POTENTIAL AND PERSPECTIVES OF ORCHARD LIGNOCELLULOSIC BIOMASS AS A SOURCE OF RENEWABLE ENERGY IN THE REPUBLIC OF MOLDOVA
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POTENȚIALUL ȘI PERSPECTIVELE BIOMASEI LIGNOCELULOZICE POMICOLE CA SURSĂ DE ENERGIE REGENERABILĂ ÎN REPUBLICA MOLDOVA

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Keywords: *fruit tree biomass; pruning residues; solid biofuels; sustainable energy potential; calorific value; ash content; Republic of Moldova*

ABSTRACT
The utilization of residues resulting from orchard pruning represents a promising solution for diversifying renewable energy sources and reducing dependence on fossil fuels in the Republic of Moldova. This study assesses the availability, quality, and sustainable energy potential of lignocellulosic biomass from seed and stone fruit species cultivated in different economic regions, based on samples collected from orchards larger than 10 ha. The analyses included biomass yield, moisture content, net calorific value, and ash content. Results indicate high sustainable energy potential values for peach (33.50 ± 6.54) GJ/ha*, apple (29.67 ± 5.17)* GJ/ha*, and pear (29.45 ± 2.51)* GJ/ha*. The Northern region, dominated by apple orchards, accounts for the largest share of the national potential (467.73 – 665.13)* TJ/yr*, while the Central region stands out for plum and pear, and the Southern region for peach and apricot. Cherry residues show the lowest sustainable energy potential 17.61* GJ/ha *and the highest predictive uncertainty Up = 8.99* GJ/ha*. At the national level, the total sustainable energy potential is estimated between 806.50 and 1161.46* TJ/yr*, and the use of this biomass could substitute significant amounts of coal, natural gas, and fuel oil, reducing greenhouse gas emissions and supporting the transition to a sustainable energy system.*

REZUMAT
Valorificarea reziduurilor provenite din tăierile de întreținere ale plantațiilor pomicole constituie o soluție promițătoare pentru diversificarea surselor de energie regenerabilă și reducerea dependenței de combustibili fosili în Republica Moldova. Studiul evaluează disponibilitatea, calitatea și potențialul energetic sustenabil) al biomasei lignocelulozice de la specii sămânțoase și sâmburoase cultivate în diferite zone economice, pe baza probelor colectate din livezi de peste 10 ha. Analizele au vizat producția de biomasă, umiditatea, valoarea calorifică netă și conținutul de cenușă. Rezultatele indică valori ridicate ale potențialul energetic sustenabil pentru piersic (33.50 ± 6.54) GJ/ha*, măr (29.67 ± 5.17)* GJ/ha *și păr (29.45 ± 2.51)* GJ/ha*. Nordul țării, dominat de livezi de măr, deține cea mai mare pondere a potențialului național (467.73 – 665.13)* TJ/yr*, Centrul se remarcă prin prun și păr, iar Sudul prin piersic și cais. Cireșul prezintă cel mai redus potențialul energetic sustenabil 17.61* GJ/ha *și cea mai mare incertitudine Up = 8.99* GJ/ha*. La nivel național, potențialul energetic sustenabil total este estimat între 806.50 și 1161.46* TJ/yr*, iar utilizarea biomasei ar putea substitui combustibili fosili, reducând emisiile de gaze cu efect de seră și susținând tranziția spre un sistem energetic durabil.*

1. INTRODUCTION
Renewable energy plays a crucial role in the current context of the Republic of Moldova, a country that imports approximately 70% of its energy resources *(NBSRM., 2024, pp. 338 - 346)*. In this context, the identification and utilization of local renewable energy sources represent a strategic priority for ensuring energy security and sup-porting the transition towards a sustainable energy system. One of the most promising renewable sources in the Republic of Moldova is biomass, which can make a significant contribution to this transition.

To stimulate the use of biomass for energy purposes, the Republic of Moldova has adopted several policies and strategies aimed at promoting renewable energy sources. Among these are the Energy Strategy of the Republic of Moldova until 2030 *(GRM, 2013)* and the Energy Strategy of the Republic of Moldova until

2050 *(GRM, 2024*). These strategies pursue the development of a sustainable and competitive energy sector through market reforms and integration into the European Union's energy market.

The strategies target a series of objectives aimed at strengthening energy security, increasing the efficiency of energy resource use, and diversifying the energy mix, with a particular emphasis on promoting renewable energy and reducing dependence on imports, in the context of the transition towards a sustainable energy system and the commitments undertaken to combat climate change.

In parallel, the National Energy and Climate Plan 2025 – 2030 was developed by the Ministry of Energy, with support from the European Union provided through the program "Addressing the Impact of the Energy Crisis in the Republic of Moldova", implemented by UNDP Moldova *(GRM, 2025)*.

This plan sets out the priorities, objectives, and policies necessary to ensure a sustainable and affordable energy system for all consumers, while also defining the national targets in the fields of renewable energy, energy efficiency, and greenhouse gas emission reduction.

To achieve these objectives, the Government of the Republic of Moldova, in collaboration with international partners, has launched and implemented financial support programs focused on the development of biomass-fueled heating plants and the expansion of capacities for the production of densified solid biofuels, such as pellets and briquettes. Academic and research institutions in the Republic of Moldova are actively involved through research and innovation projects dedicated to the development of advanced technological solutions for the valorization of biomass resources. These efforts represent a key factor in promoting and consolidating the use of renewable energy sources derived from plant biomass, a locally abundant resource with low environmental impact.

Among plant biomass sources, those originating from the agricultural sector play a particularly important role *(Janiszewska & Ossowska, 2024)*. The use of agricultural residues as raw material for solid biofuel production contributes not only to reducing dependence on fossil energy resources and decarbonizing the energy sector, but also to supporting the transition towards sustainable production and consumption models, in line with the principles of the circular economy applied to the agri-food sector *(Ciloci & Țurcan, 2023; Silvestri et al., 2024)*.

Within this category of residues, orchard lignocellulosic biomass shows the greatest potential for use as feedstock in the production of densified solid biofuels *(Aliaño et al., 2022; Cavalaglio et al., 2024; Ciolacu et al., 2022; Marian & Banari, 2025).*

Orchard biomass comprises the totality of organic materials derived from fruit trees and shrubs, generated through orchard maintenance and exploitation activities. This includes residues from formative and maintenance pruning, annual fruiting cuts, tree thinning, the removal of dry or diseased branches, the clearing of trees at the end of their productive cycle, as well as soil cleaning and care operations.

From a compositional perspective, orchard biomass consists of wood, branches and twigs, leaves, bark, as well as other wastes resulting from the industrial processing of fruits *(Cavalaglio et al., 2024; Winzer et al., 2017)*. These residues are characterized by promising energy properties, which make them suitable for direct use in the production of pellets and briquettes, offering advantageous energy characteristics *(Alakangas, 2016; Marian et al., 2022).*

The present study aims to provide a detailed qualitative and quantitative analysis of plant biomass resources derived from fruit-growing in the Republic of Moldova, with a focus on their use for the production of densified solid biofuels. In this context, it is important to note that both the quantity and the quality of orchard biomass vary significantly depending on factors such as climatic conditions, harvesting time and method, geographical characteristics, moisture and mineral content, or conditioning methods *(Ibitoye et al., 2023)*. This variability is frequently highlighted in the specialized literature, underlining the need for detailed local analyses.

For example, researchers from the Czech Republic and Poland established that apple orchards planted at a density of 3.5 × 1.2 m generate approximately 6762 kg/ha of woody biomass (*Burg et al., 2017)*. Although the amount of biomass per tree is relatively low (2.84 kg/tree), the high overall value is explained by the high planting density per unit area. This highlights the essential role played by orchard density in maximizing the total biomass yield at the field level.

Furthermore, Polish researchers, based on an analysis of data reported by five different authors, found that the biomass potential harvested from one hectare of apple orchard varies significantly depending on tree age, year of cultivation, variety, and planting density, with values ranging between 1000 and 9800 kg/ha *(Dyjakon et al., 2016, tab.1)*.

According to the same authors, the theoretical energy potential of biomass derived from apple tree pruning in Poland is estimated at 12.52 PJ/yr, calculated for a total orchard area of 193.44 $\cdot 10^3$ ha (*Dyjakon et al., 2016, tab.2)*.

A similar trend is observed in other fruit tree species. For instance, based on the analysis of biomass quantities obtained from pear pruning, Živković reported a significant variation among cultivars planted at the same density (500 trees/ha), with values ranging from 9.36 kg/tree (equivalent to 4680 kg/ha) for the 'Red-haven' cultivar to 4.85 kg/tree (2425 kg/ha) for the 'Summerset' cultivar *(Živković et al., 2013)*.

Significant amounts of woody biomass can also be recovered from orchard removal. In this regard, researchers in Germany estimated an annual biomass production potential of 10.6 Mg/ha *(Winzer et al., 2017)*. To determine the total area of cleared orchards, the authors applied a clearance coefficient of 0.05. It is noteworthy that some researchers employ conversion coefficients to estimate the biomass potential obtained from fruit tree maintenance works in relation to the total fruit yield. For example, *(Pence et al., 2024)* proposed such coefficients for several fruit species: apple – 0.19; pear – 0.22; apricot – 0.19; cherry – 0.19; peach – 0.50.

Gudîma also applied a unit conversion factor related to the mass of the main production *(Gudîma, 2017)*, using a coefficient of 0.28 for pome fruit trees and 0.26 for stone fruit trees. These coefficients were adjusted according to the availability of biomass for energy purposes and the inevitable losses occurring during its collection, transport, and processing. The author applied an availability coefficient of 0.8 and a loss coefficient of 0.9. Thus, the effective conversion coefficients, calculated for a biomass moisture content of 10%, were 0.202 and 0.187, respectively.

A similar methodology was adopted by Pavlenco, who provided detailed unit conversion factors for each species. For the pome group, the proposed values are: apple – 0.28 ± 0.02, pear – 0.20 ± 0.03, and quince – 0.14 ± 0.04; for the stone fruit group: sour cherry – 0.16 ± 0.02, sweet cherry – 0.24 ± 0.03, apricot – 0.26 ± 0.05, peach and plum – 0.26 ± 0.04 *(Pavlenco et al., 2018)*. Similarly, the authors applied an availability coefficient of 0.8 and a loss coefficient of 0.9.

The analysis of the data presented by the aforementioned authors highlights that the average production of woody mass resulting from fruit tree maintenance works varies significantly, being influenced by a range of objective and subjective factors. On average, these variations may reach values between 1.5 and 10 Mg/ha. In this context, knowledge of the average amount of biomass available, suitable for use as raw material in different regions of the country, is essential for substantiating decisions regarding the organization of solid biofuel production in specific localities.

At the same time, modern standards for solid biofuel quality (e.g., EN ISO 17225 series) require detailed knowledge of the physico-chemical properties of biomass, in order to ensure compliance with the accepted quality classes on both domestic and international markets. These requirements particularly refer to the calorific value and ash content, parameters strongly influenced by the origin of the biomass used as raw material for producing densified solid biofuels *(Toscano et al., 2023)*.

There are few studies dedicated to an integrated assessment of the sustainable energy potential (SEP), understood as the annual amount of energy obtainable from orchard biomass under real conditions of harvesting, processing, and utilization, in the Republic of Moldova, and the available data remain fragmented and uncorrelated with the geographical distribution of orchards as well as with the specific features of the country's economic development zones.

For instance, data published by Marian and Banari *(Marian & Banari, 2025)* refer to the energy potential of nut crop residues, expressed in GJ/ha, for three species—walnut, hazelnut, and almond—differentiated into two categories of biomass: woody biomass and endocarp. A more detailed evaluation of the energy potential of lignocellulosic biomass is presented for residues from vineyard plantations *(Marian et al., 2024)*.

However, there is a lack of well-substantiated data based on detailed studies concerning the energy potential of biomass derived from fruit tree plantations in the Republic of Moldova, as well as comparative analyses between different fruit species in terms of biomass productivity, calorific value, ash content, and estimation uncertainty.

In this context, the present study addresses an urgent need to substantiate, using experimental data and validated methodologies, the SEP of fruit-tree lignocellulosic biomass, differentiated by species and by regions. The results obtained can provide a scientific basis for the development of regional strategies for the collection, processing, and integration of orchard biomass into the national energy mix, thereby reducing dependence on fossil fuels and supporting decarbonization and circular economy objectives.

2. MATERIALS AND METHODS

2.1. Study area and sampling design

The research was conducted in the main fruit-growing regions of the Republic of Moldova: North, Center (including the municipality of Chișinău), and South (including the Autonomous Territorial Unit of Gagauzia). Orchards belonging to agricultural enterprises and family farms with areas larger than 10 ha were selected, as they are considered representative of the orchard structure in each region. The investigated species included fruit trees from the pome group (apple, pear, quince) and the stone fruit group (plum, cherry, sour cherry, apricot, peach), thus covering the typological diversity of orchards across the country.

The study focused on biomass generated from the annual maintenance and rejuvenation pruning of fruit trees. Samples were collected from representative plots, and the data were extrapolated to larger orchard areas. Tree sampling was carried out using the quarter method.

2.2. Biomass collection and measurement

Annual residues resulting from maintenance pruning were collected during the standard pruning period (February–March). For each orchard, tree density (number of trees/ha) and the average fresh biomass yield per tree were recorded. Moisture content at the time of collection was determined according to ISO 18134-2 by oven-drying the samples at 105 ± 2 °C until constant weight, with weighing differences ≤ 1 mg.

Based on these data, biomass yield per hectare and dry matter yield at the standard 10% moisture content were calculated.

2.3. Biomass characterization

Subsamples of each biomass type were analyzed to determine the net calorific value (NCV) at 10% moisture content, based on the gross calorific value (GCV) measured with an IKA C6000 isoperibolic bomb calorimeter, under constant volume conditions, according to ISO 18125:2017. The ash content (A, % dry basis) was determined according to ISO 18122:2015.

For comparative analysis among species, weighted averages were calculated according to the share of each species in the total orchard area.

2.4. Estimation of the sustainable energy potential

The SEP was calculated by correcting the theoretical energy potential (TEP) with factors reflecting technical losses, logistical constraints, and ecological limitations, according to the following equation:

$$SEP = TEP \cdot A_i \cdot (1-k_{il}) \tag{1}$$

where:

TEP represents the theoretical energy potential, calculated as the product between the biomass yield per hectare (dry basis at 10% moisture content) and the net calorific value of the biomass (determined at 10% moisture and constant pressure); A_i – is the availability coefficient of biomass for energy use; k_{il} - the implementation loss coefficient.

The total SEP values [TJ/yr] at regional and national levels were obtained by multiplying SEP values per hectare by the cultivated areas of each species, according to official data from the National Bureau of Statistics of the Republic of Moldova. Minimum and maximum SEP estimates were derived from the variability of field-measured biomass yields.

3. RESULTS

3.1. Assessment of the availability of orchard biomass for densified solid biofuel production

Table 1 presents the estimated amounts of biomass obtained from pome fruit plantations. The study included apple, pear, and quince varieties, which are widely cultivated in the Republic of Moldova. Samples were collected from traditional, semi-intensive, and intensive orchards, following the methodology described in Section 2.

The data show that the analyzed apple varieties vary considerably in terms of biomass generated per tree, with values ranging from 2.67 kg/tree (Fuji) to 6.23 kg/tree (Florina). A similar pattern was observed for pears, where values range from 1.21 kg/tree (Celina) to 5.27 kg/tree (Conference). These differences can be explained primarily by plantation density as well as orchard management and regeneration practices. Generally, trees from intensive orchards generate smaller amounts of biomass per tree, while more vigorous varieties grown at moderate densities (e.g., Florina, Golden, Reinette Simirenko) appear to be the most energy-efficient.

Table 1

Average biomass yield, calorific value, and ash content from pruning of pome fruit species

Species	Type	n_{th}*	m_t	M_h	m_h	$m_{M=10\%}$	$q_{Pnet\ M=10\%}$	A	$m_{sp\ M-10\%}$	$q_{sp\ Pnet\ M=10\%}$	A_{sp}
Apple	Idared	1250	2.84	43.17	3550.00	2241.63	15.58	3.93	2639 ± 456	15.61 ± 0.33	3.03±0.61
	Idared	833	5.48	42.15	4564.84	2934.18	15.63	3.82			
	Reinette Simirenko	1250	3.06	43.59	3825.00	2397.43	15.76	4.11			
	Reinette Simirenko	833	6.03	42.73	5022.99	3196.30	15.76	4.15			
	Florina	833	6.23	43.97	5189.59	3230.81	15.67	2.21			
	Golden Delicious	833	5.68	42.42	4731.44	3027.07	15.97	2.82			
	Gala	1250	3.12	43.21	3900.00	2460.90	14.93	2.96			
	Fuji	1250	2.67	43.11	3337.50	2109.67	15.58	1.96			
	Jonathan	570	5.97	43.11	3402.90	2151.01	15.63	3.16			
Pear	Conference	833	5.27	45.58	4389.91	2654.43	15.89	3.55	2620 ± 212	15.58 ± 0.41	3.35±0.31
	Noyabrskaya (Xenia)	1428	3.33	47.77	4755.24	2759.62	15.63	3.24			
	Celina	2800	1.24	42.24	3472.00	2228.25	15.57	3.27			
	Doyenné d'Hiver	833	5.21	47.28	4339.93	2542.23	16.00	3.35			
	Passe Crassane	1250	3.75	47.46	4687.50	2736.46	15.57	2.89			
	Clapp's Favourite	1428	3.10	43.12	4426.80	2797.74	14.82	3.81			
Quince	Auriu	800	3.21	43.21	2568.00	1620.41	15.39	3.49	1338±215	15.37±0.37	3.46±0.06
	Yantarnaya Moldavii	834	2.14	42.98	1784.76	1130.74	15.37	3.36			
	Zarea	800	3.04	44.21	2432.00	1507.57	15.74	3.47			
	Cometa	800	2.32	43.11	1856.00	1173.20	15.61	3.53			
	Olga	800	2.45	42.14	1960.00	1260.06	14.76	3.46			

*n_{th} – *Number of trees per hectare* [trees/ha]; m_t – *Average biomass yield per tree* [kg/tree]; M_h – *Moisture content of the biomass at harvest, percent wet basis* [$\%_W$]; m_h – *Average biomass yield per hectare at harvest* [kg/ha]; $m_{M=10\%}$ – *Average biomass yield per hectare calculated to 10% moisture* [kg/ha]; $q_{PnetM=10\%}$ - *Net calorific value at constant pressure, calculated for 10% moisture content* [MJ/kg]; *A - Ash content on a dry basis* [%];$m_{spM=10\%}$ – *Average biomass yield per species calculated to 10% moisture* [kg/ha]; $q_{spPnetM=10\%}$ - *Species average of the net calorific value at constant pressure, calculated for 10% moisture content* [MJ/kg];A_{sp} – *Average ash content on a dry basis* [%]

At the area level, pear orchards produce on average similar amounts of biomass as apple orchards. Thus, the average usable biomass yield, adjusted to a 10% moisture content, is 2620 ± 212 kg/ha for pear and 2639 ± 456 kg/ha for apple. Quince, by contrast, generates a significantly smaller amount of biomass compared with the other two species. The mean quantity per tree is only 2.63 kg, while at the hectare level the average yield is 1339 ± 215 kg/ha, estimated at 10% moisture content. The moisture content of the biomass, determined immediately after collection, did not vary significantly among the analyzed species, averaging around 44%. This highlights the need for pre-conditioning of the biomass through drying before its energetic utilization.

Among the analyzed species, apple and pear provide the highest potential for the production of densified solid biomass (briquettes, pellets), with comparable average yields of around 2,600–2,700 kg/ha (at 10% moisture content). Therefore, it is recommended to correlate biomass productivity data with economic and ecological factors in order to enable an optimal selection of cultivars for energy purposes, also taking into account the specific calorific value of biomass from different fruit tree species.

It was found that the calorific value of biomass obtained from the 9 samples of different apple cultivars, 6 of pear, and 5 of quince did not differ significantly between the fruit tree species.

Based on the average values determined for each fruit tree cultivar, the mean value for the entire group of pome fruit trees was calculated. The analysis of the results indicates that biomass at 10% moisture content presents an average net calorific value of 15.61 ± 0.33 MJ/kg for apple, 15.58 ± 0.41 MJ/kg for pear, and 15.37 ± 0.37 MJ/kg for quince.

These values highlight only a minor variation between the analyzed species, the difference being about 0.24 MJ/kg, while the overall mean for the pome group is 15.52 MJ/kg.

With reference to the requirements specified in the SM EN ISO 17225 standards, it can be stated that the woody residues from fruit trees of the pome group are suitable for briquette production, fitting into quality classes A1, A2, and B in terms of calorific value. However, the use of these residues is restricted by the relatively high ash content, which exceeds the 3% threshold. In this context, the analyzed biomass is more suitable for the production of B-class wood briquettes, meeting the criteria related to calorific value and ash content.

The physico-mechanical parameters of the final product are essentially influenced by the technology applied in the biofuel production process. In addition, this raw material has high potential for the manufacture of pellets and briquettes from non-woody biomass, including in mixtures (blends), thus expanding the possibilities of energy valorization.

Table 2 presents the characteristics of biomass from stone fruit trees, collected in March. Peach generated the highest amount of biomass ($m_{spM=10\%}$ = 2909 ± 564 kg/ha), followed by plum ($m_{spM=10\%}$ = 1980 ± 246 kg/ha) and sour cherry ($m_{spM=10\%}$ = 1854 ± 246 kg/ha), while apricot recorded the lowest value ($m_{spM=10\%}$ = 1504 ± 130 kg/ha).

Table 2

Average biomass yield, calorific value, and ash content from pruning of various stone fruit spe-cies

Species	Type	n_{th}*	m_t	M_h	m_h	$m_{M=10\%}$	$q_{Pnet\ M=10\%}$	A	$m_{sp\ M-10\%}$	$q_{sp\ Pnet\ M=10\%}$	A_{sp}
Plum	Stanley	444	7.81	47.01	3467.64	2041.67	16.21	1,7	1981 ± 246	16.21 ± 0.52	2,06 ± 0.20
	Valor	889	4.21	48.12	3742.69	2157.45	15.61	2,19			
	President	800	3.28	47.17	2624.00	1540.29	16.47	2,24			
	Ana Spath	1000	3.77	47.97	3770.00	2179.48	16.95	2,16			
	Piteştean	800	3.82	45.44	3056.00	1852.62	15.63	2,06			
	Renclod Althan	667	5.32	46.38	3548.44	2114.08	16.41	1,99			
Cherry	Kordia	333	5.91	45.58	1968.03	1190.00	15.75	2,64	1566 ± 798	15.78 ± 0.51	2.65 ± 0.31
	Regina	833	3.94	47.77	3282.02	1904.67	15.85	3,04			
	Grace Star	330	6.02	46.21	1986.60	1187.32	15.61	2,29			
	Ferrovia	330	4.02	44.79	1326.60	813.80	15.08	3,02			
	Sweet Heart	830	6.23	47.32	5170.90	3026.70	16.65	2,41			
	Bigarreau Burlat	330	6.23	44.16	2055.90	1275.57	15.77	2,52			
Sour Cherry	Oblačinska	404	7.03	48.01	2840.12	1640.64	15.56	2,61	1854 ± 289	15.58 ± 0.45	2.81 ± 0.20
	Morella	500	6.53	43.91	3265.00	2034.82	16.16	2,58			
	Crișana	833	4.23	46.18	3523.59	2107.11	15.74	2,87			
	Nordh Star	833	4.01	45.23	3340.33	2032.78	15.52	3,03			
	Mărioara	404	6.43	49.62	2597.72	1454.15	14.91	2,96			
Apricot	Kyoto	500	5.12	41.89	2560.00	1652.91	15.9	3,91	1504 ± 130	15.87 ± 0.40	2.70 ± 0.68
	Krasnoshchyokiy	280	7.98	47.77	2234.40	1296.70	15.57	2,45			
	Platimoon	500	5.37	48.28	2685.00	1542.98	16.53	2,28			
	Orange Rubis	330	7.21	42.24	2379.30	1526.98	15.58	2,38			
	Big Red	502	5.13	47.53	2575.26	1501.38	15.79	2,49			
Peach	Cardinal	500	7.74	44.55	3870.00	2384.35	15.97	2,44	2909 ± 564	16.00 ± 0.36	1.90 ± 0.47
	Maycrest	1250	4.94	47.21	6175.00	3621.98	16.6	1,34			
	Moldova	500	7.42	42.24	3710.00	2381.00	15.76	1,57			
	Redhaven	1200	4.04	47.98	4848.00	2802.14	15.97	1,85			
	Stark Sunglo	1250	4.62	47.74	5775.00	3353.35	15.69	2,32			

Moisture content at harvest varied insignificantly among species, while the net calorific values (at 10% moisture) were similar: highest for plum (16.21 ± 0.52 MJ/kg) and lowest for sour cherry (15.58 ± 0.39 MJ/kg), with a difference of 0.63 MJ/kg. Ash content ranged from 1.90 ± 0.41% (peach) to 2.81 ± 0.18% (sour cherry).

The results confirm the literature *(Burg et al., 2017; Matłok et al., 2024)*, according to which stone fruit biomass, although having lower density, exhibits a calorific value comparable to other species, a fact correlated with lignin content: 23.31 ± 2.21% for peach and 24.26 ± 1.25% for plum *(Burg et al., 2017; Matłok et al., 2024)*.

3.2. Energy potential of available orchard biomass for solid biofuel production in different regions of the Republic of Moldova

The Republic of Moldova has 85.6 thousand hectares of orchards (pome and stone fruits), including 38.4 thousand hectares of plantations larger than 10 ha *(NBSRM, 2025)* with specific concentrations across Economic Development Zones:

- Northern Zone – districts such as Edineț, Briceni, Dondușeni, Soroca, Florești (mainly apple, plum, and cherry);
- Central Zone – districts such as Orhei, Hâncești, Strășeni, Călărași, Ialoveni (apple, plum, apricot, cherry);
- Southern Zone – districts such as Cimișlia, Cahul, Taraclia, Ștefan Vodă (peach, apricot, sour cherry).

The species structure directly influences the quantity and quality of biomass obtained from orchard maintenance. Table 3 presents the results of estimating the energy potential of biomass generated from different fruit tree species, distributed by the Economic Development Zones of the Republic of Moldova. The calculations were based on the experimental data presented in subsection 3.1.

Table 3

Energy potential of fruit tree pruning residues

Parameters		Pome fruit			Stone fruit				
		Apple	Pear	Quince	Plum	Sweet cherry	Sour cherry	Apricot	Peach
$m_{b\ M=10\%}$* [kg/ha]	$\bar{m}$	2639	2620	1338	1981	1566	1854	1504	2909
	σ	456	212	215	246	798	289	130	564
$q_{Pnet\ M=10\%}$ [MJ/kg]	$\bar{m}$	15.615	15.579	15.372	16.211	15.784	15.578	15.873	15.995
	σ	0.329	0.414	0.374	0.519	0.506	0.449	0.396	0.360
A_i		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
k_{il}		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TEP [GJ/ha]		41.21	40.91	20.90	30.93	24.46	28.95	23.49	46.53
Up [GJ/ha]		7.19	3.49	3.40	3.99	12.49	4.59	2.12	9.08
PED [GJ/ha]		32.97	32.73	16.72	24.75	19.57	23.16	18.79	37.22
Up [GJ/ha]		5.75	2.79	2.72	3.19	9.99	3.67	1.69	7.27
SEP [GJ/ha]		29.67	29.45	15.05	22.27	17.61	20.84	16.91	33.50
Up [GJ/ha]		5.17	2.51	2.45	2.87	8.99	3.30	1.52	6.54

**$m_{bM=10\%}$ - average biomass yield converted to a moisture content of 10%; $q_{Pnet\ M\text{-}10\%}$ - net calorific value of biomass at 10% moisture content, calculated at constant pressure; TEP - theoretical energy potential; PED - available energy potential; SEP - sustainable energy potential; A_i – availability coefficient, equal to 0.8; k_{il} - implementation loss coefficient, equal to 0.1; Up – predictive uncertainty; m – mean value, σ – standard deviation.*

It was found that residues from peach, apple, and pear pruning exhibit the highest exploitable energy potential and are the most suitable species for energy valorization among the analyzed orchard residues. The exploitable energy — considering the efficiency of technological processes and the sustainability of biomass harvesting — is estimated at 33.50 ± 6.54 GJ/ha for peach, 29.67 ± 5.17 GJ/ha for apple, and 29.45 ± 2.51 GJ/ha for pear.

It is noteworthy that although cherry residues show a lower SESP index, they exhibit the highest predictive uncertainty (Up = 8.99 GJ/ha), which indicates significant variability of the data, most likely due to differences between species, planting schemes, pruning methods, growth conditions, and sampling locations.

The lowest values were recorded for quince (15.05 ± 2.45 GJ/ha), apricot (16.91 ± 1.52 GJ/ha), and cherry (17.71 ± 8.99 GJ/ha), which also had lower uncertainties in estimation.

This suggests a higher probability of obtaining more constant quantities of biomass from these plantations. At the same time, these species show favorable calorific values, indicating that they should not be neglected as raw material for solid biofuel production. The correlation between uncertainty and energy potential shows that species with higher yields also exhibit greater variations in the estimates, which requires more precise assessments at the level of specific orchards and localities before initiating the production of densified solid biofuels from these pruning residues. The analysis of the SEP of biomass derived from fruit trees in the Republic of Moldova (Table 4) highlights significant differences in SEP between economic development zones (Northern Zone, Central Zone including Chișinău municipality, and Southern Zone including ATU Gagauzia), as well as among the fruit species.

Table 4

Sustainable energy potential of fruit tree biomass from orchards belonging to agricultural enterprises and household farms in the Republic of Moldova, by region

Fruit tree species	Northern Zone			Central Zone + Chișinău Municipality			Southern Zone + ATU Gagauzia			National total	
	St* [ha]	SEP [TJ/yr]		St [ha]	SEP [TJ/yr]		St [ha]	SEP [TJ/yr]		SEP [TJ/yr]	
		max	min		max	min		[ha]	max	min	[ha]
Apple	13787	480.34	337.78	3302	115.04	80.90	2002	69.75	49.05	665.13	467.73
Pear	64	2.05	1.72	269	8.60	7.25	35	1.12	0.94	11.76	9.91
Quince	7	0.12	0.09	21	0.37	0.26	28	0.49	0.35	0.98	0.71
Plum	2365	59.46	45.88	5311	133.52	103.03	2634	66.22	51.10	259.19	200.01
Chery	1370	36.44	11.81	1492	39.69	12.86	502	13.35	4.33	89.48	29.00
Sour Cherry	542	13.08	9.51	856	20.66	15.01	593	14.32	10.40	48.06	34.92
Apricot	459	8.46	7.06	966	17.80	14.87	502	9.25	7.73	35.51	29.66
Peach	70	2.80	1.89	352	14.09	9.49	860	34.43	23.19	51.33	34.56
National total										***1161.46***	***806.50***

** St - total orchard area at agricultural enterprises and household farms with agricultural land holdings of 10 hectares and above*.

The total cultivated area with apple orchards is dominant in the Northern Zone (13787 ha), generating an annual SEP estimated between 337.78 and 480.34 TJ, followed by the Central Zone (3302 ha; 80.90 – 115.04 TJ/yr) and the Southern Zone (2002 ha; 49.05 – 69.75 TJ/yr). In total, the SEP of apple orchards available at agricultural enterprises and household farms in the Republic of Moldova ranges between 467.73 and 665.13 TJ/yr at the national level. For other species, such as pear, plum, and cherry, the energy potential varies according to cultivated area and local conditions, but it is noteworthy that orchards in the Central Zone generally generate higher values compared to the other regions.

For example, in the case of plum, the SEP varies between 45.88 – 59.46 TJ/yr in the North, 103.03 – 133.52 TJ/yr in the Center, and 51.10–66.22 TJ/yr in the South, summing up to a national potential between 200.01 and 259.19 TJ/yr. Overall, the orchard biomass from all the studied species provides an energy potential estimated at approximately 806.50 to 1161.46 TJ/yr for the entire country. This renewable resource can substantially contribute to the diversification of the energy mix and to the reduction of dependency on fossil fuels. Harnessing this potential would result in significant savings of fossil resources such as coal, oil, and natural gas, currently used for thermal and electrical energy generation. In addition, the integration of orchard biomass into the national energy mix supports sustainable strategies, contributing to greenhouse gas emission reductions and environmental protection.

To maximize the positive impact, detailed regional planning is required, considering the specific features of each zone, in order to ensure sustainable harvesting and efficient utilization of orchard biomass for the production of densified solid biofuels.

CONCLUSIONS

The results obtained in this study indicate that pruning residues from peach, apple, and pear orchards exhibit the highest SEP among the analyzed species, with values of 33.50 ± 6.54 GJ/ha for peach, 29.67 ± 5.17 GJ/ha for apple, and 29.45 ± 2.51 GJ/ha for pear. These findings are consistent with research carried out in Central and Eastern Europe (*Burg et al., 2017; Dyjakon et al., 2016)*, where pome and stone fruit species have been identified as promising feedstocks for solid biofuel production.

The regional distribution of biomass potential highlights clear differences determined by orchard structure and agroclimatic conditions. The Northern Zone, dominated by apple orchards, accounts for the largest share of the national potential, while the Central Zone stands out with higher values for plum and pear, and the Southern Zone for peach and apricot.

These results emphasize the need for adopting region-specific strategies for biomass collection and utilization, in order to optimize logistics and processing capacities. Although cherry residues show a lower SEP (17.61 GJ/ha), they also recorded the highest predictive uncertainty (Up = 8.99 GJ/ha). This high variability is influenced by the biological characteristics of the species, planting schemes, and pruning practices, which necessitate additional monitoring and standardization of maintenance operations. From a practical perspective, the sustainable use of this biomass could substitute significant amounts of fossil fuels—particularly coal, natural gas, and fuel oil—currently employed for heat generation.

Depending on calorific values and available quantities, replacing fossil fuels with orchard biomass would directly contribute to reducing national greenhouse gas emissions and to fulfilling the Republic of Moldova's commitments under the European Green Deal. However, certain constraints must be considered.

The relatively high ash content (> 3% for some species) may limit direct use for premium-quality briquette and pellet production, requiring either blending with low-ash feedstocks or adapting combustion systems. Furthermore, the moisture content of biomass at harvest (~44–48%) necessitates a drying stage, which increases processing costs and affects the overall energy efficiency.

Future research directions should include:

- the development of logistic models for biomass collection adapted to the regional distribution of orchards;
- techno-economic analyses of integrated pellet and briquette production chains;
- life cycle assessments to quantify the environmental benefits resulting from large-scale substitution of fossil fuels with pruning residues from fruit orchards.

ACKNOWLEDGEMENT

This research was funded by the Government of the Republic of Moldova through the National Agency for Research and Development, within the framework of the projects addressing issues of critical interest, under the theme "Resilience of the Republic of Moldova to Crisis Situations", project no. 23.70105.7007.08, contract no. 7/08R. Additional support was provided through project no. 20.80009.5107.15 "Development and implementation of good practices for sustainable agriculture and climate resilience / GREEN/020407", which offered technical and logistical assistance. The authors would like to thank the "Management of Scientific Research" Directorate of the Technical University of Moldova for providing logistical support in carrying out this study. Special thanks are extended to SC "BASADORO AGROTEH" SRL and "Agrisolution" SRL for their free assistance with the mechanized collection and transportation of vine residues to the analysis site, as well as to all the agricultural enterprises that permitted the collection of biomass samples used in this study.

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