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Pyrolysis valorisation of fruit processing residues: energy and emission potential of apricot (*Prunus armeniaca* L.) and cornelian cherry (*Cornus mas* L.) seed biochar

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A b s t r a c t. This study focuses on the use of post-production residues in the form of apricot and cornelian cherry seeds through pyrolysis, turning them into high-energy biochar. The experiments conducted reveal the potential of this waste as an alternative energy source. Pyrolysis at 500°C significantly improved their calorific value, reaching maximum values of 31.27 MJ kg^{-1} for apricot seeds and 31.26 MJ kg^{-1} for cornelian cherry seeds. Pyrolysis efficiency not only raised the energy value of the biomass, but also showed a significant reduction in emissions of harmful gases, such as CO, No_x, and SO_2, making the combustion process greener. The research points to the potential of fruit processing residues in sustainable energy production, thereby meeting the goals of a circular economy. The research also complements existing knowledge in energy recovery technologies and the potential for effective waste management in the agri-food industry.

K e y w o r d s: alternative biochars, fruit seeds, gas emissions, sustainable waste management, sustainability

1. INTRODUCTION

In the context of the growing demand for clean energy and global climate commitments, the development of alternative energy sources and fuels with high energy efficiency is becoming an important area of focus. At the same time, the European Union achieved a 10% decrease in energy consumption between 2004 and 2016, demonstrating the effectiveness of energy efficiency measures (Eurostat, 2023).

The degree of involvement of individual countries in the development of renewable energy often depends on environmental conditions and geography. For example, the use of hydropower requires the presence of numerous watercourses and significant differences in elevation, which is conducive to the development of this sector in countries such as Austria and the Nordic countries. Wind power, on the other hand, is mainly developing in open and well-ventilated areas – typical of Ireland, the Netherlands, or Denmark. In contrast, the use of solar energy is most feasible in regions with a high number of sunny days per year, such as Spain or Cyprus (Pourasl *et al.*, 2023; Solaun and Cerdá, 2017; Zhou *et al.*, 2015).

Biomass, on the other hand, is an important part of the renewable energy mix, used in the form of both plant materials and organic waste. Its technological flexibility and ability to be used in a variety of energy conversion processes (combustion, fermentation, gasification, pyrolysis) make it a competitive alternative to fossil fuels, especially in the

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context of decarbonisation and closed-loop economy strategies. One promising direction in the conversion of biomass, including waste biomass, into high-energy alternative fuels is pyrolysis, a process of thermochemical conversion of biomass in anaerobic conditions, yielding biochar, combustible gases, and oil condensate. The properties of biochar are strongly affected by process parameters, particularly pyrolysis temperature and residence time. Higher temperatures generally increase the fixed carbon content, calorific value, and aromaticity of the material, while decreasing volatile matter. Prolonged residence times improve the degree of carbonisation and stability but may reduce yield (Leng *et al.*, 2021; Mignogna *et al.*, 2024; Pal *et al.*, 2024; Rathore and Singh, 2022; Yogalakshmi *et al.*, 2022).

Biochar, derived from waste plant biomass, is gaining importance as a sustainable alternative to traditional fossil fuels. It has a high calorific value, often reaching 25-30 MJ kg^{-1}, making it competitive with lignite in terms of energy potential (Qambrani *et al.*, 2017). In addition, its highly porous structure, formed by thermochemical processes, contributes to its widespread use both as an adsorbent of environmental pollutants and as an agent for improving the physicochemical properties of soils, increasing their sorption capacity and water retention (Ahmad *et al.*, 2014). The varied properties of pyrolysate, depending on the type of raw material and the conditions of its pyrolysis, allow it to be adapted to specific technological and environmental needs, making it a versatile material that supports the goals of a circular economy (Jeyasubramanian *et al.*, 2021; Khan *et al.*, 2024; Lehmann, 2011; Saletnik *et al.*, 2019; Singh *et al.*, 2025). The burning of fossil fuels continues to account for a significant share of emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and sulphur dioxide (SO_2), posing a significant challenge in the context of achieving global climate goals and energy transition. In this context, biochar extracted from waste biomass, among other sources, can be indicated as a low emission alternative, offering both energy properties similar to lignite and a much more favourable emission profile (Fawzy *et al.*, 2021). The use of biochar can positively affect local air quality while promoting the reduction of greenhouse gas emissions, especially in the context of carbon sequestration. According to life cycle assessment data, pyrolysis of 1 t of biomass can result in biochar that sequesters up to 50-60% of the original carbon content, while the process reduces net CO_2-equivalent emissions by approximately 0.07-0.68 t kg^{-1} of biochar produced, depending on energy recovery and process optimisation (Kavindi *et al.*, 2025). Therefore, its use as a fuel in low-power installations or as an additive to other energy materials may fit into the decarbonisation strategy of the energy sector (Ganesapillai *et al.*, 2023; Gayen *et al.*, 2024; Kluska and Ramotowski, 2024; Varkolu *et al.*, 2025).

Among waste biomass, seeds from fruits used in the drying industry may be of growing interest.

In 2023, Turkey was the largest producer of apricots in the world, producing approximately 750 000 t of these fruits annually. Assuming that seeds constitute about 10% of the fruit mass, the annual production of apricot seeds in Turkey may reach around 75 000 t (Yanardağ, 2025). Cornelian cherry occurs in many countries in Europe and Asia, but commercial plantations are still scarce. In countries such as Turkey, Iran, and Georgia, the fruits are collected from both natural stands and small plantations and processed into food products. In Georgia, natural plantations cover an area of 100 000-130 000 ha, and one tree yields 2-4 kg of fruit, which corresponds to a potential production of 17 000-20 000 t annually. Assuming that seeds make up about 10% of the fruit mass, the annual production of seeds from natural plantations in Georgia may reach approximately 1 700-2 000 t, representing a potentially valuable raw material for biofuel production. Due to the possibility of maintaining numerous semi-natural sites, cornelian cherry can also be introduced into large commercial plantations, as observed in Austria (Szot, 2024). In many countries, such as Turkey, apricot seeds are already systematically collected and used in the food and cosmetics industries, suggesting the possibility of their storage and use in biofuel production as well (Yanardağ, 2025). The production of biofuel from fruit seeds can be profitable; however, it depends on multiple factors, such as the costs of harvesting, transportation, storage, and processing of the raw material. A precise assessment of the economic feasibility would require conducting a specialised cost-benefit analysis, encompassing both logistical and operational aspects as well as the potential market scale and variability of raw material prices. For instance, pyrolysis of Hass avocado seeds can be economically viable, as the revenue from bio-oil, syngas, and biochar can cover processing costs. Optimised operation of 1 tonne of seeds can yield net profit, showing the potential of fruit seeds for biofuel production (Malagón-Romero *et al.*, 2025).

The seeds of such fruits as apricot (*Prunus armeniaca* L.) and cornelian cherry (*Cornus mas* L.), for example, due to their high content of lignocellulosic organic compounds, can be a valuable raw material for the production of solid biofuels. Fruit processing processes, such as drying, generate a significant amount of organic waste, the rational management of which is in line with a circular economy (Kucharska *et al.*, 2011; Leong and Chang, 2022). The literature confirms that thermochemical conversion (pyrolysis) of fruit seeds leads to the production of biochar with good energy and sorption properties (Altantzis *et al.*, 2022). Reducing moisture and volatile content increases material stability and can bring environmental and economic benefits (Malińska, 2012). Compared to biochars from wood chips or straw, seed-derived biochar may exhibit higher carbon content, a more uniform structure, and greater porosity, while also enabling the valorisation of otherwise unused food industry residues (Sieradzka *et al.*, 2025; Venegas-Gómez *et al.,* 2019).

The food processing sector, particularly in plants specialising in drying fruits and vegetables, generates significant amounts of organic residues that can be effectively managed as feedstock for solid biofuels. In the context of the growing production of fruit and fruit preserves in Poland and the European Union, the use of such waste as fruit seeds for biochar production could be an important part of the biofuel production sector and thus energy transition and decarbonisation. According to Eurostat data, in 2023 the European Union harvested 6.3 million tons of stone fruits, including peaches, nectarines, apricots, cherries, and plums. For comparison, the harvest of all tree fruits in Poland in 2022 amounted to approximately 3.7 million tons, highlighting the scale of the country's fruit production in a broader European context (Eurostat, 2024; GUS, 2024). Residues, such as seeds, peels, or plant fibres, have high energy potential and could be successfully used in thermochemical conversion processes. This approach is in line with the idea of sustainable development and supports the implementation of the principles of a circular economy.

The study focused on analysing the energy potential of waste biomass from fruit processing. The purpose of this study was to evaluate the feasibility of using apricot and cornelian cherry seeds to produce biochar by pyrolysis. An additional goal was to optimise the pyrolysis process by determining how long the sample is held at the final temperature, which can affect the physicochemical and energetic properties of the biochar materials obtained. The resulting products were analysed for their calorific value and physicochemical properties. In addition, an assessment was made of the emissions of selected harmful compounds, such as carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur dioxide (SO_2), generated during the combustion of both raw vegetable waste and the obtained biochar. The analysis aimed to determine the impact of biomass processing on the emission profile and thus on the environmental aspect. The use of apricot seeds and, above all, the so far little studied cornelian cherry seeds as a raw material for biochar production by pyrolysis is a contribution to the development of knowledge on alternative biofuel production. While the literature shows data on the use of various types of raw materials in their valorisation processes, the biomass in the form of cornelian cherry seeds remains poorly understood in terms of its potential use. The novelty of the present work lies not only in the choice of this raw material, but also in the applied methodology: the influence of the residence time at the final pyrolysis temperature on the physicochemical and energetic properties of biochar as well as on the emissions of harmful compounds such as oxides formed during combustion, which have not previously been studied for biochar from these seeds, was systematically analysed. Previous studies on biochar production from cornelian cherry seeds are limited and do not focus on the energetic aspects of utilising these seeds. This comprehensive approach has not been described in the literature and provides a better understanding of the potential of fruit processing residues in the context of a circular economy. The research carried out is in line with current developments in the circular economy, promoting the sustainable management of organic waste.

2. MATERIALS AND METHODS

2.1. Research object

Waste biomass in the form of apricot (*Prunus armeniaca* L.) and cornelian cherry (*Cornus mas* L.) seeds from the 2024 processing season was used for the study. The raw material was a leftover from fruit drying and was obtained in September from a production and trading facility specialising in drying vegetables and fruits, located in Podkarpackie Province, Poland. The seeds were separated from the flesh mechanically during the stoning process and collected randomly, without prior sorting, to ensure that the sample was representative. The collected material was transported in sealed containers to the research laboratory. The material intended for testing was dried to a moisture level of less than 10%. Dry apricot and cornelian cherry seeds are shown in Fig. 1.

The material collected was a post-production waste fraction that was not subjected to any form of recovery or reuse in on-site conditions.

a) b)

Fig. 1. Materials prepared for the process of pyrolysis: a) apricot seeds, b) cornelian cherry seeds.

2.2. Pyrolysis process

The pyrolysis procedure was conducted using a retort furnace (model FCF 2R, CZYLOK, Jastrzębie-Zdrój, Poland) designed for thermal treatment under an inert gas atmosphere. The apparatus was equipped with a post-reaction gas cooling system incorporating a water-cooled condenser. The samples were heated at a rate of 30°C min^{-1} until the target temperature was reached. Pyrolysis was conducted at 500°C, a temperature selected based on preliminary experiments indicating that it provides a favourable balance between the stability of the produced biochar, its calorific value, and yield. Residence times of 2, 4, 6, 8, and 10 min were applied, representing the duration for which the samples were maintained at the final temperature. All experiments were carried out in a high-purity nitrogen atmosphere (99.99%) at a constant flow rate of 10 L min^{-1}. To remove residual impurities, the materials were repeatedly rinsed with distilled water and then subjected to drying at 80°C for 12 h.

2.3. Combustion process

The thermal decomposition of the waste materials, including fruit seeds and the biochar produced from them, was carried out using a TGA 701 thermogravimetric analyser (LECO Corporation, Saint Joseph, MI, USA), which was used as a furnace connected to a gas emission measurement system. Each experiment used 100 g of material, distributed across 18 crucibles, and combusted in a controlled air atmosphere at a constant temperature of 800°C. The combustion process lasted 20 min and resulted in complete mineralisation of the tested material.

2.4. Analysis of samples

For easier identification, biomass samples were coded with symbols reflecting the material type, pyrolysis temperature, and process duration (Table 1).

The key physicochemical parameters of the investigated samples, including the concentrations of total carbon, ash, nitrogen, hydrogen, and volatile components as well as the calorific value were quantified using a series of instrumental analyses (Table 4). The assessment of ash content and volatile matter was carried out via thermogravimetric analysis using the TGA 701 system (LECO Corporation, Saint Joseph, MI, USA) in controlled conditions (PN-EN ISO 18122:2023-05, PN-EN ISO 18123:2023). The elemental composition, specifically carbon, hydrogen, and nitrogen levels, was determined with a TrueSpec CHN elemental analyser (LECO Corporation, Saint Joseph, MI, USA). The energy content of the materials, expressed as calorific value, was measured employing the AC500 bomb calorimeter (LECO Corporation, Saint Joseph, MI, USA). Each measurement was performed in triplicate to ensure reproducibility. The concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) were measured using an ULTRAMAT 23 gas analyser (SIEMENS AG, Germany). In the calculation of the concentration of individual gases, their densities were considered, while the algorithm used made it possible to accurately determine their content. Table 1 presents an example of calculations related to CO.

Table 2 summarises the density parameters of the analysed gases, which were used in the calculations.

Biomass and biochar samples were analysed in the laboratory following established analytical standards (Table 3).

2.5. Statistical analysis

Differences in the parameters of biochars obtained at different pyrolysis times and compared with the control were assessed using one-way analysis of variance (ANOVA). When significant differences were detected, Duncan's multiple range test was applied for post-hoc comparisons. Prior

Table 1. Symbols for research samples

Apricot seed	Cornelian cherry seed
A0 - non-heat-treated material	D0 - non-heat-treated material
A1 - pyrolysis (500ºC, 2 min)	D1 - pyrolysis (500ºC, 2 min)
A2 - pyrolysis (500ºC, 4 min)	D2 - pyrolysis (500ºC, 4 min)
A3 - pyrolysis (500ºC, 6 min)	D3 - pyrolysis (500ºC, 6 min)
A4 - pyrolysis (500ºC, 8 min)	D4 - pyrolysis (500ºC, 8 min)
A5 - pyrolysis (500ºC, 10 min)	D5 - pyrolysis (500ºC, 10 min)

Table 3. Density parameters of the analysed gases in room temperature (20°C)

Gases analysed	Gases density (mg L^{-1})
Carbon monoxide (CO)	1 250
Nitrogen oxides (NO_x)	1 340
Sulfur dioxide (SO_2)	2 830

Table 2. Computational algorithm for determining gas concentration (example for CO)

Calculated parameter	Method of calculation
Amount of carbon monoxide (CO)	$SCO = 0.5 \times (\lvert X_{n-1} - X_n \rvert) \times (t_{n-1} - t_n)$
Amount of gas mixture taken	$S_{gases} = t_c \times 100$
Percentage of carbon monoxide (CO) in analysed gas mixture	$\%CO = SCO / S_{gases}$
Amount of gas mixture taken during the test	$AL. = t_c \times 0.025$ (l/s)
Amount of carbon monoxide (CO) taken during the test	$ACO = AL. \times \%CO$
Carbon monoxide (CO) density at room temperature (20°C) (mg l^{-1})	1 250
Amount of carbon monoxide (CO) taken during measurement (mg)	ACO × 1 250

SCO – the calculated amount of CO, S_{gases} – the amount of gas mixture taken, $X_{n-1} - X_n$ – CO concentration results recorded by the analyzer during the intervals, $t_{n-1} - t_n$ - measured time intervals, $t_c \times 100$ – 100 - percentage sum of absorbed gases, AL. – the amount of gas mixture taken during the test, ACO – the amount of CO taken during the test, 0.5 – the complement.

Table 4. Analysed parameters and corresponding research methods

Parameter	Research method
Content of carbon, nitrogen and hydrogen	Solid biofuels – Determination of total carbon, hydrogen and nitrogen content
Ash content	Solid biofuels – Determination of ash content
Volatile matter	Solid biofuels – Determination of volatile matter
Calorific value	Solid biofuels – Determination of ash content

to ANOVA, the assumptions of normality and homogeneity of variances were verified. In order to compute the statistical analyses, STATISTICA version 12.0 (StatSoft Inc., Tulsa, OK, USA) was applied. A significance threshold of ≤ 0.05 was set in all analyses. The data were analysed separately for each type of materials.

3. RESULT AND DISCUSSION

3.1. Composition analysis: C, H, N, ash, and volatile substances

Table 5 presents the results of the total nitrogen content in raw apricot and cornelian cherry seeds and in biochar obtained from these materials by pyrolysis carried out at 500°C, using variable pyrolysis time. In the case of apricot seeds, the nitrogen content in the raw material was 1%, while in the biochar obtained after pyrolysis it varied between 1.04 and 1.44%. The largest increase in nitrogen was found in biochar A5, which underwent the longest treatment (10 min of pyrolysis), where the nitrogen content increased by 42.92% (relative), compared to the untreated material. In the case of cornelian cherry seeds, the nitrogen content in the raw biomass was 0.1% and, after pyrolysis, the nitrogen content in the biochar varied between 0.13 and 0.22%. As a result of the pyrolysis process, a relative increase in nitrogen of up to 114.43% was observed, indicating a significant increase in the content of this element in the biochar. The relative increase in nitrogen in the apricot biochar was 1.44%, compared to only 0.22% for the cornelian cherry seeds (Table 5). This may suggest that apricot seeds may emit more volatile nitrogen compounds during pyrolysis, resulting in less nitrogen retention in the carbon structure, while cornelian cherry seeds are better at retaining nitrogen in the form of stable compounds. These results are consistent with the study conducted by Gagliano *et al.* (2016), who showed that when peach and apricot seeds were pyrolyzed, the initial nitrogen content was about 0.3-0.4%, and it increased after pyrolysis to 0.5-0.6%. In contrast, other types of biomass, such as grain straw and tobacco waste, had relatively low nitrogen content, which may suggest the possibility of nitrogen retention in the carbon structure. Pyrolysis of apricot and cornelian cherry seeds at 500°C for 2 to 10 min had a significant effect

Table 5. Average content of total nitrogen, total carbon, hydrogen, ash and volatile matter for apricot (*Peunus armeniaca* L.) seeds, cornelian cherry (*Cornus mas* L.) seeds and prepared biochar

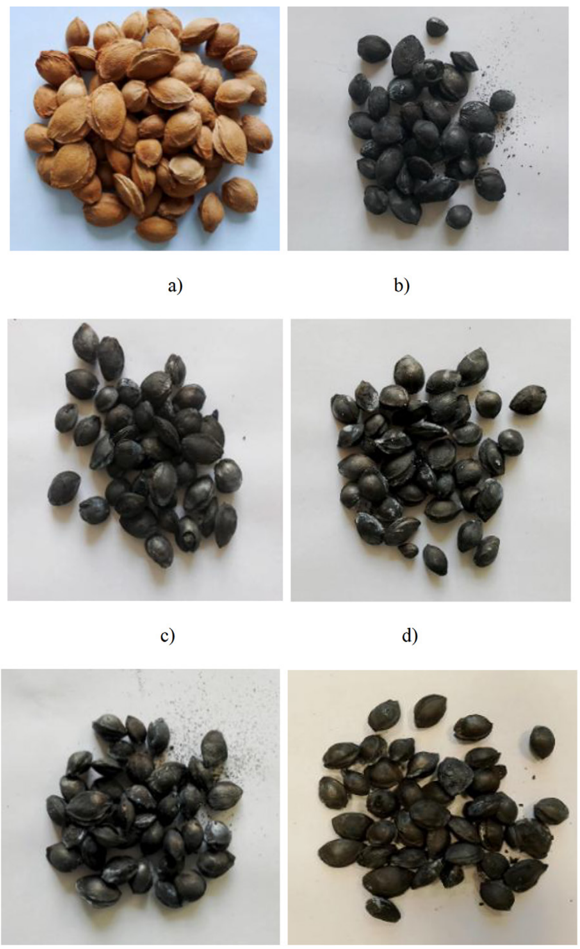
Research material	Total nitrogen	Total carbon	Hydrogen	Ash	Volatile substances
	(%)				
A0	$1.00^{a} \pm 0.002$	$53.85^{a} \pm 0.13$	$6.94^{b} \pm 0.05$	$0.82^{a} \pm 0.07$	$80.17^{b} \pm 0.06$
A1	$1.04^{ab} \pm 0{,}012$	$83.35^{b} \pm 0.12$	$2.74^{a} \pm 0.01$	$2.91^{b} \pm 0.03$	$20.36^{a} \pm 0.13$
A2	$1.12^{b} \pm 0.002$	$84.21^{b} \pm 0.09$	$2.74^{a} \pm 0.002$	$3.27^{c} \pm 0.07$	$20.09^{a} \pm 0.06$
A3	$1.24^{c} \pm 0.006$	$84.51^{bc} \pm 0.04$	$2.76^{a} \pm 0.01$	$3.3^{c} \pm 0.05$	$19.37^{a} \pm 0.11$
A4	$1.31^{c} \pm 0.007$	$85.23^{b} \pm 0.08$	$2.76^{a} \pm 0.003$	$3.46^{c} \pm 0.04$	$19.22^{a} \pm 0.09$
A5	$1.44^{d} \pm 0.008$	$85.6^{b} \pm 0.05$	$2.77^{a} \pm 0.001$	$3.79^{d} \pm 0.09$	$18.29^{a} \pm 0.07$
D0	$0.1^{a} \pm 0.003$	$50.35^{a} \pm 0.07$	$6.19^{b} \pm 0.003$	$0.92^{a} \pm 0.03$	$77.28^{b} \pm 0.15$
D1	$0.13^{b} \pm 0.006$	$83.43^{b} \pm 0.04$	$2.76^{a} \pm 0.005$	$2.99^{b} \pm 0.03$	$20.73^{a} \pm 0.12$
D2	$0.14^{b} \pm 0.003$	$84.34^{b} \pm 0.04$	$2.78^{a} \pm 0.003$	$3.11^{bc} \pm 0.01$	$20.67^{a} \pm 0.06$
D3	$0.16^{c} \pm 0.004$	$84.74^{b} \pm 0.08$	$2.79^{a} \pm 0.005$	$3.22^{bc} \pm 0.04$	$20.5^{a} \pm 0.07$
D4	$0.18^{d} \pm 0.004$	$85.46^{b} \pm 0.06$	$2.77^{a} \pm 0.004$	$3.37^{c} \pm 0.04$	$19.63^{a} \pm 0.08$
D5	$0.22^{e} \pm 0.003$	$86.05^{b} \pm 0.07$	$2.78^{a} \pm 0.004$	$3.78^{d} \pm 0.06$	$19.42^{a} \pm 0.04$

Differences between average values marked with the same letters are not statistically significant at the level of $p \leq 0.05$ according to the Duncan test. The data were analysed separately for each type of materials.

on converting organic compounds into more stable forms of nitrogen, which were trapped in the biochar structure. Nitrogen present in hemicellulose and lignin can form stable heterocyclic compounds in effect of thermal treatment. Increased pyrolysis time can lead to condensation of organic compounds and stabilisation of nitrogen in the form of permanent structures in biochar (Gagliano *et al.*, 2016; Lehmann and Joseph, 2015). Gagliano *et al.* (2016) demonstrated the possibility of transforming nitrogen into biochar during pyrolysis of different types of biomass. Although no direct data on the nitrogen content in biochar from cornelian cherry seeds was found in available sources, it is worth noting that it is the nitrogen content in the starting material that influences its transformation during pyrolysis.

Figures 2 and 3 show the biochar materials extracted from the seeds. The observations indicate that the prolonged duration of the pyrolysis process led to more intense carbonisation of the material, which showed a correlation with the increasing total carbon content in the analysed samples.

The total carbon content in the unprocessed apricot seeds was 53.85%, while the carbon content in the biochar obtained from this material ranged from 83.35 to 85.60%. In the case of cornelian cherry seeds, the carbon content in the untreated biomass was 50.35%, and in the biochar it was in the range of 83.43-86.05%. The analysis showed that there were no significant statistical differences in the total carbon content in the biochar obtained at different pyrolysis times (2-10 min). After pyrolysis, there was a marked relative increase in the total carbon content: for the apricot seeds, it reached a maximum of 58.96%, and for the cornelian cherry seeds it reached a value of 70.93% (10 min of pyrolysis) (Table 5). A study conducted by Janković *et al.* (2019) on apricot seed shells showed that the biochar obtained by carbonisation has high porosity and high specific surface area, making it an effective material for the production of activated carbon. Biochar from apricot seed shells, in addition to its high carbon content, also exhibits properties that allow it to adsorb toxic substances from water, thanks to its structure and hydrophobic surface. In the case of cornelian cherry seeds, biochar that achieves



a) b) c) d) e) f)

Fig. 2. Apricot seeds and prepared biochar: a) no heat treatment; pyrolysis (min): b) 2, c) 4, d) 6, e) 8, f) 10.

a) b) c) d) e) f)

Fig. 3. Cornelian cherry seeds and prepared biochar: a) no thermal treatment; pyrolysis (min): b) 2, c) 4, d) 6, e) 8, f) 10.

higher carbon levels may have even better properties in the context of applications requiring high-carbon materials, such as activated carbon production (Fadhil, 2017). According to studies reported by Saletnik *et al.* (2016) and Kasera *et al.* (2022), biochar extracted from various types of biomass, including seeds, has been shown to have a positive effect on improving soil structure, increasing soil pH and sorption capacity. Biochar obtained from apricot and cornelian cherry seeds, thanks to their high carbon content and stable properties during pyrolysis, can find application in the production of fertilisers to improve soil quality and also as heavy metal sorbents (Saletnik *et al.*, 2016; Kasera *et al.*, 2022). In contrast, the study conducted by Frišták *et al.* (2022) showed that biochar obtained from cherry seeds pyrolyzed at 500°C was characterised by a total carbon content of 74.41%, which indicated a significant increase compared to raw seeds (47.74%). In a study on the production of activated carbon from peach seeds, Hayashi *et al.* (2014) showed that the carbon content in the obtained material was high, which may suggest the potential of peach seeds as a raw material for the production of high-carbon materials. Cárdenas-Aguiar *et al.* (2024), who studied the effects of feedstock type, pyrolysis temperature, and reaction time on the physicochemical properties of biochar, reported that biomass with high lignin content, including wood and plant residues, yields pyrolysate with higher carbon content and better sorption properties.

In the case of the apricot seed biomass, the initial hydrogen content was 6.94%, while the hydrogen content in the biochar after the pyrolysis process was in the range of 2.74 -2.77%. The hydrogen content in the raw biomass was 6.19% in the case of the cornelian cherry seeds and varied after pyrolysis between 2.76 and 2.79% in the biochar. In both cases, there were no significant statistical differences in the hydrogen content between the biochar, regardless of the length of the pyrolysis process. Despite initial differences in the hydrogen content in the raw materials, the pyrolysis process led to an approximation of these values in the biochar obtained from both types of seeds. In the case of apricot seeds, the maximum decrease in hydrogen content was 60.55%, while in the case of the cornelian cherry seeds, the decrease was slightly smaller at 55.36%. These changes indicate that the pyrolysis process significantly reduces the hydrogen content in both materials (Table 5). According to Polish regulations contained in the Law on Renewable Energy Sources of February 20, 2015, biochar can be considered a renewable fuel, provided that certain quality standards are met. The hydrogen content in solid biofuels that does not exceed 5-7% by weight is in line with the requirements for biochar obtained from both apricot and cornelian cherry seeds. In addition, the low levels of nitrogen (<1-2%) in these materials make them suitable for use as fuels with low nitrogen oxide emissions, which is in line with environmental standards (Journal of Laws, 2015).

In the case of the non-thermally processed apricot seed biomass, the ash content was 0.82%, while its content in the biochar ranged from 2.91 to 3.79%. The highest ash content was determined in the A5 biochar, which was subjected to the longest pyrolysis time (10 min), suggesting that the length of the process has a significant impact on this parameter. A relative increase of 364.13% in the ash content compared to the starting material was also observed, demonstrating that the pyrolysis process leads to a significant concentration of minerals. A similar relative increase of 310.5% occurred in the case of the biochar obtained from the cornelian cherry, where the ash content in the untreated raw material was 0.92%, while in biochar it ranged from 2.99 to 3.78%. As with the apricot seeds, the pyrolysis time had a significant effect on the ash content (Table 5). The phenomenon of increased ash content after pyrolysis has also been reported in other studies. This effect is attributed to the concentration of mineral components as the organic fraction of biomass decomposes. For example, Song *et al.* (2023) observed that the ash content in biochar obtained from tropical crop residues increased with rising pyrolysis temperature, while Luo *et al.* (2024) reported a similar trend for straw biochar, where the ash fraction grew from 4.3 to 7.7% as the temperature increased. Saletnik *et al.* (2024) noted that the ash content in tobacco stems (residues from plantation) increased from 5.04% to a maximum of 9.55% after the pyrolysis process. The differences in the changes in the ash concentration may be due to the higher mineral content of the starting material as well as the increase in the pyrolysis time. These results are similar to those obtained in the present research, where the maximum ash content was 3.79%. Similar conclusions can be drawn from a study presented by Jelonek *et al.* (2018), who found that the ash content in hard coal ranges from 3.7 to 12.6%, depending on the seam and mine. Compared to traditional fossil fuels, biochar has much lower ash content, making it a greener alternative. The maximum ash content in biochar (3.79%) is close to the minimum ash content in hard coal (3.7%), suggesting that biochar may be an attractive alternative in terms of low ash waste. In addition, the process of biomass pyrolysis leads to a controlled increase in ash content, which can be beneficial in an industrial context, in applications that require materials with a certain mineral composition. The ash content in hard coal, on the other hand, is more difficult to control, as it results from natural geological processes and varying sedimentation conditions. Although the process of biomass pyrolysis leads to an increase in ash content, biochar has a much lower content of this component compared to traditional fossil fuels (Jelonek *et al.*, 2018).

The content of volatile substances in the apricot seeds was 80.17%, while their content in the biochar was in the range of 20.36-18.29%. On the other hand, in the case of the cornelian cherry seeds, the content of volatile substances was 77.28%, while their content in the biochar ranged from

20.73 to 19.42%. In both cases, no statistically significant differences in the volatile content were observed between the biochar obtained at different pyrolysis times (2-10 min), suggesting that the pyrolysis time in the specified range has no significant effect on this parameter. On the other hand, a statistically significant relative decrease in the volatile content was observed between the thermally untreated material and the biochar, with a maximum percentage difference of 77.22% for the apricot seeds and 74.88% for the cornelian cherry seeds (Table 5). Comparing the two types of biomass, it can be seen that apricot seeds and their biochar have a higher content of volatile substances than cornelian cherry seeds and their biochar. These differences may be due to the different chemical composition of the seeds of the two species. The volatile matter content in raw apricot kernel shells, as reported in the literature, was 73.84%, indicating a high potential for tar production during pyrolysis. This value is consistent with those reported for other herbaceous biomasses, such as red lentil hulls (74.73%) and broad bean husks (74.88%) (Manić *et al.*, 2020). The volatile matter content was shown to be less than 14% in biochar prepared from rape straw or sunflower and 22% in cherry wood biochar. These results may indicate differences in the chemical structure and composition of the starting biomass, especially with regard to cellulose, hemicellulose, and lignin content. In addition, the authors observed significant differences in volatile content as a function of temperature and pyrolysis time (Saletnik *et al.*, 2024).

3.2. Calorific value

Figure 4 presents the calorific value of the investigated biomass and biochar samples, which is one of the fundamental parameters for assessing energy efficiency.

Differences between average values marked with the same letters are not statistically significant at the level of $p \leq 0.05$ according to the Duncan test. The data were analysed separately for each type of materials.

The calorific value is a key indicator when evaluating the energy potential of different materials, as it allows comparison of their energy-generating capacity. The analysis of the calorific value of the apricot seeds showed that the raw material reached a level of 21.52 MJ kg^{-1}, while the biochar obtained after the pyrolysis process had values in the range of 30.62-31.27 MJ kg^{-1}. The lack of statistically significant differences between samples subjected to different pyrolysis durations (2-10 min) suggests that the length of the process in this range does not significantly affect the final energy value of the material. At the same time, there was a maximum relative 45.27% increase in the calorific value compared to the raw biomass, confirming the efficiency of the pyrolysis process in an energy context. Similar correlations were observed for the cornelian cherry seeds. The raw biomass reached a calorific value of 18.95 MJ kg^{-1}, while the biochar obtained by pyrolysis was in the range of 30.43-31.26 MJ kg^{-1} (Fig. 4). Again, there was no effect of the process duration on the final energy parameters. The 64.95% relative increase in the calorific value indicates the high efficiency of the transformation of this type of biomass into an energy-efficient material. It is also worth noting that apricot seeds have a higher calorific value in the raw state compared to cornelian cherry seeds, which may argue for their greater suitability as a direct biofuel.

The results obtained are reflected in the literature. For instance, Zhang *et al.* (2021) studied the effects of torrefaction on apricot shells and found that the calorific value increased from 18.25 to 24.22 MJ kg^{-1} at 280°C, indicating an improvement in energy potential. In turn, Rzeźnik *et al.* (2016) determined the calorific value of cherry seed shells at 20.59 MJ kg^{-1}, which is lower compared to the biomass analysed. For example, a study conducted by Sànchez *et al.* (2009) showed that the pyrolysis process increased the calorific value of rapeseed from 15.3 to 23.4 MJ kg^{-1}, but this value was significantly lower than the value determined for the biochar from apricot or cornelian cherry seeds in the present study. These results make it possible to claim that

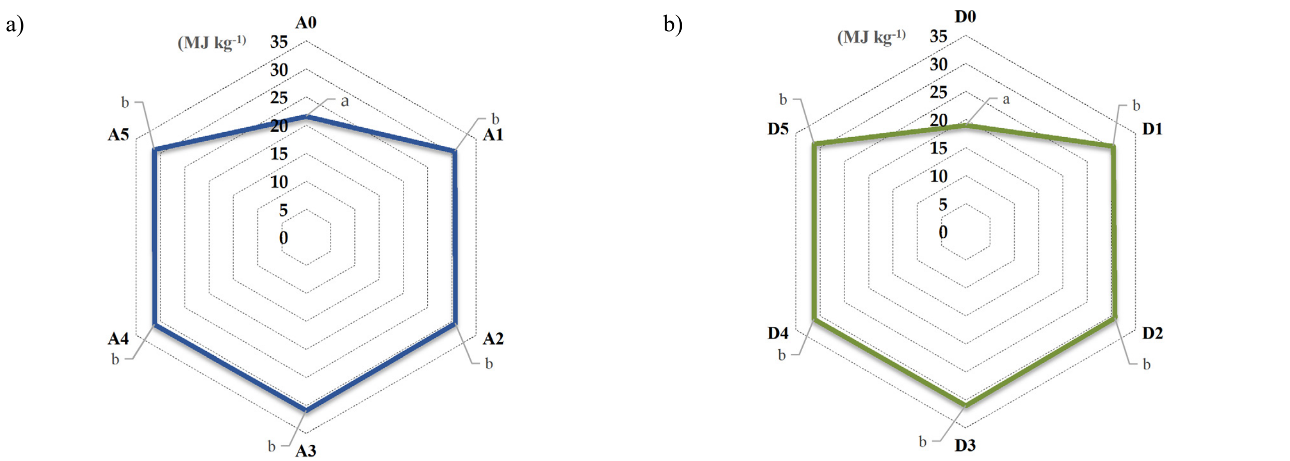


Fig. 4. Calorific value of seeds and biochar obtained from the following materials: a) apricot (*Prunus armeniaca* L.), b) cornelian cherry (*Cornus mas* L.).

the obtained material has a calorific value comparable to that of classical fossil fuels, such as hard coal, whose calorific value is in the range of 20-30 MJ kg^{-1} (Fabiańska *et al.*, 2013). The increase in the calorific value of biochar is a result of the increase in carbon content and the reduction in volatile organic compounds and moisture that occurs during pyrolysis. Such a process not only improves the material's energy properties, but also enhances its chemical stability and resistance to biodegradation, which is important for storage and transportation. For biochar obtained from different types of fruit seeds, calorific values can show variability depending on the type of raw material and pyrolysis conditions. Such differences may be due to the varying content of organic matter in the initial raw material and differences in the chemical structure of different fruit species (Saletnik *et al.*, 2021).

3.3. Emissions of CO, NO_x, and SO_2

The analysis of emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) during the combustion of the apricot and cornelian cherry seeds and the biochar produced from them showed significant differences between the raw biomass and the materials pyrolyzed at 500°C (Fig. 5).

Gas emissions were significantly higher for the raw seeds compared to the biochar. The apricot seeds showed the highest levels of CO (2631.21 g kg^{-1}), (NO_x) (159.31 g kg^{-1}), and SO_2 (92.43 g kg^{-1}). In the case of the cornelian cherry seeds, the analogous values were 2479.57 g kg^{-1} (CO), 79.44 g kg^{-1} (NO_x), and 90.11 g kg^{-1} (SO_2), respectively. The use of pyrolysis had a favourable effect on the emission profile of both types of biomass. Regardless of the process time used, sulphur dioxide emissions were completely eliminated for all biochar samples. This indicates that the sulphur content is effectively reduced during the pyrolysis process. In addition, both CO and NO_x emissions in the pyrolysate steadily decreased, showing a positive correlation with the increase in the duration of thermal processing. For the biochar obtained from the apricot seeds, carbon monoxide emissions decreased from 790.11 (pyrolysis time: 2 min) to 679.55 g kg^{-1} (10 min), while nitrogen oxide emissions were reduced from 61.19 to 44.21 g kg^{-1}. Even lower values were recorded for the biochar obtained from the cornelian cherry seeds – CO decreased from 711.23 to 598.25 g kg^{-1} and NO from 79.44 to 4.22 g kg^{-1} (Fig. 5). These differences may be due to the different chemical composition of the two raw materials, including the lower nitrogen content in the cornelian cherry seeds, which in turn may translate into a different emission profile after pyrolysis. Particularly significant seems to be the complete absence of SO_2 emissions during the combustion of all types of prepared biochar (regardless of the time of the pyrolysis process). Extending the pyrolysis process time for the preparation of biochar has significantly reduced CO and NO_x emissions during its use as a biofuel. The results of these analyses are in line with numerous reports in the literature indicating a significant difference in emissions following prior thermochemical treatment of biomass. According to Nelissen *et al.* (2014), pyrolysates produced at higher temperatures are characterised by a lower content of volatile organic compounds, which can contribute to lower CO emissions during the combustion process. As reported by Zhong *et al.* (2023), a longer pyrolysis process time leads to a more stable biochar structure, which may result in a better emission profile. Pyrolysates produced above 400°C generally have low sulphur content, resulting in limited SO_2 emissions (Ahmad *et al.*, 2014; Shen *et al.*, 2015; Yuan *et al.*, 2011). Nitrogen content in the feedstock strongly influences NO_x emissions during combustion (Sethuraman *et al.*, 2011), whereas coal can produce NO_x concentrations exceeding 700 ppm (Sher *et al.*, 2020). These findings highlight that thermal pretreatment of biomass can effectively reduce harmful gas emissions. Similar quantitative relationships were recorded for sulphur dioxide emissions: the value for coal was 593 ppm, for untreated beech wood 13.47 ppm, while for beech biomass after torrefaction it was in the range of 1.07-1.98 ppm. The authors report that replacing some of the coal with torrefied biomass in the combustion process significantly affects the

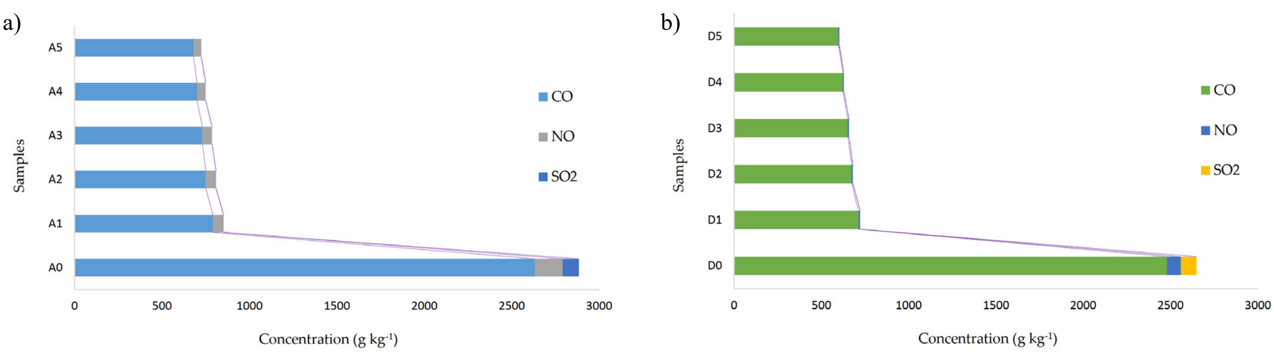


Fig. 5. Comparison of emission parameters of seeds and biochar obtained from the following materials: a) apricot (*Prunus armeniaca* L.); (b) cornelian cherry (*Cornus mas* L.).

exhaust emission profile. Reductions of about 30% in nitrogen oxides and about 50% in emissions of sulphur oxides, compared to burning pure coal, have been observed (Sher *et al.*, 2020). Juszczak (2014), on the other hand, reports that the concentration of CO during the combustion of softwood pellets can be in a wide range, *i.e.* from 180 to 3 806 mg m^3 for 10% O_2 content in flue gas, depending on how the fuel is fed. The author indicates that not only the type of material but also the control of the process, taking into account dynamic changes in combustion and the appropriately regulated supply of air and fuel, influence the profile of gas emissions.

4. CONCLUSIONS

In light of the circular economy principles, the integration of thermochemical technologies, such as pyrolysis, into agri-food waste management is particularly important. The use of fruit seeds as a raw material for biochar production demonstrates effective biomass valorisation, enabling energy recovery, emission reduction, and waste minimisation. Transforming residues into value-added products can support sustainable development goals and EU climate neutrality strategies. Increasing environmental demands and pressure to decarbonise energy sectors further justify research on the scalability of such solutions. The main conclusions from the analyses are summarised as follows:

High energy potential: The biochar obtained from the apricot and cornelian cherry seeds reached average calorific values of approximately 30.9 MJ kg^{-1}, showing a significant relative increase compared to the raw seeds.

Effect of pyrolysis time: No significant differences in the calorific value were observed for pyrolysis durations between 2 and 10 min, indicating that energy content is largely independent of the residence time in this range.

Ash and volatile matter: The ash content increased with pyrolysis duration (up to 3.8%), while the volatile matter significantly decreased, confirming the effectiveness of thermal processing.

Carbon content: The total carbon content in the biochar was high (84-85%), reflecting efficient conversion of biomass into stable carbon-rich material.

Environmental benefits: The emissions of CO, NO_x, and SO_2 were substantially reduced in the biochar compared to the raw seeds, with SO_2 completely eliminated. Longer pyrolysis durations tended to further decrease CO and NO_x emissions.

Practical implications: Biochar from fruit seeds can serve as a sustainable feedstock for biofuel production. Effective transformation of fruit processing residues requires appropriate production and quality frameworks to support circular economy goals and sustainable development.

Conflicts of Interest: The Authors do not declare any conflict of interest.

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