production, 177: 387-397. https://doi.org/10.1016/j.jclepro.2017.12.233
13. Hu, Y.; Wang, X., 2020: Flame Retardant Polymeric materials: a Handbook (Series in Materials Science and Engineering). CRC Press, Boca Raton.
14. ***ISO 5660-1, 2015: Reaction-to-fire tests – Heat release, smoke production and mass loss rate. Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement). ISO, Geneva, Switzerland.
15. Jarre, M.; Petit-Boix, A.; Priefer, C.; Meyer, R.; Leipold, S., 2020: Transforming the bio-based sector towards a circular economy – What can we learn from wood cascading? Forest Policy and Economics, 110: 101872. https://doi.org/10.1016/j.forpol.2019.01.017
16. Kawa, A., 2023: Reverse supply chain of residual wood biomass. Logforum, 19: 295-302. https://doi.org/10.17270/J.LOG.2023.799
17. Köhl, M.; Linser, S.; Prins, K.; Talarczyk, A., 2021: The EU climate package "Fit for 55" – a double-edged sword for Europeans and their forests and timber industry. Forest Policy and Economics, 132: 102596. https://doi.org/10.1016/j.forpol.2021.102596
18. Lelieveld, J.; Evans, J. S.; Fnais, M.; Giannadaki, D.; Pozzer, A., 2015: The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature, 525: 367-371. https://doi.org/10.1038/nature15371
19. Lerma-Arce, V.; Oliver-Villanueva, J.-V.; Segura-Orenga, G., 2017: Influence of raw material composition of Mediterranean pinewood on pellet quality. Biomass Bioenergy, 99: 90-96. https://doi.org/10.1016/j.biombioe.2017.02.018
20. Mazur, Ł. K.; Winkler, J., 2025: Timber construction in Poland: An analysis of its contribution to sustainable development and economic growth. Drewno, 68 (215). https://doi.org/10.53502/wood-196236
21. Mizera, K.; Borucka, M.; Przybysz, J.; Gajek, A., 2024: Identification of substances emitted during combustion and thermal decomposition of wood-based materials. Chemical Engineering Transactions, 111: 283-288. https://doi.org/10.3303/CET24111048
22. Mizera, K.; Przybysz, J.; Borucka, M.; Gajek, A., 2023: Evaluation of the combustibility and smoke evolution of selected wood-based materials. Przemysł Chemiczny, 102: 1349-1353. https://doi.org/10.15199/62.2023.12.8
23. Mortadha, H.; Kerrouchi, H. B.; Al-Othman, A.; Tawalbeh, M., 2025: A comprehensive review of biomass pellets and their role in sustainable energy: Production, properties, environment, economics and logistics. Waste Biomass Valorization, 16: 4507-4539. https://doi.org/10.1007/s12649-024-02873-x
24. Naeher, L. P.; Brauer, M.; Lipsett, M.; Zelikoff, J. T.; Simpson, C. D.; Koenig, J. Q.; Smith, K. R., 2007: Woodsmoke health effects: A review. Inhalation Toxicology, 19: 67-106. https://doi.org/10.1080/08958370600985875
25. Pędzik, M.; Tomczak, K.; Janiszewska-Latterini, D.; Tomczak, A.; Rogoziński, T., 2022: Management of Forest Residues as a Raw Material for the Production of Particleboards. Forests, 13: 1933. https://doi.org/10.3390/f13111933
26. Pelyukh, O.; Ilkiv, M.; Kiyko, O.; Soloviy, I.; Chelepis, T.; Lavnyy, V., 2025: Ecological footprint of wood-based products in the Ukrainian Carpathians region. Drewno, 68 (215). https://doi.org/10.53502/wood-196630
27. Pradhan, P.; Mahajani, S. M.; Arora, A., 2018: Production and utilization of fuel pellets from biomass: A review. Fuel Processing Technology, 181: 215-232. https://doi.org/10.1016/j.fuproc.2018.09.021
28. Ram Mahala, K., 2024: The impact of air pollution on living things and Environment: A review of the current evidence. World Journal of Advanced Research and Reviews, 24: 3207-3217. https://doi.org/10.30574/wjarr.2024.24.3.3929
30. Rhodes, R., 2018: Energy: A human history. Simon and Schuster.
31. Sommerhuber, P. F.; Welling, J.; Krause, A., 2015: Substitution potentials of recycled HDPE and wood particles from post-consumer packaging waste in wood-plastic composites. Waste Management, 46: 76-85. https://doi.org/https://doi.org/10.1016/j.wasman.2015.09.011
32. Sun, X.; Wen, B.; Wang, F.; Zhang, W.; Zhao, K.; Liu, X., 2024: Research advances on the catalytic conversion of biomass-derived furfural into pentanediols. Catalysis Communications, 187: 106864. https://doi.org/10.1016/j.catcom.2024.106864
33. Wang, S.; Song, R.; Xu, Z.; Chen, M.; Di Tanna, G. L.; Downey, L.; Jan, S.; Si, L., 2024: The costs, health and economic impact of air pollution control strategies: a systematic review. Global Health Research and Policy, 9: 30. https://doi.org/10.1186/s41256-024-00373-y
34. Ward, T.; Lange, T., 2010: The impact of wood smoke on ambient PM2.5 in northern Rocky Mountain valley com-

munities. Environmental Pollution, 158: 723-729. https://doi.org/10.1016/j.envpol.2009.10.016
35. Xu, Q.; Chen, L.; Harries, K. A.; Zhang, F.; Liu, Q.; Feng, J., 2015: Combustion and charring properties of five common constructional wood species from cone calorimeter tests. Construction and Building Materials, 96: 416-427. https://doi.org/10.1016/j.conbuildmat.2015.08.062
36. ***European Commission, 2018: Directorate-General for Climate Action. Going climate-neutral by 2050 : a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy. Publications Office. https://doi.org/https://data.europa.eu/doi/10.2834/02074
37. ***Eurostat, 2023: Wood products – production and trade [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_-_production_and_trade (Accessed Feb. 20, 2025).
38. ***FAO, 2020: Global Forest Resources Assessment 2020, Food and Agricultural Organization of the United Nations. Rome, Italy.
39. ***FAO, 2000: FAO Global Forest Resources Assessment 2000, Food and Agricultural Organization of the United Nations. Rome, Italy.
40. ***GUS, 2023: Zużycie energii w gospodarstwach domowych w 2021 roku, Główny Urząd Statystyczny.
41. ***ISO/TS 19700, 2016: Controlled equivalence ratio method for the determination of hazardous components of fire effluents – Steady-state tube furnace. ISO, Geneva, Switzerland.
42. ***European Commission, 2021: New EU Forest Strategy for 2030. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, Belgium.
43. ***Raosoft, 2025: Sample size calculator. http://www.raosoft.com/samplesize.html (Accessed Feb. 20, 2025).

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