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Ol'ga Kunickaya
*Yakut State Agricultural Academy, Department of Technology and equipment of forest complex,
Yakutsk, Russian Federation*

Artem Zhuk
Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation

Valentina Nikiforova
Bratsk State University, Department of Ecology, life safety and chemistry, Bratsk, Russian Federation

Svetlana Chzhan
Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation

Mariia Gorodnichina
Petrozavodsk State University, Federal State Budget Educational Institution of Higher Education, Department of Transport and Production Machines and Equipment, Petrozavodsk, Russian Federation

Elena Runova
Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation

Ivan Garus
Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation

Viktor Ivanov
Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation

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REDUCING ENERGY CONSUMPTION OF BARKWOOD RESIDUE GRINDING ON EQUIPMENT WITH KNIFE-BASED OPERATIONAL UNITS

Ol'ga Kunickaya[1], Artem Zhuk[2], Valentina Nikiforova[3], Svetlana Chzhan[2], Mariia Gorodnichina[4], Elena Runova[2], Ivan Garus[2], Viktor Ivanov[2]*

[1]*Yakut State Agricultural Academy, Department of Technology and equipment of forest complex, Yakutsk, Russian Federation*
[2]*Bratsk State University, Department of reproduction and processing of forest resources, Bratsk, Russian Federation*
[3]*Bratsk State University, Department of Ecology, life safety and chemistry, Bratsk, Russian Federation*
[4]*Petrozavodsk State University, Federal State Budget Educational Institution of Higher Education, Department of Transport and Production Machines and Equipment, Petrozavodsk, Russian Federation*

In the coming decades, wood waste management for biofuel production is regarded as a promising renewable energy source and a key factor in reducing carbon dioxide emissions. Mechanical grinding is seen as one of the main techniques in wood waste pre-treatment operations that increases the value of feedstock used for fuel. The application potential of the ground product highly depends on the energy efficiency of the process.This work aimed to establish a consistent pattern for estimating the energy consumption required for grinding spruce and pine barking waste depending on the degree to which materials are ground and their relative moisture content. The energy consumption parameters at grinding were analyzed employing three grinding energy models of Rittinger, Kripichev-Kik, and Bond. The results of estimation showed that specific energy consumption is associated with relative moisture content and the grinding degree by nonlinear dependence according to the Kripichev-Kik grinding model for spruce and pine bark. It has been established that the specific energy consumptionat grinding spruce and pine barking waste at the optimum humidity of 25% and 27%, respectively, is proportional to the natural logarithm of the grinding degree. It was concluded that the wood waste grinding by 5–15 times requires higher energy consumption at optimum moisture content, which is 5–10% and 7–14% of the heating value for spruce and pine, respectively. The knowledge acquired through this research will contribute to developing possible approaches for wood waste recycling in a more energy-efficient way.

Key words: model of grinding, specific energy consumption, wood grinding, wood waste recycling

INTRODUCTION

The technological cycle of wood production assumes a large amount of wood residues during main production (sawdust, cuttings, bark, limbs, etc.). The volume of wastes by logging and woodworking is much more than 50% of the total volume of harvested or processed wood [1]. By wood harvesting, main production wastes include the tops of trees, brushwood, branch wood, butts, and debris. In Russian woodworking companies, most logging waste is used for strengthening skidding trails or building haul-roads [2]. In sawmills, most of the waste constitutes cuttings, slabs, wood strips, and bark. The largest amount of bark is generated in woodworking shops for pulp and paper mills during bulk mechanical barking performed in barking drums [3]. Generally, wood residues in the main woodworking plants are used as fuel for boiler plants or processed to produce fuel briquettes and pellets [4,5].

As the world's energy strategy is currently focused on expanding renewable energy sources like biofuels, the study and development of technologies for efficient wood processing is a highly relevant and promising area [6,7]. The energy potential from the waste wood industry is known to comprise about 32% of the total resources [8]. When estimating the value and potential supply of biomass resources in the 27 EU countries, the recycling of forest residues was found to have a significant effect on in creasing the total volume of bioresources, although the costs for recycling remain quite high [9]. However, by setting particular limits for forest logging and land exploitation, the bioenergy potential of forest waste is predicted to increase 4–5 times its current level by 2050 [10-12]. Such conclusions of the oretical analyses demonstrate that forest waste can become a major source of bioenergy without risk to reduce the sale of industrial round-wood and wood fuels like fuel briquettes or pellets. Besides, waste wood is valuable not only for fuels but also for various chemical agents, materials, and fertilizers [13]. For example, low-quality wood can be used for the production of wood-based panels, which reduces waste management and recycling costs [14].

Regardless of the feedstock type, the grinding of forest materials is an important aspect of the industrial appli-

*kunickayaolga44@rambler.ru

cation [15]. Since wood grinding is one of the most important and the most energy-intensive operations in the bark waste cycle, the main challenge for increasing the efficiency of this process is to minimize energy consumption [16,17].

One of the key quality parameters of ground feedstock is the particle size, refinement of which increases the bulk density and surface area of particles [18,19]. These parameters are important for the efficient use of raw materials in fuel production, transportation, or chemical treatment [20,21].

However, reducing the size of wood particles is quite energy-intensive process. The specific energy consumption is usually calculated by measuring the energy consumed over a certain period to grind a certain mass of material. Net energy input is calculated by deducting the specific energy consumption at idling from total calculated values [22]. Besides, the amount of energy consumed can be strongly influenced by such factors as wood type, its original size, and moisture content. For example, grinding 1 kg of beech to the size of 0.5 mm requires 3060 kJ of electricity, while that for spruce amounts to 2700 kJ for [23].The value of specific energy consumption depends on the handling method and the parameters of equipment construction. Results of overviewingresearch reported the lowest energy consumption by a hammer mill for grinding herbaceous materials up to 1-2 mm in size, while knife mills consume 2-3 times more energy under the same grinding conditions. Such variant is appropriate though at a low moisture content of starting raw materials (10–15%). For materials with higher moisture content and denser structure, e.g., forest species, disc mills are applied, which are highly energy-consuming. Also, the sieve size used in milling machines affects the particle size and, thus, energy consumption [24]. Therefore, modeling the barking waste recycling process is highly relevant and important for the optimization of its efficiency and product quality.

Mathematical modeling that adequately describes the wood waste grinding on modern knife-based equipment (the most common in practice) is not sufficiently covered by scientific literature. Single works in this research field have attempted to establish a relationship between energy consumption and particle size reduction in the form of a power dependence [25,26]. In powder metallurgy, rocks classification, and other spheres, different grinding theories [27,28], namely the laws of Rittinger, Kirpichev-Kik, and Bond, are used to study the impact of different energy-intensive parameters on particle size. The use of theoretical data for modeling energy consumption in wood waste grinding with the help of dimensional characteristics will be the first step to optimize the grinding process, which has great potential for industrial applications.

This work aimed to establish a consistent pattern for estimating the energy consumption required for grinding spruce and pine barking waste depending on the degree to which materials are ground and their relative moisture content. To achieve this goal, experimental studies were conducted using a wide range of dependencies.The results of experimental measurements were checked for compliance of energy consumption values required for bark grinding with the laws of Rittinger, Kirpichev-Kik, and Bond. The knowledge acquired through this research will contribute to developing possible approaches for wood waste recycling in a more energy-efficient way.

MATERIALS AND METHODS

Grinding models

Grinding operation is determined by following mathematical expressions according to Rittinger's theory [29]:

$$A_Q = K_R Q \cdot \frac{i-1}{D_{mn}} \quad 1)$$

where K_R is the proportionality factor, Q is the mass of the raw material to be ground, and i is the grinding degree:

$$i = \frac{D_{mn}}{d_{mn}} \quad 2)$$

where *dmn* is the mean size of material pieces after grinding and *Dmn* is the mean size of material pieces before grinding:

$$d_{mn} = \frac{\sum w_j}{\sum \frac{w_j}{d_j}} \quad 3)$$

$$D_{mn} = \frac{\sum w_j}{\sum \frac{w_j}{D_j}} \quad 4)$$

where w_j is a percentage of pieces of a certain fraction (narrow class), d_j and D_j are a mean size of pieces of a certain fraction (narrow class), and *j* is a serial number.

The mathematical expression of the Kirpichev-Kik's law may be as follows [30]:

$$A_Q = K_K Q \cdot \ln i \quad 5)$$

where K_K is a proportionality factor.

Mean sizes in this case are calculated using formulas:

$$d_{mn} = \frac{\sum w_j \, ln\, d_j}{\sum w_j} \quad 6)$$

$$D_{mn} = \frac{\sum w_j \, ln\, D_j}{\sum w_j} \quad 7)$$

The calculation of the grinding operation according to Bond's theory can be expressed as [29]:

$$A_Q = K_B Q \cdot \left(\frac{1}{\sqrt{d_{mn}}} - \frac{1}{\sqrt{D_{mn}}} \right) \quad 8)$$

where K_B is a proportionality factor.

Mean sizes in this case are calculated using formulas:

$$d_{mn} = \left(\frac{\sum w_j}{\sum \frac{w_j}{\sqrt{d_j}}} \right)^2 \quad 9)$$

$$D_{mn} = \left(\frac{\sum w_j}{\sum \frac{w_j}{\sqrt{D_j}}} \right)^2 \quad 10)$$

Rittinger's law assumes the application of not only the obvious indicator like the degree of grinding but also the initial size of material pieces. Therefore, the starting size of the ground bark samples should be considered when conducting experiments. By Bond's law, the size of the ground product plays a significant role along with the starting particle size of the material. A larger particle size range for the ground bark will be thus applied during the experiment. Functions (1), (5), and (8), i.e., grinding laws, allowed considering the plan for the second-order experiment as the most relevant, which should be taken into account when developing the program of experimental research.

Thus, experimental measurements and applicability estimation of a certain theoretical model enable establishing a pattern for energy consumption evaluation, which is required for bark waste grinding in relation to the grinding degree i and wet based moisture W.

Materials and preparation for the experiments

The main manageable factors and their varying ranges are shown in Table 1. Experiments were performed with wood waste after barking operations on two types of wood, namely spruce and pine.

Table 1: Manageable factors and their varying ranges in experiments on the energy consumption for bark waste grinding

Factor	Value			Range
	bottom level	basic level	top level	
W, [%]	10	40	70	30
i	6	10	14	4

The number of observations during experiments varied between 10 and 30 due to the results of the preliminary studies and the different amounts of the available experimental material. The first stage in preparing the experimental material was to create the desired relative moisture content of the waste. Three moisture groups were examined: waste immediately after barking (W ≈ 70%), air-dried waste (W ≈ 40%), and waste dried in a drying chamber (W ≈ 10%). Then, for the experimental material of a certain moisture group, the preliminary separation was carried out at ALGM-3 equipment with a sieve set of different diameters. The waste was selected in such a way that the mean particle size of the pieces before grinding *D* amounted to 70, 50, and 30 mm.

Thus, 9 groups of experimental material were obtained to enable testing with factors and ranges of their variation corresponding to Table 1.

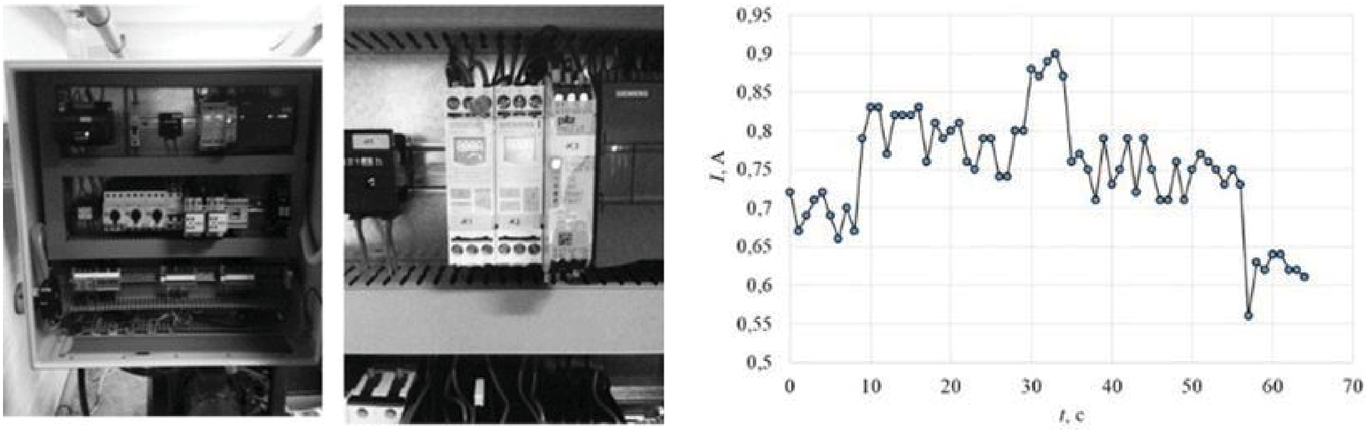
Grinding experimental methods

Afterward, samples weights of 10 kg were selected specifically for the experiment. The weight of experimental samples was controlled on the commercial scales. Selected samples were ground separately in the experimental facility of industrial shredder Erdwich M600/1-400 presented in Fig. 1 with the description of technical data in Table 2.

Table 2: Description of technical data for the Erdwich M600/1-400 shredder

Number of shafts, pcs	1
Amount of stator knives, pcs	2
Amount of rotor knives, pcs	17
Diameter of the knives, mm	220
Width of the knife, mm	25
Configuration of the knives	3-double hook with overlapping
Diameter of shafts, mm	65
Rotational velocity of the cutting unit, RPM	35
Diameter of punched sieve, mm	25.30 or 35
Drive power, kW	5.5
Supply voltage, V/Hz	400/50

Figure 1: Industrial shredder Erdwich M600/1-400



a) b)

Figure 2: Current sensors of the experimental facility (a) and an example of the time dependency curve of the power consumed (b)

Methods for measuring and estimating experimental data

The power consumption data were recorded by the current sensors (Fig. 2). After grinding, the mean particle size of the handled sample was determined employing laboratory separator with 3 samples of experimental material weighing 0.1 kg. For the exact determination of moisture content, 3 samples weights of ground experimental material were selected as well, and moisture content was then determined by the weighting method.

Operation *A* performed during material grinding was calculated from the graphs of current consumption at a known line voltage (380 V) in MS-Excel 2013 application (Fig. 2) by the formula:

$$A = U \cdot \int_0^T I(t)dt \qquad 11)$$

Integral in expression (11) was calculated automatically using the trapezium method in MS-Excell 2013. Estimating the specific energy consumption implies calculations by formula (11) and the sample weights.

The heating value of dry organic matter contained in Q_{DRY} spruce barking waste relative to the energy consumption for its grinding and considering the moisture content and grinding degree was estimated by the formula:

$$Q_{DRY} = \frac{100 - W}{100} \cdot Q_{DB} \qquad 12)$$

where Q_{DB} is the heating value for 1 kg of absolutely dry bark accepted in estimations as equal to 18.75 MJ/kg.

RESULTS

Experimental results on grinding of spruce barking waste (average values) are presented in Table 3.

Repeatability of the experiments was estimated using *T*-statistics, *T* = 1.1282, which is less than the critical value *F* = 1.9391.

Table 3: Experimental results on grinding the spruce barking waste

Nr. Of Experiment	*W*, [%]	*i*	*Q*, [MJ/kg]	S^2	*n*
1	9.82	13.97	1.868	0.2290	11
2	40.17	13.83	1.013	0.2773	15
3	70.13	13.99	0.909	0.3728	23
4	9.98	10.13	1.659	0.2651	12
5	40.74	9.91	0.895	0.3077	14
6	71.07	9.79	0,833	0.1963	21
7	10.10	5.89	1.135	0.1052	11
8	39.60	6.07	0.768	0.1292	15
9	70.55	5.97	0.700	0.1765	23

During processing the experimental data results it has been established that the mathematical model linking the relative moisture content *W* [%] of the barking waste and the degree of its grinding i with the specific energy consumption of the grinding Q_{GRIN} [MJ/kg] can be expressed by the formula, which repeats the structure of the Kirpichev-Kik's grinding law:

$$Q_{GRIN} = a_0 W^{a_1} \ln i \qquad 13)$$

where a_0 and a_1 are coefficients, namely a_0 = 1.43 MJ/kg and a_1 = -0.33.

The determination coefficient of the mathematical model (13) amounts to R^2 = 0.9696, which allows stating the satisfactory approximation accuracy.

Estimation indicators required to assess the applicability of the mathematical model are presented in Table 4.

From Table 4 follows that the model is coincident with the experimental data. The calculated Fisher criterion value F_{CALC} = 0.2523 is smaller than the critical *F*-distribution value at the significance level of 0.05 F_{CRIT} = 2.5140.

Table 4: Assessing the applicability of the mathematical model for spruce barking waste grinding

Indicator	Value
S^2_S	0.2288
S^2_{COIN}	0.0577
F_{CALC}	0.2523
F_{CRIT}	2.5140

The dependence of the specific energy consumption of the spruce waste grinding on the relative moisture content and the grinding degree by formula (13) is shown in Fig. 3.

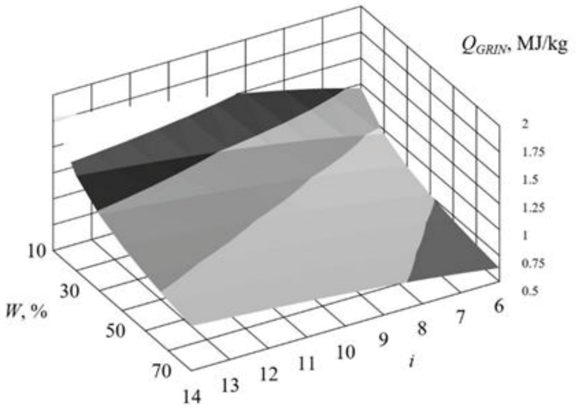


Figure 3: Dependence of the specific grinding energy consumption Q_{GRIN} of the spruce bark waste on the relative moisture content $_W$ and grinding degree i

Fig. 3 demonstrates that with decreasing moisture content of the bark, the specific energy consumption of the grinding increases at different grinding degrees. However, the ground material contains not only the organic matter of the bark but water as well. In terms of energy-related properties of the product, the value of the mass of the ground bark at different moisture content is not the same. This requires estimating the energy heating value of the ground bark Q_{dry}. Considering the obtained mathematical model (13) and the formula (12), follows the ratio:

$$\frac{Q_{GRIN}}{Q_{DRY}} = a_0 W^{a1} \ln i \Big/ \frac{100 - W}{100} Q_{DB} \quad 14)$$

Estimation results are shown in Fig. 4.

The correlation between the heating value of the dry matter of in the product of bark grinding (energy cost) and the energy consumed for its obtaining, i.e., for bark grinding (energy production cost), is nonlinear. At that, and the dependence has a bending point equal to the minimum. Considering the coefficient value a_1 by the formula (14), the optimal moisture content of spruce barking waste to be ground will be W_{OPT} = 25%.

Thus, at optimum moisture content follows the equation, which describe the specific energy consumption [MJ/kg] required for grinding spruce barking waste:

$$Q_{GRIN} = 0.5 \ln i \quad 15)$$

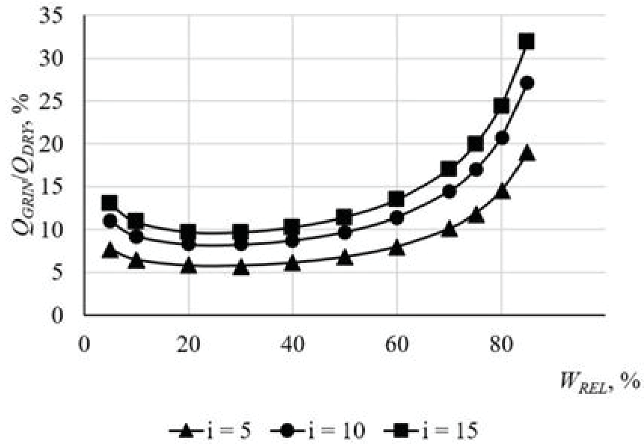


Figure 4: The heating value of dry matter contained in spruce barking waste versus energy consumption at grinding relative to the moisture content and grinding degree

Calculations show that grinding the spruce barking waste at optimum moisture content by 5–15 times requires energy comprising 5–10% of the heating value.

Noteworthy is that the proportionality factor in the law of grinding (13) is functionally related to the ultimate strength limit of the bark when cutting across the fibers in the tangential direction. A sufficient description of this phenomenon is available in the scientific literature. Due to limited knowledge on the strength properties of wood bark, further research into the correlation between the bark grinding process and its strength properties is believed as highly relevant at this stage.

The results of the experiments on grinding the pine barking waste (average values) are presented in Table 5.

Table 5: Results of experiments on grinding pine barking waste

Nr. Of Experiment	*W*, %	*i*	*Q*, MJ/kg	S^2	*n*
1	10.12	14.13	2.693	0.3537	9
2	40.71	14.19	1.441	0.2863	16
3	69.73	14.12	1.244	0.2749	24
4	9.97	9.71	2.348	0.3336	12
5	40.88	10.03	1.277	0.6075	13
6	68.98	9.93	1.128	0.3176	24
7	9.99	6.01	1.617	0.1259	8
8	39.56	5.95	1.059	0.1142	11
9	68.79	5.91	0.945	0.1396	25

As in experiments on spruce waste grinding, the statistical value *T* = 1.7983 is less than the critical value of *F*-distribution (1.9393). Thus, the experiments can be considered as reproducible.

Similarly to the spruce waste grinding, the mathematical model linking the relative moisture value *W* [%] of barking waste and the degree *i*, to which the material is to be ground, with the specific energy consumption of grinding Q_{GRIN} [MJ/kg] is expressed by the formula, which repeats the structure of the Kirpichev-Kik's grinding law:

$$Q_{GRIN} = 2.24W^{-0.36}\, ln\, i \qquad 16)$$

Determination coefficient of the mathematical model (16) is R^2 = 0.9736.

Estimation indicators required to assess the applicability of the mathematical model are presented in Table 6.

Table 6: Assessing the applicability of the mathematical model for pine waste grinding

Indicator	Value
S^2_S	0.2837
S^2_{COIN}	0.1095
F_{CALC}	0.3860
F_{CRIT}	2.5140

Data in Table 6 allow concluding that the model is coincident with the experimental data. The calculated Fisher criterion value F_{CALC} = 0.3860 is smaller than the critical *F*-distribution value at the significance level of 0.05 F_{CRIT} = 2.5140.

The dependence of the specific energy consumption of the pine waste grinding on the relative moisture content and grinding degree by the formula (16) is shown in Fig. 5.

Similar to spruce waste grinding, it is required to set the optimal moisture content of pine waste to be ground. Considering the value of the coefficient a_1 from the formula (16), the minimum ratio (14) and the optimum moisture content of the pine waste to be ground is W_{OPT}= 27%.

At optimum moisture content follows the equation, which describe the specific energy consumption [MJ/kg] required for grinding pine barking waste:

$$Q_{OPT} = 0.6785\, ln\, i \qquad 17)$$

Thus, grinding the pine barking waste at optimum moisture content by 5–15 times requires energy comprising 7–14% of the heating value.

DISCUSSION

From the above results regarding the applicability of the grinding energy model by Kirpichev-Kik follows that optimal conditions for minimizing energy consumption by the relation of the dry matter heating value to the energy consumed on its grinding are 25% moisture content for the spruce bark 27% for the pine. Research performed by Temmerman [31] reported that at grinding beech, oak, pine, and spruce, the specific energy consumption depends mainly on the moisture content of the material, the difference in particle size between the feedstock and the product, and the type of wood. It has been shown that the change in specific energy consumption in relation to the particle size is subject to the Rittinger's grinding laws. The

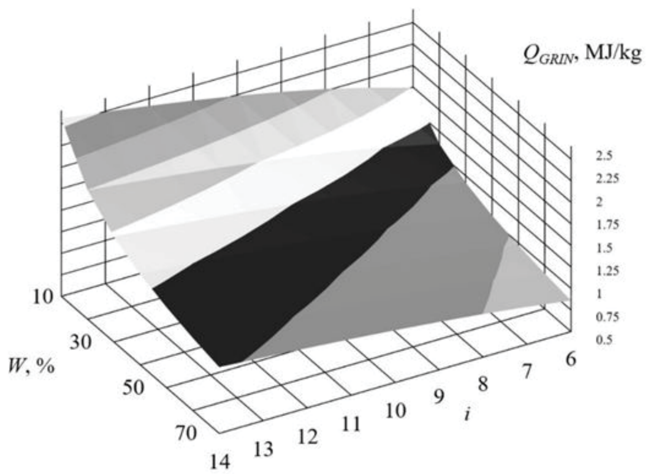


Figure 5: Dependence of the specific energy consumption of pine barking waste grinding on the relative moisture content and grinding degree

value of the calculated grinding parameter is proportional to the amount of energy consumed for grinding and the moisture content of the material. Similar results were obtained when studying the impact of moisture content and starting particle size on the specific energy consumption for the grinding of Douglas fir [32]. The paper shows that the most suitable model for describing the correlation between specific energy consumption and changes in particle size changes is Rittinger's model. The authors also noted that effective biomass micrometric grinding with lower energy consumption requires a multistage approach. These results coincide with that presented in this study and point out their novelty and originality. Besides, the variability in energy models demonstrates the importance of considering not only the species but also the type of wood, which differs in composition and physical properties. Therefore, handling a certain type of wood residue may involve particular process requirements.

A slightly different approach was applied in the study by [33]. The comparative analysis for the grinding of silver-grass, millet, willow, and reed waste showed that the specific energy consumption increases by almost 2 times with a reduction in particle size during grinding and an increase in biomass moisture content (15%). Besides, the authors reported the specific energy consumption of biomass grinding to be directly proportional to the grinding coefficient. Applying the linear regression method is quite effective in describing the correlation between the specific energy of grinding and the grinding factor for different sizes of Douglas fir particles [34]. The authors of the article also noted that an increase in moisture content from 11 to 17% intensifies the energy consumption for grinding. A study of the impact of sieve size on energy consumption at grinding poplar wood waste [35] showed an inverse relationship. Moreover, the use of a larger sieve size (4 mm) results in a high sugar yield for hydrolysis, which is an important aspect for handling this type of raw material. Among the listed examples of other methods, noteworthy is the importance of considering not only the type or species of forest feedstock but also the requirements for industrial application. Acquiring new knowledge about various factors that affect the energy efficiency of feedstock production contributes significantly to the development of new application areas and encourages further research on its implementation in industrial utilization.

CONCLUSIONS

Thus, the obtained results of this study allow drawing the following conclusions. Evaluation of energy consumption required for grinding the spruce and pine barking waste showed that the specific energy consumption correlates with the relative moisture content and the grinding degree by nonlinear dependence, which repeats the structure of the Kirpichev-Kik's grinding law in both cases. Analyzing this dependence, it has been established that the specific energy consumption at spruce and pine grinding waste with optimum moisture content is proportional to the natural logarithm of the grinding degree. Wood waste grinding by 5–15 times at optimum moisture requires energy consumption equal to 5–10% and 7–14% of the heating value for spruce and pine, respectively. Thus, these conclusions allow stating that the optimum conditions for minimizing energy consumption by the correlation between the heating value of dry matter to the energy spent on its grinding for spruce bark are 25% moisture content for spruce and 27% for pine. Due to the limited information on the strength properties of wood bark, no studies have been performed on the relationship between bark strength and the proportionality factor in the grinding law, but still are of great interest and relevance for industrial application. Therefore, more extensive investigation of the mentioned relationship is subject to further research.

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