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COMPARATIVE EVALUATION OF ENERGY POTENTIAL AND COMPOSITION OF WALNUT, HAZELNUT, AND ALMOND RESIDUES FOR SOLID BIOFUEL PRODUCTION

Grigore Marian, ORCID: 0000-0002-9975-2522,
Alexandru Banari*, ORCID: 0000-0001-9132-610X

Technical University of Moldova, 168 Stefan cel Mare Blvd, Chisinau, Republic of Moldova

* Corresponding author: Alexandru Banari, alexandru.banari@sfc.utm.md

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Abstract. Interest in renewable energy, particularly biomass-derived energy, has significantly increased in recent decades. As one of the most readily available resources in the Republic of Moldova, biomass energy plays an essential role in the country's evolving national energy framework. This study aims to evaluate the quality of tree biomass generated by nut trees, specifically walnut, hazelnut, and almond, considering its potential use as raw material for solid biofuel production. A comprehensive qualitative and quantitative assessment was conducted, focusing on calorific value, ash content, volatile matter content, and the concentrations of C, H, S, N, and Cl—key components contributing to pollutant emissions (CO, CO₂, NO_x, SO₂, etc.). The findings highlight that nut residues meet quality standards for solid biofuels derived from non-woody biomass, showcasing their significant potential for sustainable energy production.

Keywords: Nucifera Biomass, Solid Biofuels, Walnut, Hazelnut, Almond, Energy Potential.

Rezumat. Interesul pentru energiile regenerabile, în special pentru cea obținută din biomasă a crescut în mod semnificativ în ultimele decenii. Fiind una din sursele cu disponibilitate mare în Republica Moldova energia din biomasă joacă un rol important în noul cadru energetic național. Scopul acestui studiu a fost de a estima calitatea biomasei vegetale pomicole generate de nuciferi, având în vedere potențialul utilizării acesteia ca materie primă pentru producerea biocombustibililor solizi. S-au efectuat estimarea calitativă și cantitativă a reziduurilor de nuc, alun și migdal ținând cont de valoarea calorifică, conținutul de cenușă și materii volatile, conținutul de C, H, S, N și Cl) care sunt constituenți ai factorilor poluanți (CO, CO₂, NO_x, SO₂ etc.). Rezultatele demonstrează că reziduurile nucifere pot îndeplini standardele de calitate pentru biocombustibilii solizi pe bază de biomasă nelemnoasă, cu un potențial semnificativ pentru producerea de energie durabilă.

Cuvinte cheie: Biomasă nucifere, Biocombustibili solizi, Nuc, Alun, Migdal, Potențial energetic.

1. Introduction

In the current global context, marked by the depletion of conventional energy resources, the ongoing energy crisis, the increasingly pronounced impact of climate change, and the identification and effective use of renewable energy sources have become a key priority for the Republic of Moldova.

To encourage the continuous development of renewable energy, the Republic of Moldova has implemented a series of policies and strategies highlighting its commitment to sustainability. Among these, the Energy Strategy of the Republic of Moldova until 2030 [1] and the Energy Strategy of the Republic of Moldova until 2050 [2] stand out as essential documents. These strategies aim to achieve essential objectives such as ensuring energy security, improving energy efficiency, and diversifying energy sources. A central aspect of these initiatives is the promotion of renewable energy, including biomass-derived energy, as a means to reduce dependency on energy imports. This approach not only strengthens national energy independence but also supports the transition to a more sustainable and resilient energy system. The use of biomass as a fuel source represents a promising solution for meeting global energy demands, providing significant economic and environmental benefits. As a renewable resource, biomass has gained significant popularity worldwide, particularly among energy-import-dependent countries such as the Republic of Moldova [3]. Despite its potential, the biomass sector faces certain challenges, including ensuring the consistent quality of raw materials [4–6].

In Europe, concerns regarding biomass quality and sustainability, as well as its impact on the performance of solid biofuels, have been a focal point of policy development. These issues were formally addressed with the adoption of Directive 2009/28/EC, which promotes the use of energy from renewable sources, where biomass playing a pivotal role [7]. According to various authors [8–11], the quality of biomass is a critical factor in ensuring the quality of the final product. Biomass used as raw material for producing solid biofuels consists of a highly heterogeneous range of biogenic materials from diverse origins, including agriculture, forestry, wood processing industries, and the food industry. This variability poses significant challenges for standardization and predicting its impact on the quality of the final product [8, 12–14].

Among the existing types of biomass, orchard-derived biomass stands out as one of the most promising options with considerable potential in the Republic of Moldova [15–17]. Being available in various forms – both dedicated and residual – it offers relatively stable and predictable energy production [18]. This study aims to analyze the quality and potential of orchard biomass generated from nut trees, considering its potential use as raw material for the production of solid biofuels. The research hypothesis suggests that residues generated from nut tree cultivation could serve as a viable resource for manufacturing solid biofuels with properties that comply with ENplus standards.

Nut trees play an important role in global agriculture, including in the Republic of Moldova, given their nutritional and economic value. Nuts are highly appreciated on international markets, offering competitive prices, which encourage local producers to expand cultivated areas [19, 20]. *Nut trees* share significant common features as woody plants that produce hard-shelled fruits, which allow for extended storage and provide effective protection against external factors. In this context, a study conducted on biomass from various fruit tree species in intensive plantations in Croatia revealed that hazelnuts generate the highest residue yield among nut trees, producing 1,848 kg/ha, followed by almonds with 1.627 kg/ha, and walnuts with only 538.5 kg/ha [21]. However, the same author highlights that almonds, despite their lower planting density, yield the largest amount of biomass per tree (5.81 kg), positioning them as a highly attractive option for using residues in thermal energy production. In addition to residues from tree pruning and maintenance, nut trees generate a significant amount of biomass in the form of endocarps (the hard, woody shells

protecting the seeds). The literature identifies various methods for transforming these residues into energy sources. For instance, studies demonstrate that pelletizing almond shells can yield fuels with high calorific value, suitable for use in thermal plants and electricity generation [22]. Beyond energy production, almond shells have industrial applications, including the preparation of activated carbon, abrasive stones, and fine linoleum blends [23]. Walnut and hazelnut shells present promising potential as raw materials for producing particle boards [24]. Beyond their traditional use as fuel, walnut shells have found innovative applications in the food industry, specifically as a substrate in the acetic fermentation process for producing white wine vinegar. This method involves washing and drying the shells at controlled temperatures to prepare them for inoculating acetic bacteria. This approach highlights the sustainability of utilizing walnut shells as active biological materials in processes that yield high-quality food products [25]. The research was conducted at the Scientific Laboratory of Solid Biofuels (LSBCS) of Technical University of Moldova using validated standard methods. Biomass samples were collected from various agricultural households across the Republic of Moldova. The results confirmed the initial hypothesis, demonstrating that plant residues from nut trees represent a sustainable and reliable raw material for producing solid biofuels, meeting the qualitative requirements specified in the SM EN ISO 17225:2021 standards.

2. Materials and Methods

The investigation methodology was based on a systematic study conducted at the LSBCS of UTM, accredited by the National Accreditation Center of the Republic of Moldova [26]. The research was carried out in two distinct phases. In the first phase, biomass quantities from various walnut, hazelnut, and almond varieties were estimated. Experimental samples were collected from multiple locations: the Voinești Nursery in Voinescu village, Hâncești district; the CC Dumbrava Veche SRL in Radeni village, Straseni district; and various individual farms in Truseni commune, Chisinau municipality. Figure 1 presents sequences from the biomass sampling process.



Figure 1. Sequences of walnut biomass sampling in Truseni commune, Chisinau municipality.

Samples were coarsely shredded on-site immediately after collection using a *Murena* branch shredder and weighed with an accuracy of 10.0 g using the ACFN balance. The weighed samples were packed in polyethylene bags and transported to the LSBCS on the same day, where their moisture content at the time of harvest was determined. In the second phase, the residue mixtures from various walnut, hazelnut, and almond varieties collected across different regions of Moldova were analyzed for their calorific value, ash content, volatile matter content, and elemental composition, including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and chlorine (Cl).

Sample collection was performed in accordance with the requirements of the SM EN ISO 18135:2017 standard, while sample preparation followed the guidelines outlined in SM EN ISO 14780:2017/A1:2020.

The collected samples were conditioned by grinding using a Retsch SM 100 mill equipped with a 1 mm mesh sieve (Figure 2a). The grinding process was performed at a rotor speed of 1500 min^{-1} , ensuring uniform particle size reduction while minimizing excessive dust formation.

The gross calorific value of the biomass was determined at constant volume using an IKA C6000 isoperibolic calorimeter (Figure 2c). The methodology for calculating the net calorific value, reported on a dry basis and adjusted for a predetermined moisture level, is detailed in our previous work [27].

Moisture content was assessed by measuring the weight loss of the biomass after heating at $105 \pm 2 \text{ }^\circ\text{C}$ in a UNB 500 - Memmert oven (Figure 2f), in accordance with the SM EN ISO 18134-1:2017 standard. The resulting moisture content was reported on a dry basis, applying the calculation method described in [28].

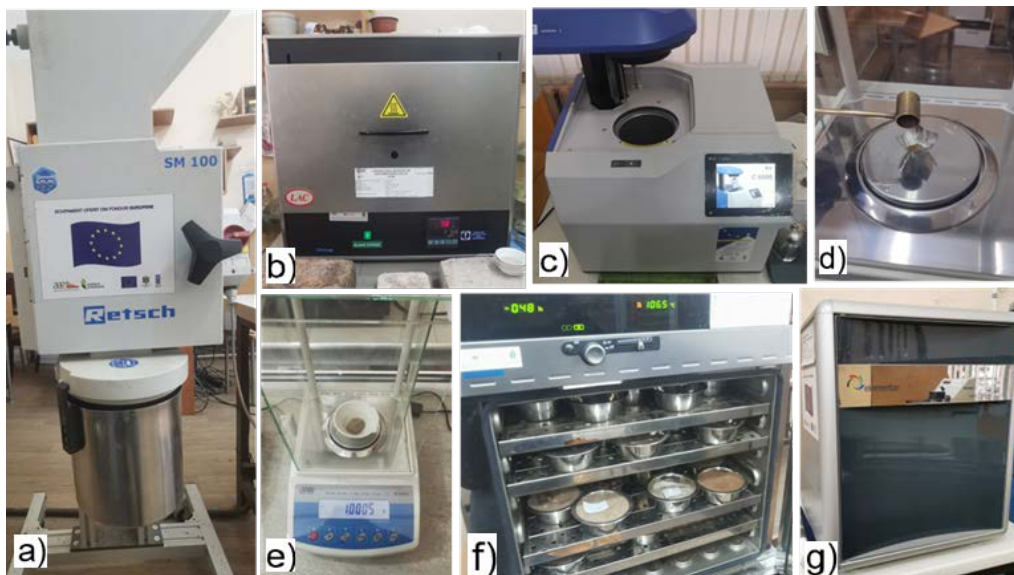


Figure 2. Equipment used for testing: a) Retsch SM 100 mill; b) LAC LH 06/13 muffle furnace; c) IKA C6000 isoperibolic calorimeter; d) Sample weighing; e) AS220/C2 analytical electronic balance; f) UNB 500-Memmert oven; h) Vario MACRO cube elemental analyzer.

The ash content of the samples was determined by incinerating approximately one gram of each sample. The samples, placed in crucibles, were progressively heated following this procedure:

- heated to $250 \pm 10 \text{ }^\circ\text{C}$ at a rate of $+5^\circ\text{C}/\text{min}$ for 50 min;

- maintained at 250 ± 10 °C for 60 min, then gradually heated to 550 ± 10 °C over 60 min;

- held at 550 ± 10 °C for 120 min, then cooled to an ambient temperature. Chemical analysis of the samples was performed using the Vario MACRO cube CHNS Cl elemental analyzer (Figure 2h). Detection and quantitative analysis were carried out using a thermal conductivity detector. The results were processed using EAS software, which enabled data display, monitoring, recording, and analysis for chemical element characterization.

All tests were repeated five times, and the standard deviation and confidence intervals were determined. The corresponding tables present the average values from these repetitions.



Figure 3. Biomass samples prepared according to SM EN ISO 14780:2017 requirements: a) hazelnut original fruits and endocarp; b) almond original fruits and endocarp; c) walnut kernel and endocarp; d) hazelnut branches; e) shredded hazelnut endocarp; f) shredded walnut endocarp.

3. Results

In the Republic of Moldova, the most important nut species are walnut (*Juglans regia* L.), hazelnut (*Corylus avellana* L.), and, to a lesser extent, almond (*Prunus dulcis*). In recent years, the area of nut plantations has increased significantly, reaching a total of 39.1 thousand hectares, of which 26.8 thousand hectares are productive plantations [29]. Walnut dominates, accounting for about 95% of the plantations, followed by hazelnut (~3%) with almond and other nut species making up the remainder. It is noteworthy that hazelnut and almond cultivation are experiencing a significant upward trend.

Table 1 presents data on the total nut yield for 2022–2023, categorized by type, highlighting the role of individual households in production. These households contribute approximately 60–65% of the total yield, indicating that the majority of nut production occurs at the individual level.

Table 1

The global walnut harvest in the Republic of Moldova for the reference years, thousand tons [29]

2022				2023			
HhAC	AE	SFF	IHh	HhAC	AE	SFF	IHh
19.1	6.5	0.9	11.7	21.2	4.9	0.9	15.4

Note: HhAC- households of all categories; AE - agricultural enterprises; SFF - small family farms; IHh - individual households.

Walnuts are the most widely consumed dried fruit worldwide and are considered both economically and ecologically significant, with diverse applications in the medical, nutritional, agricultural, and industrial sectors [30]. Native to the Old World, walnuts have been cultivated in Europe since 1000 BC, with their origin spanning an extensive region from the Balkans to the western Himalayan range [20]. This species is well-adapted to temperate-continental climates and offers numerous valuable qualities, including health benefits, use in the furniture industry, and an essential role as a forest tree for preventing and controlling soil erosion [31].

Today, walnuts are commercially grown in various regions worldwide, including North Africa, East Asia, the United States, western South America, and Southern Europe, especially in countries such as Romania and the Republic of Moldova [32]. In the Republic of Moldova, walnut orchards include both traditional local varieties, such as *Pescianski*, *Cazacu*, and *Calarasi*, as well as imported ones. Modern plantations are primarily dominated by French varieties like *Fernor* and *Franquette*, American varieties like *Chandler*, or those developed at the Voinești nursery, including *Carpatica* and *Ovata*. All of these varieties are listed in the Republic of Moldova's Plant Variety Catalog and are authorized for cultivation within the national agri-food sector [33].

In rural households, the walnut tree has been a common feature. Production traditionally focused on harvesting walnut kernels, the edible part of the fruit, which accounted for 20% to 60.3% of the total weight, with an average of 42.70% [23]. Shells from kernel processing were abundantly available and traditionally used for heating stoves. Due to their high calorific value, walnut shells provided a practical and economical solution for individual households.

The walnut tree's longevity of 200 to 300 years ensures a continuous biomass yield without the need for frequent replanting [23].

Hazelnuts, native to Europe and Asia Minor, are cultivated for their nuts, used both for direct consumption and in the food industry. Rich in minerals and vitamins, hazelnuts offer tonic, energetic, and digestive benefits, making them a valuable source of essential nutrients [34]. In Moldova, the main varieties grown include Tonda Gentile, Fertile de Coutard (Barcelona), Nocchione, and Tonda Franciscana (B). These varieties thrive in areas with moderate rainfall and possess a shallow root system, which makes them sensitive to drought.

Hazelnuts can be cultivated with either a single trunk or multiple trunks, depending on growers' preferences and objectives. Single-trunk forms facilitate mechanical harvesting and optimal light exposure, while multi-trunk forms allow for gradual regeneration by replacing old shoots with new ones. A hazelnut bush typically produces approximately 3-7 kg of green biomass. According to authors' analysis and the study [35], the average biomass per plant was 4.17 kg of fresh material, highlighting the significant potential of hazelnuts as a sustainable biomass source. This biomass mainly results from periodic pruning of branches

and shoots during maintenance and care operations, as well as residual materials from nut harvesting.

The almond tree, native to the arid regions of the Middle East and Central Asia, grows naturally along the Mediterranean coast, in China, and India [36]. Recently, several almond varieties have been adapted for cultivation in the southern regions of the Republic of Moldova. These include local varieties such as Meteor, Victoria, Alb Moldovenesc, Hramov Standard, and Pervenet Hramova (sold by SRL Dumbrava Veche); Tuono (an Italian variety noted for late blooming and resistant to late frosts); Nonpareil (a Californian variety famous for its large, sweet almonds); and Nocchione (an Italian variety known for medium-sized fruits and high productivity).

Almond trees can be shaped like traditional trees or managed as large bushes. During pruning and processing, almonds yield significant amounts of plant biomass, which can be converted into raw material for producing densified solid biofuels. The edible kernel of almonds accounts for approximately 20-40% of the entire nut, including the shell and outer husk, with this ratio varying depending on the variety and growing conditions [37]. This biomass, including shells and husks, can be a valuable source for bioenergy production, making almonds not only a nutritional commodity but also a sustainable option for solid biofuels.

Overall, the amount of plant biomass resulting from pruning nut trees is influenced by several factors, including:

- Crop type (different nut species produce varying amounts of biomass based on their growth characteristics and branching patterns).
- Tree age and size (older and larger trees typically generate more woody material than younger, smaller trees, as their growth produces more biomass).
- Harvesting technology (the use of specialized equipment can optimize biomass collection by reducing labor costs and improving efficiency).

Pruning type (maintenance pruning produces less biomass than regeneration or formative pruning) [38]. There are three main types of nut tree pruning: formative, maintenance, and rejuvenation [39], specific to each group of nut trees, producing different amounts of residual biomass.

Table 2 shows the results regarding the biomass quantities obtained from cultivating various walnut, hazelnut, and almond varieties. To better reflect real-world conditions, where biomass collection does not involve sorting by varieties or species, average values for different nut groups were determined. The dispersion and confidence intervals were also calculated to provide a more accurate representation of biomass yield across different conditions.

The analysis of nut residue potential, as summarized in Table 2, was conducted using samples collected from orchards over 10 years of age. Each biomass sample comprised a mixture of one-year-old and perennial shoots. Sampling procedures followed the methodology described in [40].

Tree selection was performed according to SM EN ISO 18135:2017 standard. Specifically, trees in a specific area of the plantation were assigned a two-digit identifier: the first digit denoting the row number and the second digit indicating the tree's position within the row. The quartering method was employed to ensure a representative selection of samples.

Table 2

The amount of residues generated by different varieties of walnut, hazelnut, and almond trees

Variety of fruit trees	Average number of trees, trees/ha	Average biomass quantity, kg/tree	Biomass quantity, kg/ha	Moisture content at harvest, %wt	Biomass quantity adjusted to 10%wt, kg/ha	Average nut yield in shell, kg/ha	Average endocarp/kernel ratio, %	Endocarp quantity, kg/ha
Walnut								
Pescianski	200	9.63	1926.0	46	1155.6	1750	56	980
Ovata	200	8.41	1682.0	48	971.8	2200	48	1056
Fernor	250	8.52	2130.0	43	1349.0	2800	48	1344
Franquette	200	9.16	1832.0	47	1078.8	2000	57	1140
Chandler	250	8.35	2087.5	42	1345.3	2500	44	1100
Mean	220.0	8.81	1931.5	45.2	1180.1	2250.0	50.6	1124.0
Standard Deviation	27.4	0.56	184.3	2.6	165.9	412.3	5.6	136.6
Confidence Interval	24.0	0.49	161.6	2.3	145.4	361.4	4.9	119.7
Hazelnut								
Tonda Francescana	820	4	3436	44	2138	2290	56	1282
Tonda Gentile	500	4	2080	43	1317	2240	55	1232
Barcelona	500	4	2070	42	1334	2190	57	1248
Fertile de Coutard	820	4	2968	45	1814	2210	52	1149
Nocchione	820	4	3091	46	1855	2090	53	1108
Mean	692.0	4.0	2729.1	44.0	1691.6	2204.0	54.6	1203.9
Standard Deviation	175.3	0.3	621.2	1.6	356.6	74.0	2.1	72.7
Confidence Interval	153.6	0.2	544.5	1.4	312.6	64.9	1.8	63.8
Almond								
Meteor	350	7.8	2730	48	1577	2500	78	1950
Alb Moldovenesc	280	8.6	2408	52	1284	1800	77	1386
Tuona	350	7.4	2590	58	1209	2200	69	1518
Nanparil	400	6.3	2520	54	1288	2400	68	1632
Victoria	280	8.2	2296	43	1454	2400	66	1584
Mean	332.0	7.7	2508.8	51.0	1362.5	2260.0	71.6	1614.0
Standard Deviation	51.7	0.9	166.7	5.7	149.9	279.3	5.5	209.4
Confidence Interval	45.3	0.8	146.1	5.0	131.4	244.8	4.8	183.5

Note: wt - percentage by weight.

The results indicate significant variability in the amount of vegetal biomass resulting from pruning operations across the studied nut trees species. Hazelnuts produced the largest amount of vegetal residues, averaging 2729.1±544.5 kg/ha, while walnuts yielded the lowest, with an average of 1931.5±161.6 kg/ha. For endocarp residues, almonds recorded the largest

quantity, averaging 1614 ± 183.5 kg/ha, whereas walnuts had the smallest amount, with an average of 1124 ± 119.7 kg/ha.

To fully assess the potential of nut residues as raw materials for biofuel production, their thermochemical characteristics were analyzed. The following Table presents the results of the analysis of the main characteristics of nut residues, which are of interest for evaluating their energy applications. A comparative evaluation of these characteristics (see Table 3) highlights significant differences in residue quality, especially in ash content, which ranged from 1.4% for hazelnut branches and shoots to 5.5% for walnut branches. In terms of calorific value, walnut branches recorded the lowest energy potential ($q_{\text{Pnet } M=10\%} = 15501.1$ J/g), while almond branches demonstrated the highest ($q_{\text{Pnet } M=10\%} = 15968.4$ J/g). Additionally, walnut branches exhibited the highest sulfur and nitrogen content among the tested samples, posing potential environmental challenges during combustion.

Table 3

Average results of characteristics of vegetable biomass generated from nut trees

Biomass origin	$q_{V_{ds}}$ J/g	$q_{V_{net } d}$ J/g	$q_{Pnet } M=10\%$	A, %	M rec., %	MV, %	C, %	N, %	H, %	Cl, %	S, %	O, %	
Walnut	branches	18823	17494.9	15501.1	5.5	46.9	77.9	48.8	0.62	6.11	0.04	0.08	38.89
	endocarp	20083	18757.3	16637.3	0.9	11.0	79.0	45.9	0.18	6.07	0.03	0.04	46.89
Hazelnut	branches	19119	17771.7	15750.3	1.4	44.5	80.2	47.5	0.57	6.18	0.05	0.07	44.26
	endocarp	20297	18941.2	16802.7	0.9	10.9	77.1	45.2	0.19	6.21	0.03	0.05	47.42
Almond	branches	19421	18014.1	15968.4	2.4	44.6	79.7	51.2	0.54	6.48	0.05	0.04	39.30
	endocarp	19856	18462.0	16371.5	1.6	12.7	78.4	49.7	0.29	6.41	0.04	0.04	42.01

Note: A – ash content on a dry basis; MV – volatile matter content; $q_{V_{ds}}$ – higher calorific value measured at constant volume; $q_{V_{net } d}$ J/g lower calorific value at constant pressure; $q_{\text{Pnet } M=10\%}$ – lower calorific value at constant pressure calculated for a moisture content of 10%.

All residues in the form of branches and shoots require conditioning through drying, as their moisture content at harvest significantly exceeds the recommended values for pellet and briquette processing [41].

In contrast, endocarp residues generated by all studied nut species can be processed directly without prior conditioning through drying due to their low moisture content, which ranges from 10.9% for hazelnut to 12.7% for almond. These moisture values fall within the recommended limits for raw materials used in the production of densified solid biofuels [41]. Notably, walnuts, hazelnuts, and almonds the endocarp residues can also be used directly, without densification, in both traditional stoves and most modern thermal power plants [42]. Comparing the data obtained in this study with the requirements outlined in the SM EN ISO 17225 standards, it can be concluded that biomass derived from walnut pruning is suitable exclusively for the production of pellets and briquettes classified as non-woody biomass products, blends, and biomass mixtures. Specifically, walnut pruning biomass is categorized as A for pellets and A2 for briquettes, while branches from hazelnut and almond trees meet the criteria for use as raw material in the production of A2-grade wooden briquettes.

Synthesizing the data presented in Tables 2 and 3, the energy potential of biomass generated by nut tree species was calculated per hectare of plantation area. The analysis of nut biomass energy potential considered several perspectives, each playing an essential role for resource evaluation and efficient planning for solid biofuel production. These perspectives

include the theoretical potential, the available potential, and the economic potential, which some authors refer to as the sustainable implementation potential.

The theoretical energy potential (TEP) represents the total energy available in the biomass produced, without considering any limiting factors such as collection efficiency or losses during processing. It provides a maximum estimate based on the total amount of biomass generated by agricultural activities. The TEP is calculated based on the calorific value of the biomass and assumes its complete utilization [43]. For example, if all agricultural residues were collected and 100% utilized, this potential would reflect the total energy contained in those residues. The theoretical energy potential calculated for one hectare of nut plantations was determined using the following equation:

$$TEP = m_{b,M=10\%} \cdot q_{p.net.M=10\%}, \quad (1)$$

where: $m_{b,M=10\%}$ - the average amount of biomass converted to a moisture content of 10%; $q_{p.net.M=10\%}$ - the net calorific value of biomass at a moisture content of 10%, calculated at constant pressure.

The available energy potential (AEP) is lower than the theoretical energy potential, being defined as the part of the theoretical potential available for energy production, limited by constraints related to the use of this biomass for non-energy purposes, the efficiency of the technological process, etc. [44]. For example, not all biomass can be harvested from the field, as part of it must be left for ecological purposes to maintain soil fertility. The available energy potential was determined as the product of theoretical energy potential and the availability coefficient (A). This coefficient, which reflects these limitations, is commonly accepted in the literature for fruit trees and is set at a value of 0.8 [40, 43, 45].

The sustainable energy potential for implementation (SEPI) represents the portion of the available energy potential that can be profitably utilized, considering the costs associated with biomass collection, processing, and usage, as well as technical and sustainability factors. This potential depends on economic, technological, and policy factors [46, 47] and also factors such as transport and storage losses [40]. For example, if the costs of biomass harvesting and processing exceed the value of the energy produced, this biomass will not be considered part of the economic potential, as it would not be financially viable for energy production.

The sustainable energy potential for implementation was calculated using the following equation:

$$SEPI = AEP \cdot (1 - k_{il}), \quad (2)$$

where: k_{il} - implementation loss coefficient.

The analysis of these three types of energy potential is essential for developing efficient strategies for utilizing agricultural biomass in solid biofuel production. The theoretical potential offers a broad overview, representing the maximum energy available from biomass without considering practical constraints. The available potential reflects the real-world limitations, such as biomass losses during collection and processing, as well as competition with non-energy uses. Finally, the SEPI assesses the economic and technical feasibility of utilizing the biomass, considering the costs involved and the market context. Together, these potential types guide the planning and implementation of biomass-based energy projects, ensuring both practicality and profitability.

Figure 4 illustrates the energy potential of biomass from three types of nut trees—walnut, hazelnut, and almond—categorized into two distinct types of biomass: woody biomass (WB) and endocarp biomass (EB). This differentiation allows for a clearer comparison of the energy potential of each biomass type, providing insights into their respective contributions to the overall energy potential of the nut tree residues.

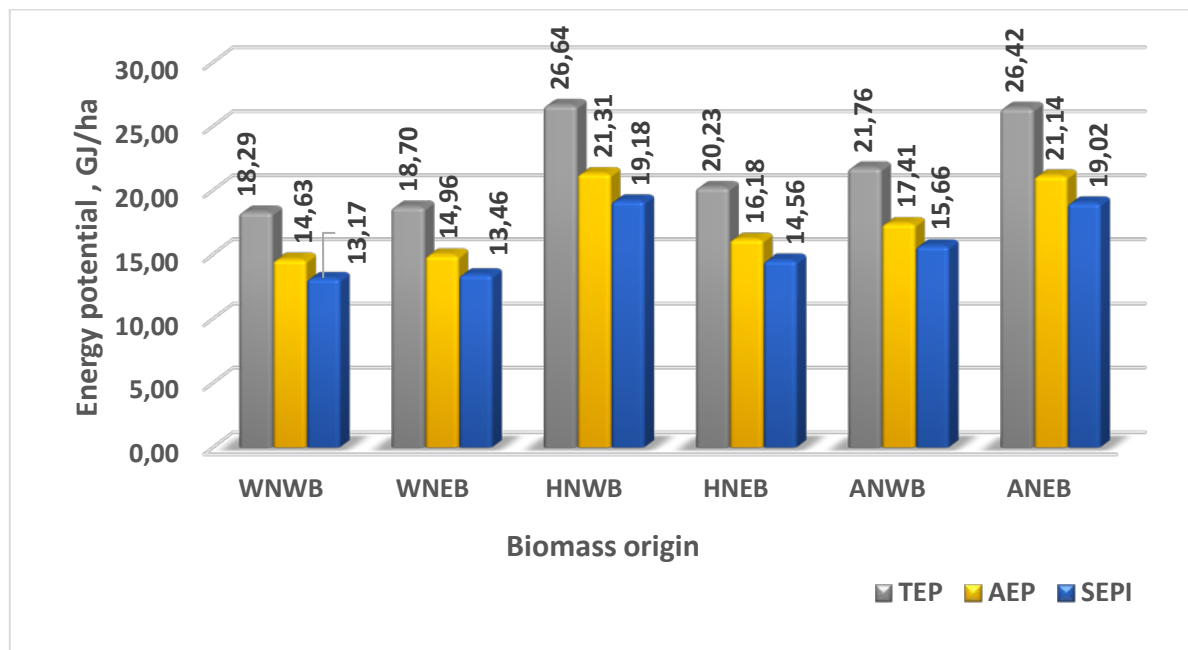


Figure 4. Energy potential of biomass generated by nut trees: TEP - theoretical energy potential; AEP - available energy potential, SEPI - sustainable energy potential of implementation; WNWB - walnut woody biomass; WNEB - walnut endocarp biomass; HNWB – hazelnut woody biomass; HNEB - hazelnut endocarp biomass; ANWB - almond woody biomass; ANEB - almond endocarp biomass.

When comparing the energy potential values across the types of biomass studied, significant differences emerge between woody biomass and endocarp, with hazelnut woody biomass yielding the highest energy values, followed by walnut and almond biomass, which exhibit slightly lower values.

The highest energy potential can be harnessed from processing almond residues, with a total SEPI of 34.69 GJ/ha, closely followed by hazelnut residues, with a total SEPI of 33.75 GJ/ha. Walnut residues, however, have the lowest energy potential, with a total SEPI of 26.64 GJ/ha.

These findings emphasize the importance of evaluating different types of energy potential when planning biomass utilization. Specifically, TEP offers a maximum estimate of energy capacity, while the AEP and SEPI reflect how practical and economic constraints shape the actual biomass availability for energy production.

4. Conclusions

1. Nut tree residues, including branches and endocarps, represent a sustainable and valuable source of biomass for solid biofuel production in the Republic of Moldova.

2. Endocarps, characterized by low moisture and ash content, are suitable for direct use in energy production without requiring drying or pre-conditioning.

3. Among the studied residues, hazelnut exhibited the highest calorific value (20.297 J/g), followed by walnut (20.083 J/g) and almond (19.856 J/g).

4. The energy potential of nut tree biomass is influenced by practical and economic factors, with almond residues demonstrating the highest energy yield per hectare of plantation.

5. The proper use of walnut tree residues effectively aligns with renewable energy strategies, contributing to energy independence and reducing reliance on imported energy sources.

These findings highlight the significant role of nut tree residues as a renewable energy resource, advocating their integration into sustainable biomass utilization strategies.

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