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The carbon dioxide emission balance and ability to chip wood by 10 kW machines used in urban areas in terms of increasing interest in using wood biomass resources for personal use

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ABSTRACT

Urbanized areas are spaces that provide interesting amounts of wood wastes to address as renewable resources. Due to limited working space in these areas, small, low-power wood chippers are used. Machines with similar power but different cutting mechanisms are available on the market. The article presents a study of four machines with four different cutting mechanisms: disc, drum, two cylinders, and flail. Wooden beams of three wood species (ash, pine, spruce) with varying hardness according to the Janka classification and ten cross-sectional dimensions ranging from 10 × 10 mm to 100 × 100 mm, along with a moisture content (MC) of 10 ± 2%, were chipped. In the tested machines, stopping the working mechanism caused slippage of the V-belt transmission, protecting the machine from the consequences of overload. It was shown that in terms of chipping capabilities, drum, disc, two cylinders, and flail chippers, respectively, exhibit the highest to lowest capabilities. The range of materials shredded by the tested machines varies from 80 × 80 mm to 10 × 10 mm depending on the wood type and cutting mechanism. The average energy consumption of the tested machines is 2.07 ± 0.73 kWh, and the maximum value recorded for the drum chipper is 5.21 ± 0.2 kWh. Wood species and cross-section are key factors in energy consumption, while the chipper model has little impact. Considering that the average emissions during the production of electricity from fossil fuels are 0.95 kg CO_2 per 1 kWh, these machines produce from 0.5 kg CO_2 h^{-1} to a maximum of 4.49 kg CO_2 h^{-1} (mean 1.97 kg CO_2 h^{-1}). Assuming that one tree absorbs from 7 kg CO_2 per year, it can be assumed that one tree reduces CO_2 emissions from 3 hours of machine work over a year. This is a time significantly shorter than the time required to chip the branches of a single tree subjected to the pruning process. This allows for maintaining a positive CO_2 reduction balance.

Keywords: wood chipper, wood shredder, energy consumption, overload of the drive system, cutting wood.

INTRODUCTION

Biomass in urbanized areas refers to the organic material, primarily plant-based, raised in parks, gardens, urban forests and green areas both private and public. Plant-based materials include trees, shrubs, grasses, and other vegetation. Researchers have been studying urban biomass for various reasons, including its potential contribution to carbon sequestration [1–3], air quality improvement [4–6], temperature regulation [7–9], and overall urban ecosystem health [10, 11].

Wood material collected from trimming, pruning or felling urban trees and shrubs can be disposed of or serve, for example, as a source of renewable energy for generating heat, power, biofuel [12], or be converted in valuable reinforcing fillers as biocomposites for injection moulding or thermoforming applications [13]. As stated by the same Authors, in Europe the average quantity of urban green waste is around 150 kg person^{-1} year^{-1} and the trend is increasing year after year. This context draws attention on comminuting machines – woodchippers – that reduce trunks, branches, twigs in small and more homogenous pieces – woodchips.

One of the basic characteristics of wood chippers is the power of their own engine or of their drive unit. Since a higher power corresponds to a higher productivity, that is a higher amount of woodchips produced per unit of time, those chipper models are employed for industrial applications. Machines with engines rated at 250–840 kW are used primarily for the industrial sector [14–18], while models in the range of 63–230 kW are mainly employed for industrial cleaning of green urban areas: parks, orchards, roadside areas [19–22]. On the other hand, less powerful machines are deployed in amateur applications: home gardens [23–25] or areas with difficult access, e.g. orchards in steep mountain areas [26] (Fig. 2).

Wood chippers used in industrial applications are fueled by loaders - integral or not [27–29], which feed the material through channels equipped with hydraulic "no-stress" systems [30, 31]. This kind of devises, available routinely on industrial machines, recognizes potential overloads on the power capacity and reduces the rotational speed of the drum or of the disc to let the engine regain strength. In such a situation, the feeding mechanism either stops supplying wood or reduces the rotational speed, allowing the chipping of the wood already in the chamber and relieving the cutting system. In manually-fed low power machines [32], there is no wood feeding control system [25, 33] nor protections for the comminuting mechanisms in case of overload. The only safeguards against any potential damage are typically cable-driven belt transmissions, which can also serve as overload clutches [34, 35].

Collection of lignocellulosic material in urban greenery maintenance often occurs in spaces with a limited maneuverability, therefore calling for small-size comminuting machines. In the European Union, spark-ignition internal combustion engines with a power of up to 17 kW are subject to special homologation regulations (Regulation 2016/1628/EU) [35, 36]. In literature many studies have been conducted to assess the impact caused by the comminuting systems on efficiency, and energy and fuel consumption [23, 36, 37] in the chipping process. However, there is a lack of studies regarding the ability to perform the cutting process while maintaining the same power unit parameters and properties cut material. Likewise, studies on time losses resulting from the slowing down of the chipping mechanism are missing. Research has been mainly focused on determining the idle time for chippers, resulting from a downtime in the organization of the operative yard, which can range from 20% to 70% [25, 38, 39] of the overall working time. The aim of the article is to determine the suitability of low power wood chippers (10 kW) to shred wood with a specified cross-sectional dimension depending on the cutting mechanism. The presented findings will allow for a better selection of models according to consumer expectations, potentially improving satisfaction of users and increasing the popularity of utilizing wood biomass for household (Fig. 1). Additionally, the results of energy consumption for the tested machines are presented depending on the type and cross-sectional area of the chipped wood. These studies enable the calculation of the CO_2 emissions balance generated by the machines used for green infrastructure maintenance in urban areas and the capacity of trees in these areas to absorb CO_2 emissions. The reduction of CO_2 emissions is an important issue in technical sciences, both in terms of the natural absorption of emissions by the environment and the reduction of emissions from machinery used in the maintenance of green infrastructure.

MATERIALS AND METHODS

Models with a power of 10 kW representative of the low power chippers group were selected for the study. These machines differed in the comminuting mechanisms: disc, drum, two cylinders, flail (Table 1). The engine was a Four-stroke, OHV (over head valve) Lifan GX390, single-cylinder, characterized by a maximum power of 9.56 kW (13 HP) at 3600 rpm, and a maximum torque of 26.5 Nm at 2500 rpm [40]. The internal combustion engine was connected to the cutting mechanism through a belt drive. In case of blocking, this transmission served as an overload clutch [35] and was implemented by one or two belts in two sizes, A13 and B17 (Fig. 2). The blockage of the cutting mechanism was the limit of the machine's wood chipping capability. The machines under investigation are not

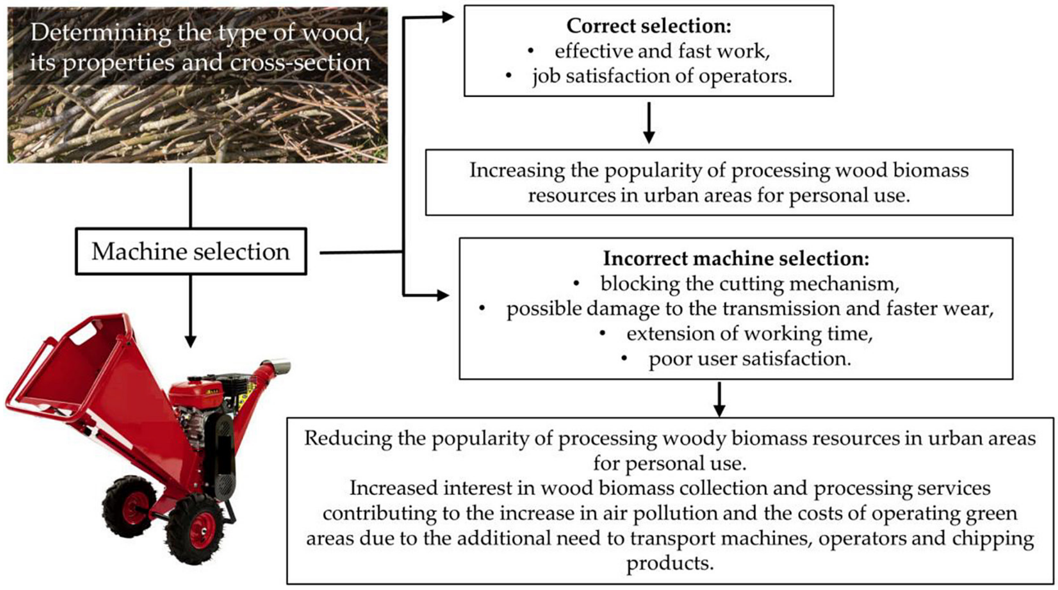

Figure 1. Effects of the correct selection of a chipping machine on the possibility of increased utilization of wood biomass for personal use

Table 1. Characteristics of wood chipper cutting mechanisms

Type of cutting mechanism	Drum	Two-cylinders	Disc (A)	Disc (B)	Flail
Manufacturer	HECHT MOTORS, s.r.o., Mukařově - Tehovci, Czech Republic	Remet CNC Technology Sp. Z O.O., Kamień, Poland	Remet CNC Technology Sp. Z O.O., Kamień, Poland	HECHT MOTORS, s.r.o., Mukařově - Tehovci, Czech Republic	
Model	HECHT 6642	Red Dragon RS-100	RTS-630	HECHT 6421	
Number of knives	2 knives per drum and 1 counter blade	4 knives (2 knives on one shaft)	4 knives per disc and 1 counter blade	2 knives per disc and 1 counter blade	20 knives (5 knives on one shaft)
Average mass productivity during 1 h of wood size reduction[23]	0.25 ton/h	0.45 ton/h	0.19 ton/h	0.21 ton/h	0.07 ton/h

equipped with a system that forces the feed of wood; however, based on the known length of the processed wooden log and the processing time, the mean feed rate was determined. Two-meter wooden beams with cross-sectional dimensions ranging from 10 ×10 mm to 100 × 100 mm (Fig. 3) were comminuted, increasing the cross-sectional area of the square by 10 mm on each side. Ten sample per dimensional category were used and the moisture content (MC) was maintained at 10 ± 2%. The material was free from defects such as decay, knots, or insect damage and was obtained from three wood species: hard wood – ash (*Fraxinus* Tourn. ex L. Sp. Pl. 1057. 1753), medium-soft wood – pine (*Pinus* L. Sp. Fri. 1000, 1753-Scots pine), and very soft wood – spruce (*Picea abies* (L.) H. Karst Deut. Fl. 324. 1881), with hardness classified according to the Janka classification. To measure energy during shredding, torque T and rotational speed n were measured using a torque sensor and integrated rotational speed sensor, the characteristics of the device are presented in Table 2 (Roman Pomianowski Electronics Studio, Poznań, Poland). The measurement system was installed before the cutting mechanism, as shown in Figure 4. Based on Equation 1, power P was determined, and based on Equation 2, energy E was calculated. The value of average energy consumption while the machine was chipping wood was taken into account for analysis.

$$P = \frac{T \cdot n}{9500}, \left[\frac{(N \cdot m) \cdot rpm}{9550} = kW\right] \quad (1)$$

$$E = P \cdot t, [kW \cdot h = kWh] \quad (2)$$

where: t – time.

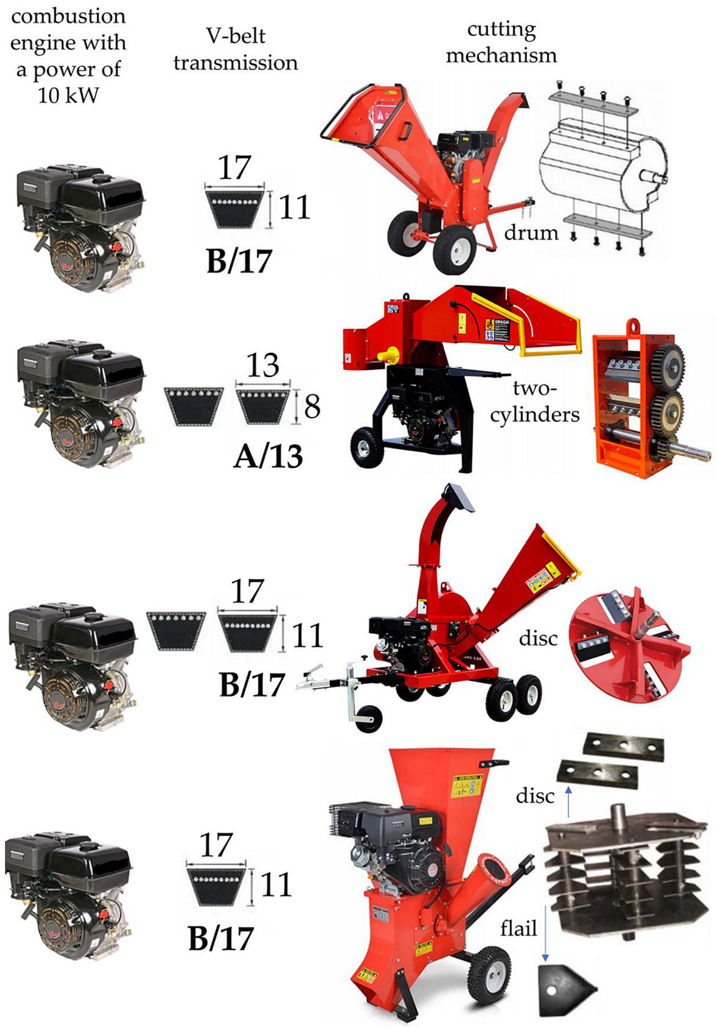

Figure 2. Tested wood chippers characterized by different transmission elements and cutting mechanisms

Table 2. Characteristics of the torque meter with the rotational speed measurement function

Parameter	Measurement range	Resolution	Measurement accuracy
Torque measurement	0–100 Nm	0.001 Nm	± 0.5 %
Rotation speed measurement	0–5000 rpm	0.001 rpm	± 1 %

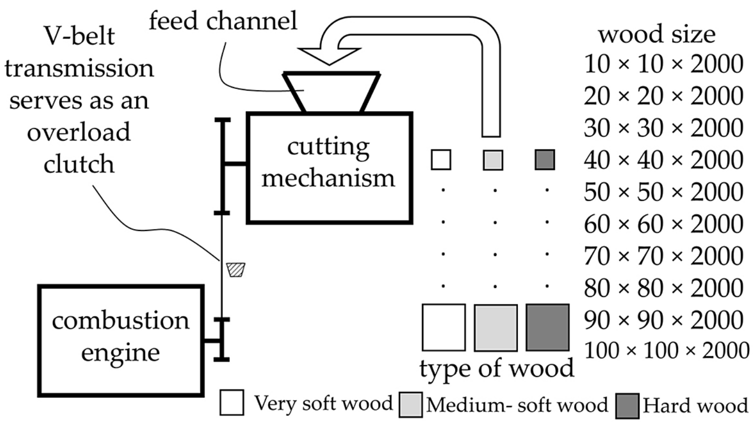

Figure 3. Diagram of the research process

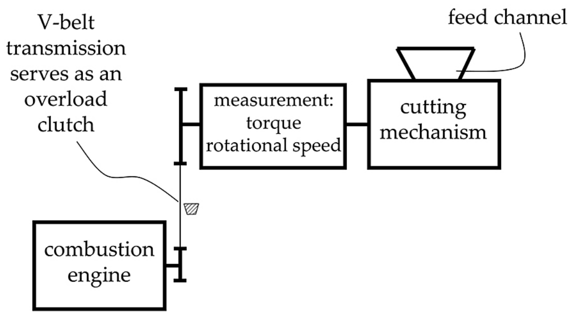

Figure 4. Basic components of a measuring system

RESULTS AND DISCUSSION

Chipping ability

The results of the test show the different suitability of chippers powered by a 10-kW engine to comminute wood depending on their configuration (Fig. 5). The drum chipper exhibits the best outcome, by shredding wood in the range 50 × 50 mm (hard wood) and 80 × 80 mm (very soft wood). The next best result is shown by the disc model for the categories 30 × 30 mm (hard wood) and 50 × 50 mm (very soft wood and medium-soft wood). The two-cylinders model shows similar values (from 30 × 30 mm to 40 × 40 mm), while the flail woodchipper exhibits the worst result, facing the category 10 × 10 mm and 20 × 20 mm. Among other factors, the cutting force significantly depends on the surface area of the wood to be shredded, meaning that it increases with the size of the cross-sectional area of the material [41–43]. By operating within the engine's power characteristic at maximum power (3600 rpm), two fundamental factors determine the cutting force: the gear ratio, with values ranging from 1:3 to 1:5, and the inertial mass of the working mechanism, which joins to the cutting force relative to the engine's driving power. Analogously to the chipping capacity, the drum chipper has a cutting mechanism with the highest momentum of inertia, followed by the disc chipper, the two cylinders chipper, and the flail chipper. In industrial machine studies, it can be observed that drum chippers have higher chipping efficiency compared to disc chippers, indicating their ability to cut a larger quantity of wood in the same amount of time [23, 36, 37]. It is also worth noting that the chipping capacity is influenced by the number and size of V-belts in the transmission [44], where the contact area with the pulley affects the ability to transmit driving force.

During the tests, it was observed that a prolonged blocking of the working mechanism without promptly turning off the power unit can lead to damage to the V-belt, as described by Krawiec et al. in 2021 [35] (Fig. 6). This can also be a cause of fire or a source of harmful exhaust emissions [45–47].

According to the information gathered from users, one of the most crucial aspects in the assessment and selection of chippers is their productivity, which is the fulfillment of the machines' primary function. Other factors taken into consideration include noise levels, fuel consumption, the position of the feed channel, the method of discharging woodchips, the time spent in unlocking in case of overload, and the storage space occupied. One of the main factors worrying professional users are the size limits of wood to be chipped and the issue of branches getting stuck in the feed channel.

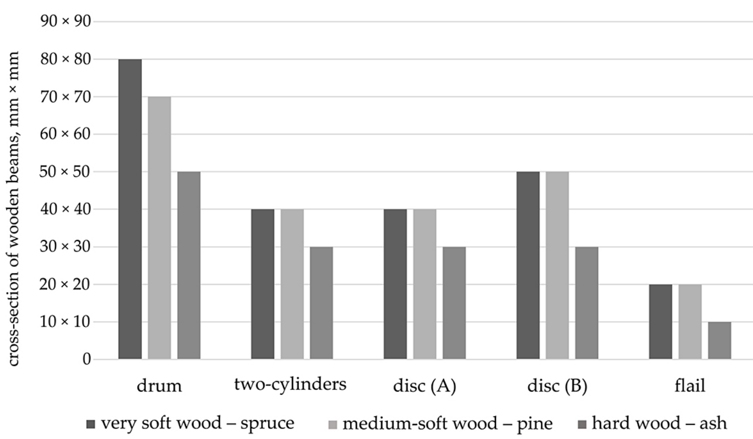

Figure 5. The ability to chop wood with a wood chipper with a power of 10 kW depending on the type of cutting mechanism

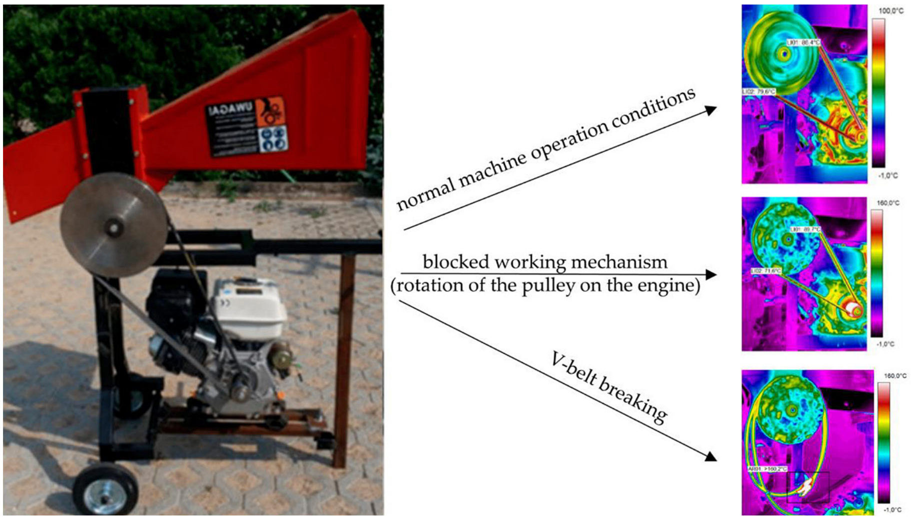

Figure 6. The impact of blocking the working mechanism on a V-belt transmission without additional safety systems (based on Krawiec et al., 2021 [35])

The need to reduce the bulk density of the greenery maintenance in urbanized areas encourages garden or orchard owners to deploy these machines, addressing wood residues to a personal or industrial use. Most of the 10-kW models are designed to treat wood with cross-sectional dimensions of 30 × 30 mm for hard wood species and 40 × 40 mm for very soft wood and medium soft wood species. In the case of the flail chippers, these values are lower, but these machines are equipped with an additional feed channel connected to a second cutting mechanism (disc B) for chipping wood with larger cross-sectional dimensions. High power machines often use hydraulic wood feed systems, which limit the possibility of blocks due to overload [26, 27]. Often safeguards for the working unit is the overload protection system called "No Stress" (Qingdao Kainengda Machinery Co., Ltd, Xiaojinjia Industrial Park, Jimo District, Qingdao, Shandong Province, China), most commonly used in disc and drum chippers. The application of this system in a two-cylindrical wood chipper is pointless because in such a chipper, there are no sudden drops in rotational speed due to overload but rather dynamic ones. Furthermore, a patented

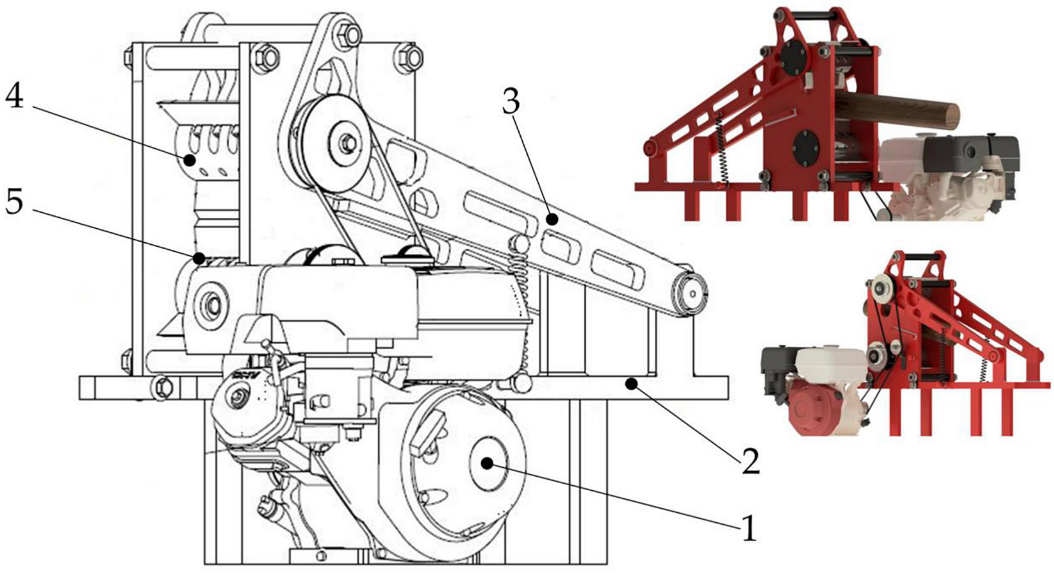

Figure 7. Two-cylinders wood chipper with a divided cutting mechanism, characterized by an anti-overload function, where: 1 – combustion engine, 2 – frame, 3 – rocker arm, 4 – upper cutting cylinder, 5 – lower cutting cylinder (details in PL241362 or [48])

solution PL241362 in the Polish Patent Office is known in the conceptual phase of the project, concerns a design for a locking-resistant cutting mechanism (Fig. 7). To overcome possible interruptions due to the presence of flexible branches or oversize pieces in the material to be chipped, a special solution has been realised and patented by the Polytechnic of Poznan. The idea is contained in a two-cylinders woodchipper, which cut the wood fibers by rotating in opposite directions. This mechanism transports the material outside the comminuting chamber in two forms: chips (whose strength doesn't exceed the maximum moment of the cutting mechanism) and oversize pieces (whose strength exceeds the maximum moment of the cutting mechanism). Unchipped wood moves together with the woodchips to the outer channel, where it can then undergo to segregation. The two-cylinders woodchipper relies on a combustion engine with a pulley drive. The engine is connected to the comminuting system through a transmission belt equipped with a double-sided toothed belt and a mechanical tensioner working with a tension spring. The upper cutting cylinder is mounted on a rocker fixed along the rotation axle to the chipper case through a pin connection. The tension of the rocker, and consequently of the working component, is regulated by a tension spring. The engine, through the belt transmission, drives the comminuting system consisting of two cylindrical rollers equipped with knives. The synchronization of the cutting cylinders is ensured by a belt transmission equipped with a tensioning system, also serving as a counterbalance system in case of overloading. In such cases, the working rollers, by increasing the distance between the rotation axles, push unchipped material towards the outer channel until the cutting moment regain power and allows the material comminution. This value is regulated by a compression spring pressing the upper cutting roller, which is mounted on a rocker [48].

The biomass resources in urbanized areas, such as family allotment gardens, where harvesting is challenging due to dense construction, and centralized on larger areas, allow for considering the development of infrastructure for biogas extraction [49, 50]. Technologies exist for powering wood chippers with gas fuels [40, 51–53], based on technologies from automotive vehicles characterized by the highest fuel dosing control standards [54–56].

Energy consumption

Power was determined by measuring rotational speed and torque. An example of the torque and rotational speed measurement characteristics is presented in Figure 8 for the chipping of a wooden beam with a cross-section of 10 × 10 mm made of ash wood. For further analysis, the average values of torque and rotational speed were adopted. Power expressed per unit of time exhibits the energy consumed during the wood chipping process, as shown in Figure 9. In order to compare the results, they were described with ellipses indicating the area of variation of energy demand during the size reduction of wood beams with different geometric and species characteristics. The geometric center of this area is the average energy demand. This value was taken to compare the energy intensity of the tested cutting mechanisms and on their basis the average energy consumption for the tested group of wood chippers was determined.

As the cross-sectional area of the wood increases, the energy consumption during chipping also increases, showing a correlation between the cross-sectional area of the wood and the energy consumption. The larger the cross-sectional area of the wood, the higher the energy consumption is, as confirmed by studies conducted by Orłowski et al., 2013 and 2017, and Kováč et al., 2011 [41–43]. The energy required for wood chipping increases with its hardness according to the Janka classification, a standard method of determining wood hardness by measuring the force required to embed a steel ball of a specified size into its surface. The higher the Janka value, the greater the wood hardness and the more energy is needed for its chipping. This relationship stems from the fact that harder wood requires more force for cutting and chipping. In practice, this means that wood will require stronger tools or a more intensive chipping process, resulting in increased energy consumption. Such relationships are confirmed by studies utilizing wood chippers [57], milling machines [58], and chain saws [59].

The drum chipper exhibits the highest energy consumption, followed by the disc chipper and the two-cylinder chipper. This is consistent with the findings of other researchers; similar conclusions were drawn by Manzone in 2015 when comparing wood chipper drum and disc mechanisms [37]. It can be observed that the energy efficiency of cutting mechanisms strongly depends on their ability to shred the cross-sectional area. The drum

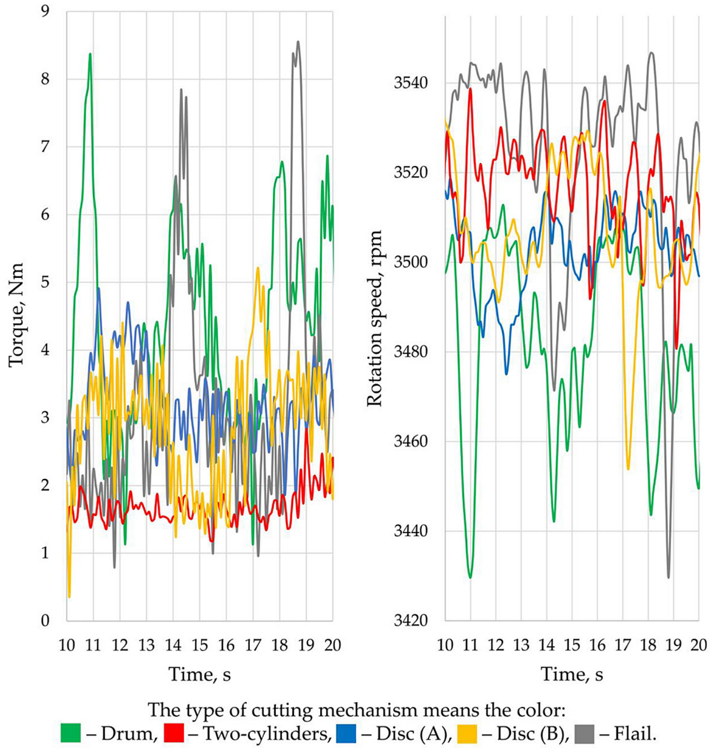

Figure 8. Torque and rotational speed when chipping ash wood with a cross section of 10 × 10 mm

chipper has the greatest inertia among the investigated cutting mechanisms. The energy from the rotating cutting mechanism (the mass in rotation is the largest) makes it the least susceptible to stoppage, translating into the ability to shred the largest cross-sectional areas of wood. However, this capability decreases as energy accumulates in the cutting mechanism, as confirmed by subsequent research on other cutting mechanisms. Following in terms of energy consumption are disc chippers, with even lower energy consumption values for two-cylinder mechanisms. In many studies comparing disc and drum cutting mechanisms, the machine's design consistently allows for the shredding of the supplied material each time. In such studies, disc chippers typically exhibit lower energy consumption, likely due to the lower inertia of the cutting mechanism, requiring less energy for its rotation [36, 60]. The methodology adopted in this article, where the cross-sectional area of the wood is known, allowed for the conclusion that the energy consumed by cutting mechanisms is strongly dependent on the ability to shred the cross-section. In the case of studies conducted under real working conditions of machines with large feeding channels and wood hoppers, determining the value of the cross-sectional area of the cut wood can be challenging despite knowing the cross-section of the supplied wood. This is because the wood pieces may overlap within the working area of the machine.

The examined machines with power units of 10 kW are characterized by an average energy consumption of approximately 2.07 ± 0.73 kWh during wood shredding, with an average cross-sectional area of shredded wood around 39 × 39 mm. The highest energy consumption value was demonstrated by the drum chipper during shredding of a cross-sectional area of very soft wood measuring 80 × 80 mm, at 5.2 ± 0.28 kWh. The average values for the drum chipper were 3.41 ± 0.11 kWh, for disc chipper (B) 2.6 ± 0.13 kWh, for disc chipper (A) 1.82 ± 0.1 kWh, and for two-cylinder chipper 1.05 ± 0.12 kWh (Fig. 9). The registered values are within the ranges of results obtained by other researchers for machines of similar power [23]. Di Fulvio in 2015 conducted research on the influence of the cross-sectional area of round pine wood ranging from 10 cm^2 to 85 cm^2, with a value of 10 cm^2 showing a power of approximately 4 kWh [61], the research presented in the article was conducted for the disc chipper (A and B) in the range from 1 cm^2 to 5 cm^2, supplementing the knowledge base and

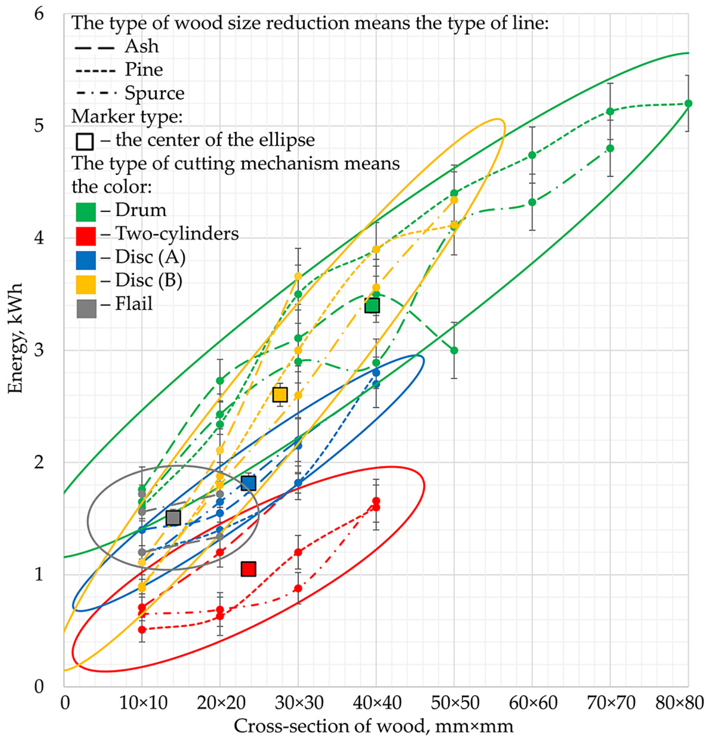

Figure 9. The influence of the cross-section, type of wood and cutting mechanism on the energy consumption of a wood chipper

showing energy consumption in this range ranging from 1 kWh to 4 kWh.

Assuming that wood chippers in urban areas can be powered by electricity, one can estimate the emission of CO_2 into the environment. Mittal et al. in 2014 noted that thermal power plants exhibit varying efficiency due to differences in technologies and maintenance standards. According to these estimates, the average CO_2 emission per unit of electricity generated ranged from 0.91 to 0.95 kg kWh^{-1} [62]. Adopting the value of 0.95 kg CO_2 kWh^{-1}, one can determine the average and maximum CO_2 emission values by wood chippers. These machines produce from 0.5 kg CO_2 h^{-1} to a maximum of 4.49 kg CO_2 h^{-1} (mean 1.97 kg CO_2 h^{-1}). CO_2 emission values for gasoline-powered chippers are presented in the literature, but their conversion to kWh is not always straightforward [37, 63, 64]. A two-cylinder wood chipper with a spark ignition engine power of 10 kW, during shredding of wood with a diameter of 100 mm, was characterized by CO_2 emissions from exhaust gases at a level of approximately 2.5 kg CO_2 kWh^{-1}[24], confirming the accurately estimated range of CO_2 emissions. According to Akbari et al. in 2002, one tree in urban areas absorbs an average of about 7 kgCO_2 per year [65]. Assuming this value for discussion, one tree can offset the operation of an average 10 kW wood chipper for approximately 3 hours. It can be assumed that the process of shredding branches with low-power wood chippers in urban areas allows for maintaining a negative CO2 balance in the environment.

Researchers focusing on machinery for the maintenance of green infrastructure are developing technologies aimed at reducing CO_2 emissions through two primary approaches. The first approach involves designing machines with lower energy requirements, thereby minimizing the overall energy consumption during operation [66, 67]. The second approach focuses on improving the efficiency of combustion processes in internal combustion engines, enhancing their performance while simultaneously reducing the emissions produced [68]. These efforts are crucial for advancing sustainable practices in green infrastructure management and contribute significantly to the broader goal of minimizing the environmental impact of such operations.

The value adopted for the wood feed rate

The tested machines are not equipped with a wood feeding system that ensures a constant feed rate. In this group of machines, the wood typically falls by gravity or is simply "pulled" into the cutting mechanism. In the case of hard or brittle wood, the wood may bounce off the cutting mechanism, but in such cases:

- it falls back by gravity into the cutting mechanism, or
- the operator pushes it towards the cutting mechanism.

The speed was not monitored or recorded, but it can be assumed to be fairly consistent. This value can be calculated based on the chipping time and the length of the processed log (in the study, 2-meter logs were chipped). The estimated average wood feed speed results are presented in Figure 10.

Multicriteria analysis of energy consumption for four chippers processing three wood species with eight cross-sections

The data considered in this analysis involve the energy consumption for different chipper models (Two-cylindrical, Disc A, Disc B, Drum, Flail) when chipping three wood species (ash, pine, spruce) with eight different cross-sections (e.g., 10 × 10, 20 × 20, etc.). Cross-sections are expressed as, for example, 10 × 10, corresponding to an area in mm² (e.g., 10 × 10 equals 100 mm²). The aim of the analysis is to determine which factors influence energy consumption during wood processing. The following variables were analyzed: dependent variable – energy consumption, independent variable – chipper model (5 levels: Two-cylindrical, Disc A, Disc B, Drum, Flail), independent variable – wood species (3 levels: ash, pine, spruce), independent variable – wood cross-section (8 levels: e.g., 10 × 10, 20 × 20, etc.). To analyze the data, we used a multifactorial analysis of variance (ANOVA) to examine the influence of each of the three factors (chipper model, wood species, and cross-section) on energy consumption. ANOVA allows us to determine whether the differences in these factors have a statistically significant impact on the dependent variable. The ANOVA model is shown in Equation 3.

$$E = M + G + P + I \quad (3)$$

where: E – energy consumption, M – chipper model, G – wood species, P – cross-section, I – interactions.

From the ANOVA results (Table 3), based on the p-values, we can determine which factors significantly affect energy consumption. According to the analysis, the chipper model does not

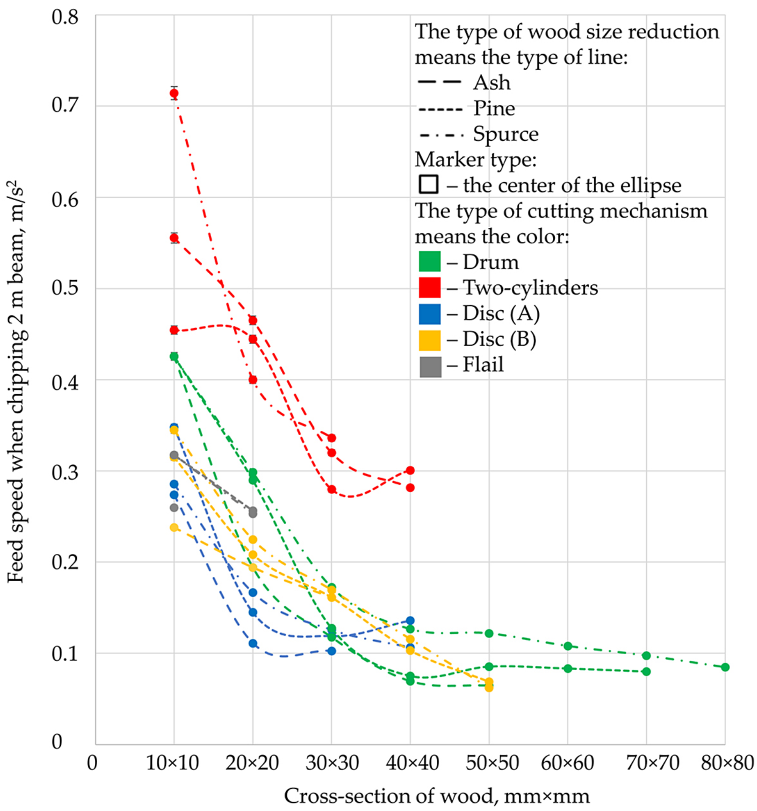

Figure 10. The average value corresponding to the wood feed rate

have a statistically significant impact on energy consumption (p = 0.35), suggesting that the differences between the chippers are energetically insignificant. Wood species has a statistically significant effect on energy consumption (p = 0.033). This means that different wood species (ash, pine, spruce) have varying effects on energy consumption, which could be related to properties like hardness, density, and other characteristics of the wood. Cross-section also significantly affects energy consumption (p = 0.024). Larger cross-sections lead to higher energy consumption, which is logical since a greater amount of material requires more energy to process. The result of the Shapiro-Wilk test for normality of energy consumption distribution: Test statistic: 0.954, p-value: 0.142. Since the p-value (0.142) is greater than the typical significance level of 0.05, we have no grounds to reject the null hypothesis, which assumes that the distribution of energy consumption data is normal. This means that the energy consumption distribution can be considered normal, satisfying the assumptions for the conducted analysis. Based on the multicriteria analysis, the following conclusions can be drawn. The most important factors affecting energy consumption are the wood species and the cross-section. The chipper model does not significantly impact energy consumption, suggesting that different chippers consume similar amounts of energy regardless of the other variables. Energy optimization should focus on selecting the appropriate wood species and cross-section to minimize energy consumption.

Mathematical model of energy consumption

The mathematical model that combines the influence of the chipper model parameters, wood species, and wood cross-section on energy consumption can be represented by an equation that takes into account the effect of three independent variables: the chipper model, wood species, and cross-sectional area, on the dependent variable, which is energy consumption (4).

$$E = f(M, G, P) \tag{4}$$

where: E – energy consumption (kWh), M – chipper model (category), G – wood species (category), P – cross-section of the wood (mm²).

Assuming that multiple linear regression can be used, the formula for the model (5) may look as follows.

$$E = \alpha + \beta_1 M + \beta_2 G + \beta_3 P + \epsilon \tag{5}$$

where: α – constant, β_1, β_2, β_3 – regression coefficients assigned to the variables of the chipper model, wood species, and cross-section, ϵ – model error.

The proposed interpretation suggests that M (chipper model) is a categorical variable (e.g., Two-cylindrical, Disc A, Disc B, Drum, Flail), G (wood species) is a categorical variable representing different types of wood (ash, pine, spruce), and P (cross-section) is the area in mm², converted from numerical values such as 10 × 10 mm, 20 × 20 mm, etc. In order to refine this model, the cross-sectional values can be normalized, and appropriate numerical values can be assigned to the categorical variables (chipper model, wood species). Then, a multiple linear regression can be performed.

The results of the linear regression analysis show that the coefficient of determination (R^2) is 0.636, indicating that the model explains 63.6% of the variance in energy consumption based on the independent variables (chipper model, wood species, cross-sectional area). The p-value for the F-statistic is 0.0365, meaning that the model is statistically significant, and thus at least one of the independent variables significantly affects energy consumption.

The regression coefficients obtained from the model are as follows: the constant is 4.4019, the chipper model coefficient is -1.4312 (statistically insignificant, p = 0.317), the wood species coefficient is -0.6596 (statistically insignificant, p = 0.811), and the cross-sectional area coefficient is 0.0447 (statistically significant, p = 0.015).

These results suggest that the cross-sectional area has the greatest influence on energy

Table 3. ANOVA results

Factor	Sum of squares	Degrees of freedom	F-Value	p-Value
Chipper model	69,203.59	4	1.144	0.348
Wood species	110,530.13	2	3.655	0.033
Cross-section	82,049.73	1	5.426	0.024
Residual error	710,738.14	47		

consumption, which corroborates previous findings. In contrast, the chipper model and wood species did not demonstrate a statistically significant impact on energy consumption in this particular sample. The model highlights that the cross-sectional area of the wood is the key variable affecting energy consumption.

The proposed values for the coefficients are as follows: α – constant (intercept), this coefficient corresponds to the value of energy consumption when all other variables (chipper model, wood species, and cross-section) are zero. In our model, this value is α = 4.4019. β_1 – coefficient for the variable M (chipper model): This coefficient represents the effect of the chipper model on energy consumption. The estimated value is $\beta_1 = -1.4312$, suggesting that a change in the chipper model reduces energy consumption by 1.4312 kWh compared to the reference value. However, this coefficient is not statistically significant. β_2 – Coefficient for the variable G (wood species), this coefficient accounts for the impact of wood species on energy consumption. The value is $\beta_2 = -0.6596$, indicating that changing the wood species decreases energy consumption by 0.6596 kWh, although this coefficient is also not statistically significant. β_3 – coefficient for the variable P (cross-sectional area), this coefficient defines the effect of the wood cross-sectional area on energy consumption. The value is $\beta_3 = 0.0447$, meaning that each additional unit of cross-sectional area (mm²) increases energy consumption by 0.0447 kWh. This coefficient is statistically significant. The model error ϵ represents the difference between the predicted and actual values of energy consumption. This error can be estimated at approximately 27%. In the future, it is necessary to refine the construction characteristics of the chippers, which will allow for improving the model's accuracy.

CONCLUSIONS

Cutting configuration in chippers affects their ability in comminuting wood, depending on the size of cross-sectional profile of wood pieces. Within the group of low power wood chippers (10 kW), drum models have the highest chipping capacity (from 50 × 50 mm to 80 × 80 mm). A second rate is achieved by disc models (from 30 × 30 mm to 50 × 50 mm), followed by the two cylinders version (from 30 × 30 mm to 40 × 40 mm), and lastly by the flail mechanism (from 10 × 10 mm to 20 × 20 mm) for hard, medium soft, very soft wood species, according to the Janka classification with a moisture content of 10 ± 2%. The research focused on chipping dry wood, which offers the greatest resistance to cutting. In case of wood with higher moisture content, the chipping capacity of the machines increases. Choosing the right machine is decisive to guarantee users with a safe, fast, and satisfying work. The results achieved provides new information on the chipping capabilities of low-power wood chippers and indicated the potential for encouraging their use in urban areas. The study focused on basic and popular machines on the market, without additional systems limiting the effects of the working mechanism overload. Additionally, the average energy consumption by this group of machines was determined to be 2.07 ± 0.73 kWh, which, when powered by electricity, may contribute to CO_2 emissions into the environment if the nearby power plants are fueled by solid fuels. However, the CO_2 emissions balance resulting from the necessity of shredding tree branches after maintenance processes is decidedly favorable, as one low-power chipper (up to 10 kW) during the wood chipping process contributes to emissions of 1.97 kg CO_2 h^{-1}. Assuming that one tree absorbs an average of 7 kg CO_2 per year, this allows the machines to operate for 3 hours without adverse environmental impact in terms of CO_2 emissions. The analysis shows that wood species and cross-section are key factors in energy consumption, while the chipper model has little impact, indicating similar energy use across different chippers. Authors are aware that validation research of wood chippers into the field, in real conditions, is necessary to prove the reliability of these machines. Further research should be conducted in that direction and towards the development of overload mechanisms facilitating the unlocking of machines after overload, which could facilitate operation. The growing interest in such machines will evolve in parallel with the increasing awareness of the positive effects of expanding green infrastructure in urban areas, especially in cities.

REFERENCES

1. Agbelade, A.D.; Onyekwelu, J.C. Tree species diversity, volume yield, biomass and carbon sequestration in urban forests in two Nigerian cities. Urban Ecosyst 2020, 23, 957–970, https://doi.org/10.1007/s11252-020-00994-4

2. Kiran, G.S.; Kinnary, S. Carbon sequestration by urban trees on roadsides of Vadodara City. International Journal of Engineering Science and Technology 2011, 3.
3. Timilsina, N.; Staudhammer, C.L.; Escobedo, F.J.; Lawrence, A. Tree biomass, wood waste yield, and carbon storage changes in an urban forest. Landscape and Urban Planning 2014, 127, 18–27, https://doi.org/10.1016/j.landurbplan.2014.04.003
4. Siouti, E.; Kilafis, K.; Kioutsioukis, I.; Pandis, S.N. Simulation of the influence of residential biomass burning on air quality in an urban area. Atmospheric Environment 2023, 309, 119897, https://doi.org/10.1016/j.atmosenv.2023.119897
5. Selmi, W.; Weber, C.; Rivière, E.; Blond, N.; Mehdi, L.; Nowak, D. Air pollution removal by trees in public green spaces in Strasbourg City, France. Urban Forestry & Urban Greening 2016, 17, 192–201, https://doi.org/10.1016/j.ufug.2016.04.010
6. Eisenman, T.S.; Churkina, G.; Jariwala, S.P.; Kumar, P.; Lovasi, G.S.; Pataki, D.E.; Weinberger, K.R.; Whitlow, T.H. Urban trees, air quality, and asthma: An interdisciplinary review. Landscape and Urban Planning 2019, 187, 47–59, https://doi.org/10.1016/j.landurbplan.2019.02.010
7. Zaki, S.A.; Toh, H.J.; Yakub, F.; Mohd Saudi, A.S.; Ardila-Rey, J.A.; Muhammad-Sukki, F. Effects of roadside trees and road orientation on thermal environment in a Tropical City. Sustainability 2020, 12, 1053, https://doi.org/10.3390/su12031053
8. Tan, Z.; Lau, K.K.-L.; Ng, E. Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas. Building and Environment 2017, 120, 93–109, https://doi.org/10.1016/j.buildenv.2017.05.017
9. Zaki, S.A. Influence of roadside trees and road orientation on outdoor thermal environment: case study in Kuala Lumpur, Malaysia. In Urban Forestry and Arboriculture in Malaysia: An Interdisciplinary Research Perspective; Maruthaveeran, S., Chen, W.Y., Morgenroth, J., Eds.; Springer Nature: Singapore, 2022; 237–253.
10. Nowak, D.J.; Hirabayashi, S.; Doyle, M.; McGovern, M.; Pasher, J. Air pollution removal by urban forests in Canada and its effect on air quality and human health. Urban Forestry & Urban Greening 2018, 29, 40–48, https://doi.org/10.1016/j.ufug.2017.10.019
11. O'Brien, L.E.; Urbanek, R.E.; Gregory, J.D. Ecological functions and human benefits of urban forests. Urban Forestry & Urban Greening 2022, 75, 127707, https://doi.org/10.1016/j.ufug.2022.127707
12. Meisel, F.; Thiele, N. Where to dispose of urban green waste? transportation planning for the maintenance of public green spaces. Transportation Research Part A: Policy and Practice 2014, 64, 147–162, https://doi.org/10.1016/j.tra.2014.03.012
13. Viretto, A.; Gontard, N.; Angellier-Coussy, H. Urban parks and gardens green waste: A valuable resource for the production of fillers for biocomposites applications. Waste Management 2021, 120, 538–548, https://doi.org/10.1016/j.wasman.2020.10.018
14. Nati, C.; Spinelli, R.; Fabbri, P. Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 2010, 34, 583–587, https://doi.org/10.1016/j.biombioe.2010.01.005
15. Spinelli, R.; Magagnotti, N.; Paletto, G.; Preti, C. Determining the impact of some wood characteristics on the performance of a mobile chipper. Silva Fennica 2011, 45, 85–95.
16. Han, S.-K.; Han, H.-S.; Bisson, J.A. Effects of grate size on grinding productivity, fuel consumption, and particle size distribution. Forest Products Journal 2015, 65, 209–216, https://doi.org/10.13073/FPJ-D-14-00072
17. Spinelli, R.; Eliasson, L.; Magagnotti, N. Increasing wood fuel processing efficiency by fine-tuning chipper settings. Fuel Processing Technology 2016, 151, 126–130, https://doi.org/10.1016/j.fuproc.2016.05.026
18. Irdla, M.; Padari, A.; Kurvits, V.; Muiste, P. The chipping cost of wood raw material for fuel in Estonian conditions. Forestry Studies 2017, 66, 65–74, https://doi.org/10.1515/fsmu-2017-0007
19. Spinelli, R.; Cavallo, E.; Eliasson, L.; Facello, A.; Magagnotti, N. The effect of drum design on chipper performance. Renewable Energy 2015, 81, 57–61, https://doi.org/10.1016/j.renene.2015.03.008
20. Choi, Y.-S.; Cho, M.-J.; Paik, S.-H.; Mun, H.-S.; Kim, D.-H.; Han, S.-K.; Oh, J.-H. Factors affecting the chipping operation based on the screen size of the drum chipper. Forests 2019, 10, 1029, https://doi.org/10.3390/f10111029
21. Kormanek, M. Analysis of wood chipping capacity of the bandit 990XP chipper – Case study. Journal of Forest Science 2020, 66 (2020), 63–69, https://doi.org/10.17221/146/2019-JFS
22. Suardi, A.; Latterini, F.; Alfano, V.; Palmieri, N.; Bergonzoli, S.; Pari, L. Analysis of the work productivity and costs of a stationary chipper applied to the harvesting of olive tree pruning for bio-energy production. Energies 2020, 13, 1359, https://doi.org/10.3390/en13061359
23. Warguła, Ł.; Kukla, M.; Wieczorek, B.; Krawiec, P. Energy consumption of the wood size reduction processes with employment of a low-power machines with various cutting mechanisms. Renewable Energy 2022, 181, 630–639, https://doi.org/10.1016/j.renene.2021.09.039
24. Warguła, Ł.; Lijewski, P.; Kukla, M. Effects of changing drive control method of idling wood size reduction machines on fuel consumption and exhaust

emissions. Croat. j. for. eng. (Online) 2023, 44, 137–151, https://doi.org/10.5552/crojfe.2023.1700

25. Warguła, Ł.; Kukla, M.; Krawiec, P.; Wieczorek, B. Impact of number of operators and distance to branch piles on woodchipper operation. Forests 2020, 11, 598, https://doi.org/10.3390/f11050598
26. Gong, Y.; Ren, L.; Han, X.; Gao, A.; Jing, S.; Feng, C.; Song, Y. Analysis of Operating Conditions for vibration of a self-propelled monorail branch chipper. Agriculture 2023, 13, 101, https://doi.org/10.3390/agriculture13010101
27. Nati, C.; Eliasson, L.; Spinelli, R. Effect of chipper type, biomass type and blade wear on productivity, fuel consumption and product quality. Croatian Journal of Forest Engineering : Journal for Theory and Application of Forestry Engineering 2014, 35, 1–7.
28. Spinelli, R.; Mitchell, R.; Brown, M.; Magagnotti, N.; McEwan, A. Manipulating chain type and flail drum speed for better fibre recovery in chain-flail delimber-debarker-chipper operations. Croatian Journal of Forest Engineering : Journal for Theory and Application of Forestry Engineering 2020, 41, 137–147, https://doi.org/10.5552/crojfe.2020.632
29. Laitila, J.; Routa, J. Performance of a small and medium sized professional chippers and the impact of storage time on scots pine (*Pinus Sylvestris*) Stem Wood Chips Characteristics. 2015.
30. Trzepieciński, T.; Stachowicz, F.; Niemiec, W.; Kępa, L.; Dziurka, M. Development of harvesting machines for willow small-sizes plantations in East-Central Europe. Croat. j. for. eng. 2016.
31. Homišin, J. Selection of wood waste chipper drive located on automobile chassis. Acta Mechanica Slov. 2011, 15, 80–86, https://doi.org/10.21496/ams.2011.032
32. Warguła, Ł.; Wieczorek, B.; Giedrowicz, M.; Kukla, M.; Nati, C. Wood chippers: Influence of feed channel geometry on possibility of musculoskeletal system overload. Croat. j. for. eng. (Online) 2025, 46, https://doi.org/10.5552/crojfe.2025.2501
33. Micheletti Cremasco, M.; Giustetto, A.; Caffaro, F.; Colantoni, A.; Cavallo, E.; Grigolato, S. Risk assessment for musculoskeletal disorders in forestry: A comparison between RULA and REBA in the manual feeding of a wood-chipper. International Journal of Environmental Research and Public Health 2019, 16, 793, https://doi.org/10.3390/ijerph16050793
34. Krawiec, P.; Różański, L.; Czarnecka-Komorowska, D.; Warguła, Ł. Evaluation of the thermal stability and surface characteristics of thermoplastic polyurethane v-belt. Materials 2020, 13, 1502-1-1502–1518.
35. Krawiec, P.; Warguła, Ł.; Różański, L. Diagnostics of the Thermal Condition of the Cable Gear Used in the Drive of a Wood Chipper. IOP Conf. Ser.: Mater. Sci. Eng. 2021, 1016, 012013, https://doi.org/10.1088/1757-899X/1016/1/012013
36. Spinelli, R.; Cavallo, E.; Eliasson, L.; Facello, A. Comparing the efficiency of drum and disc chippers. Silva Fennica 2013, 47.
37. Manzone, M. Energy Consumption and CO_2 analysis of different types of chippers used in wood biomass plantations. Applied Energy 2015, 156, 686–692, https://doi.org/10.1016/j.apenergy.2015.07.049
38. Spinelli, R.; Visser, R.J.M. Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy 2009, 33, 429–433, https://doi.org/10.1016/j.biombioe.2008.08.003
39. McEwan, A.; Brink, M.; Spinelli, R. Efficiency of different machine layouts for chain flail delimbing, debarking and chipping. Forests 2019, 10, 126, https://doi.org/10.3390/f10020126
40. Warguła, Ł.; Lijewski, P.; Kukla, M. Influence of non-commercial fuel supply systems on small engine si exhaust emissions in relation to european approval regulations. Environ Sci Pollut Res 2022, 29, 55928–55943, https://doi.org/10.1007/s11356-022-19687-w
41. Orlowski, K.; Ochrymiuk, T. A newly-developed model for predicting cutting power during wood sawing with circular saw blades. Maderas. Ciencia y tecnología 2017, 19, 149–162, https://doi.org/10.4067/S0718-221X2017005000013
42. Orlowski, K.A.; Ochrymiuk, T.; Atkins, A.; Chuchala, D. Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Sci Technol 2013, 47, 949–963, https://doi.org/10.1007/s00226-013-0551-x
43. Kováč, J.; Krilek, J.; Mikleš, M. Energy consumption of chipper coupled to a universal wheel skidder in the process of chipping wood. Journal of Forest Science 2011, 57, 34–40, https://doi.org/10.17221/27/2010-JFS
44. Krawiec, P.; Warguła, Ł.; Waluś, K.J.; Gawrońska, E.; Ságová, Z.; Matijošius, J. Efficiency and slippage in draw gears with flat belts. Energies 2022, 15, 9184, https://doi.org/10.3390/en15239184
45. Krawiec, P.; Warguła, Ł.; Czarnecka-Komorowska, D.; Janik, P.; Dziechciarz, A.; Kaczmarzyk, P. Chemical compounds released by combustion of polymer composites flat belts. Sci Rep 2021, 11, 8269, https://doi.org/10.1038/s41598-021-87634-9
46. Krawiec, P.; Warguła, Ł.; Małozięć, D.; Kaczmarzyk, P.; Dziechciarz, A.; Czarnecka-Komorowska, D. The toxicological testing and thermal decomposition of drive and transport belts made of thermoplastic multilayer polymer materials. Polymers 2020, 12, 2232, https://doi.org/10.3390/polym12102232
47. Krawiec, P.; Warguła, Ł.; Dziechciarz, A.; Małozięć, D.; Ondrušová, D. Ocena emisji związków chemicznych podczas rozkładu termicznego i spalania pasów klinowych. Przemysł Chemiczny 2020, T. 99, nr 1, https://doi.org/10.15199/62.2020.1.12

48. Warguła, Ł.; Rosiak, S.; Gierz, L.; Gavrilin, A.; Bykadorov, S. The concept of a wood chopping machine with a mechanical overload system ensuring continuity of work. Material and Mechanical Engineering Technology 2021, 3, 21–26, https://doi.org/10.52209/2706-977X_2021_3_22
49. Mikielewicz, D.; Kosowski, K.; Tucki, K.; Piwowarski, M.; Stępień, R.; Orynycz, O.; Włodarski, W. Influence of different biofuels on the efficiency of gas turbine cycles for prosumer and distributed energy power plants. Energies 2019, 12, 3173, https://doi.org/10.3390/en12163173
50. Wasiak, A.; Orynycz, O. The effects of energy contributions into subsidiary processes on energetic efficiency of biomass plantation supplying biofuel production system. Agriculture and Agricultural Science Procedia 2015, 7, 292–300, https://doi.org/10.1016/j.aaspro.2015.12.050
51. Warguła, Ł.; Kukla, M.; Lijewski, P.; Dobrzyński, M.; Markiewicz, F. Impact of compressed natural gas (CNG) fuel systems in small engine wood chippers on exhaust emissions and fuel consumption. Energies 2020, 13, 6709, https://doi.org/10.3390/en13246709
52. Warguła, Ł.; Kukla, M.; Lijewski, P.; Dobrzyński, M.; Markiewicz, F. Influence of the use of liquefied petroleum gas (LPG) systems in woodchippers powered by small engines on exhaust emissions and operating costs. Energies 2020, 13, 5773, https://doi.org/10.3390/en13215773
53. Simsek, S.; Uslu, S.; Simsek, H.; Uslu, G. Improving the combustion process by determining the optimum percentage of liquefied petroleum gas (LPG) via response surface methodology (RSM) in a spark ignition (SI) engine running on gasoline-LPG blends. Fuel Processing Technology 2021, 221, 106947, https://doi.org/10.1016/j.fuproc.2021.106947
54. Szpica, D. Investigating fuel dosage non-repeatability of low-pressure gas-phase injectors. Flow Measurement and Instrumentation 2018, 59, 147–156, https://doi.org/10.1016/j.flowmeasinst.2017.12.009
55. Szpica, D. Coefficient of engine flexibility as a basis for the assessment of vehicle tractive performance. Chin. J. Mech. Eng. 2019, 32, 39, https://doi.org/10.1186/s10033-019-0352-8
56. Szpica, D. Validation of indirect methods used in the operational assessment of LPG vapor phase pulse injectors. Measurement 2018, 118, 253–261, https://doi.org/10.1016/j.measurement.2018.01.045
57. Kuptz, D.; Hartmann, H. Throughput Rate and Energy Consumption During Wood Chip Production in Relation to Raw Material, Chipper Type and Machine Setting. Proceedings of the 22nd European Biomass Conference and Exhibition 2014, 23–26 June 2014, 6 Pages, https://doi.org/10.5071/22NDEUBCE2014-2CO.1.5
58. Guedes, T.O.; Moreira da Silva, J.R.; Hein, P.R.G.; Ferreira, S.C.; Guedes, T.O.; Moreira da Silva, J.R.; Hein, P.R.G.; Ferreira, S.C. Cutting energy required during the mechanical processing of wood species at different drying stages. Maderas. Ciencia y tecnología 2020, 22, 477–482, https://doi.org/10.4067/S0718-221X2020005000406
59. Pandur, Z.; Bačić, M.; Šušnjar, M.; Landekić, M.; Šporčić, M.; Jambreković, B.; Lepoglavec, K. Energy consumption and cutting performance of battery-powered chainsaws. Forests 2023, 14, 1329, https://doi.org/10.3390/f14071329
60. Facello, A.; Cavallo, E.; Spinelli, R. Chipping machines: Disc and drum energy requirements. Journal of Agricultural Engineering 2013, 44, https://doi.org/10.4081/jae.2013.317
61. Di Fulvio, F.; Eriksson, G.; Bergström, D. Effects of wood properties and chipping length on the operational efficiency of a 30 kW electric disc chipper. Croatian Journal of Forest Engineering : Journal for Theory and Application of Forestry Engineering 2015, 36, 85–100.
62. Mittal, M.L.; Sharma, C.; Singh, R. Decadal emission estimates of carbon dioxide, sulfur dioxide, and nitric oxide emissions from coal burning in electric power generation plants in India. Environ Monit Assess 2014, 186, 6857–6866, https://doi.org/10.1007/s10661-014-3894-3
63. Manzone, M. CO_2 emissions and energy consumption of loaders in woodchip loading operation. Biomass and Bioenergy 2018, 109, 10–15, https://doi.org/10.1016/j.biombioe.2017.12.012
64. Spinelli, R.; Conrado de Arruda Moura, A.; Manoel da Silva, P. Decreasing the diesel fuel consumption and CO_2 emissions of industrial in-field chipping operations. Journal of Cleaner Production 2018, 172, 2174–2181, https://doi.org/10.1016/j.jclepro.2017.11.196
65. Akbari, H. Shade trees reduce building energy use and CO_2 emissions from power plants. Environmental Pollution 2002, 116, S119–S126, https://doi.org/10.1016/S0269-7491(01)00264-0
66. Orawiec, A.; Suryan, L.; Parmigiani, J. An evaluation of the performance of chainsaw lubricants. Croat. j. for. eng. (Online) 2020, 41, 325–332, https://doi.org/10.5552/crojfe.2020.689
67. Kováč, J.; Kuvik, T.; Krilek, J.; Tylek, P. Influence of the shape of the knife's cutting edge on the cutting force in the chipless cutting of three tree species. BioResources 2024, 19, 8388–8399.
68. Martins, J.; Brito, F.P. Alternative fuels for internal combustion engines. Energies 2020, 13, 4086, https://doi.org/10.3390/en13164086