

Effect of Origin on the Chemical Contents, Including Heavy Metals, in Pellets Made from Eastern Beech Wood

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Wood pellets, which are regarded as a sustainable and nature-friendly energy source, occupy an important place in biomass production, and global pellet production is constantly increasing. Pellet quality varies significantly according to the structural properties of the wood used as raw material, and the wood structure is the most important factor that determines the quality of the pellet. Numerous studies have been conducted on the quality of pellets produced from various raw materials. Although different origins of the same species can significantly affect pellet quality, the study on this subject is very limited. C, O, N and H contents, pH and heavy metal contents of pellets produced from *Fagus orientalis* wood obtained from 12 different origins were compared. As a result of the study, it was determined that there was a statistically significant difference between the pellets produced from wood obtained from different origins in terms of Cd and Ni concentrations, as well as oxygen, nitrogen, and hydrogen contents. The results indicate that the highest quality pellets among the origins studied were those produced from beeches from the Andırın, Yazıcık, Gökçebey, and Kalkım origins, which had both low heavy metal content and low oxygen, nitrogen, and hydrogen contents. It is proposed that these origins be given priority in pellet production.

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INTRODUCTION

Over the last century, developments in industry and technology have brought about radical changes in nearly every field worldwide. In this process, the rapid development in production processes has led to the concentration of the population in urban areas. Urbanization has become a global phenomenon (Bayraktar *et al.* 2024; Dogan *et al.* 2024). The raw material needed by industry is extracted from the underground deposits and released into nature, making the environment and especially air pollution a global problem (Özel *et al.* 2024; Sevik *et al.* 2025). In this process, the use of fossil fuels to meet the energy needs in the industrial sector has also disrupted the gas balance in the atmosphere, leading to global climate change (Arıcak *et al.* 2024; Isinkaralar *et al.* 2024). As of today, urbanization and global climate change are widely acknowledged as irreversible problems worldwide (Cantürk *et al.* 2024; Gur *et al.* 2024).

Although global climate change is considered irreversible, sectoral studies are being carried out in almost every field to mitigate its effects. One of the most significant factors contributing to global climate change is the growing demand for energy from fossil

fuels. However, increases in oil and natural gas prices, the gradual depletion of fossil fuel reserves, and growing environmental concerns draw attention to renewable energy sources even more (Kamperidou 2022).

As of 2018, about 20% of the world's total energy consumption was generated from renewable sources. Among renewable energy sources, biomass ranks first, with a global share of 9% (Wei *et al.* 2024). Wood biomass is also used extensively as a fuel, and it can be used directly or after pre-processing, such as grinding, drying, and compression, making it a sustainable fuel (Szewczyk and Polowy 2020). Condensed biomass fuels provide significant advantages in terms of transportation, storage, and sales (Rodrigues *et al.* 2021). Due to this, the use and production of pellets is constantly increasing. Global total biomass pellet production reached 25.6 million tons in 2015, and global total pellet trade reached 16.5 million tons in 2016. Bioenergy is considered a promising alternative to fossil fuels (Wei *et al.* 2024).

Renewable fuels are also important because of their low environmental impact (So and Eberhardt 2018). Pollution, notably air pollution, is one of the primary problems in nearly all countries worldwide. Air pollution has reached such serious levels that, according to World Health Organization (WHO) reports, 99% of the world's population is exposed to poor air quality, resulting in approximately 6.7 million premature deaths per year (Ghoma *et al.* 2023; Öztürk Pulatoğlu *et al.* 2025). Raw materials and fossil fuels used in industry, mining activities, vehicles, and fuels used for heating in urban areas are shown as the primary sources of this pollution (Istanbullu *et al.* 2023; Kuzmina *et al.* 2023; Koç *et al.* 2025).

Therefore, the demand and production of pellets are constantly increasing because they are renewable, easy to produce, provide economic support to people living in rural areas, and are much more environmentally friendly than fossil fuels (So and Eberhardt 2018; Valverde *et al.* 2021; Latterini *et al.* 2022). However, the quality of the pellets plays a decisive role in this area (De Souza *et al.* 2021). Density, mechanical stability, hydrophobicity, and energy content are the major properties that control the quality of fuel pellets. These properties are influenced by biomass type, pretreatments, formulations such as binders, additives and lubricants, densification methods and conditions including temperature, pressure and relaxation time (Sarker *et al.* 2023). Pellet quality can be assessed by considering factors such as calorific value, ash content, mechanical durability, bulk density, moisture content, dimensions, color, and surface roughness (Kamperidou 2022). One parameter that determines pellet quality is heavy metal content, which is inversely proportional to pellet quality (Latterini *et al.* 2022). As a result, numerous studies have been conducted on the heavy metal content in pellets (Pazalja *et al.* 2021; Kim *et al.* 2022; Song *et al.* 2024).

However, these studies generally focus on the heavy metal content of pellets produced from agricultural waste, and it is known that pellets obtained from agricultural waste contain extremely high levels of heavy metals (Spinelli *et al.* 2018; Latterini *et al.* 2022). On the other hand, the number of studies on the quality of pellets produced from forest trees are very low (Latterini *et al.* 2022). There are almost no studies to determine the heavy metal content of pellets produced from different origins of the same tree species. However, wood structure is one of the most important factors affecting pellet quality and chemical content. Wood structure, like all other phenotypic characters, depends on the characteristics of origin and therefore the place of growth (Yigit *et al.* 2021; Tandogan *et al.* 2023; Özdikmenli *et al.* 2024), and it is even known that it can change depending on the genetic structure in individuals growing up in the same ecological conditions (Yigit *et*

al. 2023; Hrivnak *et al.* 2024). Therefore, this study aimed to determine the change in heavy metal contents, which is one of the most important quality indicators of wood-based pellets obtained from various origins.

METHOD

Within the scope of the study, pellets produced from beech (*Fagus orientalis* Lipsky) wood obtained from 12 different origins were used. The origins of beech wood in the study are given in Table 1.

Table 1. Origins of Beech Wood Pellets

Population No.	City	County
1	Adapazarı	Karasu
2	Balıkesir	Dursunbey
3	Bartın	Kumluca
4	Bursa	İnegöl
5	Çanakkale	Kalkım
6	Düzce	Yığılca
7	Kahramanmaraş	Andırın
8	Karabük	Yenice
9	Ordu	Akkuş
10	Zonguldak	Devrek
11	Zonguldak	Gökçebey
12	Zonguldak	Yazıcık

Beech is one of the most important tree species for Turkey's forests. Eastern beech (*Fagus orientalis* Lipsky) constitutes approximately 8.5% of Turkey's forests, with a distribution area of approximately 1.9 million ha (Özel *et al.* 2021). Approximately 70 thousand ha of beech forests are rejuvenated every year in Turkey, and 2.2 million m³ of yield is taken during these rejuvenation works. In this respect, the amount of wood produced from beech forests constitutes approximately one-fifth of the total wood taken from all trees in Turkey (Bircan 2008).

The production process of the pellets used in the study includes collecting beech sawdust, drying (reducing the sawdust's moisture content to 10-15% in ovens or drying machines), grinding, pressing under high pressure, and cooling. Beech pellets, especially oven-dried raw material, which has a high density and high calories (300% more efficient), are pressed at 120 to 130°C, then cooled and screened, and packed in 18 to 25 kg sacks. Beech (*Fagus*) pellets are high-quality biofuels with a high calorific value and long combustion time, thanks to their high density (680 to 720 kg/m³) and hard structure. They are generally hardwood pellets with a light color, a homogeneous structure, and low ash and moisture content, providing an environmentally friendly and efficient heating solution. However, the structure of beech pellets varies depending on several factors, primarily the raw material used. In this study, the aim was to determine this change across different raw material sources.

Within the scope of the study, pellets produced from beech trees obtained from the locations shown in Table 1 were procured. The study was carried out on pellets produced from these locations. This was because the raw materials for beech pellets produced in Turkey are largely supplied from these regions. There are beech forests with a wide and dominant distribution in these locations, and they differ in terms of ecological structure.

Then, the heavy metal contents of these pellets were determined first. While determining the heavy metal concentrations, the samples were dissected and placed in glass petri dishes, with the mouths of the petri dishes left open for 15 days to air-dry. The samples were then dried in an oven at 45 °C for one week. About 0.5 g was taken from the dried samples, 6 mL of 65% HNO₃ and 2 mL of 30% H₂O₂ were added, and the samples were placed in the microwave oven designed for the analyses in question. The sample solutions thus obtained were transferred into balloon cells and made up to 50 mL with ultrapure water. The prepared samples were analyzed using the ICP-OES device, and the obtained values were multiplied by the dilution factor. The concentrations of Cr, Cd, As, Ni, Cu, Pb, and Zn contents were then calculated. Such an analysis approach has been frequently used in recent studies on this subject (Isinkaralar *et al.* 2023; Sevik *et al.* 2024; Gültekin *et al.* 2025).

According to EN ISO 16948 (2015), ten capsules of 1 mg each were placed into a CHNS-O Costech ECS 4010 (Cernusco sul Naviglio, Italy) combustion oven to analyze the carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) contents. The pH analysis on the pellets was also performed. For pH measurement, 0.5 g of pellets was weighed and finely shredded, 50 mL of pure water was added, and the mixture was left for 48 hours before measurement with a pH meter. pH measurements were made 10 times for each sample, and the average values were calculated. This method is frequently used in similar studies (Mohammadi *et al.* 2022). The effect of the parameters subject to the study on pellet quality is given in Table 2.

Table 2. List of Investigated Parameters and Influence of Single Parameter on Pellet Quality (Latterini *et al.* 2022)

Parameter	Influence on Pellet Quality
Heavy metal content (mg/kg)	-
Carbon content (%)	+
Oxygen content (%)	-
Nitrogen content (%)	-
Hydrogen content (%)	-
pH	0

The symbol “+” indicates that a high parameter value had a positive influence on pellet quality, whereas the symbol “-“ indicates that a high parameter value had a negative influence on pellet quality.

The data obtained were evaluated using the SPSS package program, and the Duncan test was applied to data for factors with statistically significant differences at a 95% confidence level ($P < 0.05$) *via* analysis of variance. The data obtained were simplified, tabulated, and interpreted.

RESULTS

The results of the analysis of variance and Duncan test regarding the change of heavy metal concentrations in the pellets subject to the study are given in Table 3.

Table 3. Change of Heavy Metal Concentrations

Origin	Cr (mg/kg)	Cd (mg/kg)	As (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
1	0.209	0.194cd	0.0067	1.406bcd	0.695	0.064	12.007
2	0.207	0.190cd	0.0070	1.365abc	0.701	0.064	11.702
3	0.204	0.188cd	0.0063	1.35abc	0.672	0.063	11.568
4	0.211	0.196d	0.0070	1.432cd	0.701	0.064	12.206
5	0.203	0.185bc	0.0070	1.336abc	0.660	0.064	11.246
6	0.206	0.185bc	0.0067	1.346abc	0.655	0.064	11.359
7	0.200	0.168a	0.0070	1.290a	0.647	0.062	10.780
8	0.209	0.193cd	0.0070	1.372abcd	0.679	0.064	11.797
9	0.214	0.198d	0.0070	1.459d	0.711	0.064	12.274
10	0.208	0.187bcd	0.0070	1.347abc	0.664	0.063	11.362
11	0.202	0.177ab	0.0067	1.312ab	0.648	0.063	10.890
12	0.201	0.168a	0.0070	1.302a	0.661	0.063	10,839
F-value	0.312ns	9.525***	1.341ns	3.164**	0.546ns	2.166ns	0.908ns

Upon examining the table values, it is evident that the changes in Cd and Ni, the elements under study, based on origin, were statistically significant. The lowest concentrations of Cd and Ni were obtained at origins 7, 11, and 12, while the highest concentrations of Cd and Ni were obtained at origins 9, 4, and 1. The mean values of C, O, N, and H elemental contents, as well as pH levels, in the pellets subjected to the study, analysis of variance, and Duncan test results are presented in Table 4.

Table 4. Elemental Contents of C, O, N, H, and pH Levels in Pellets

Origin	C-Content (%)	O-Content (%)	N-Content (%)	H-Content (%)	pH
1	42.017	41.880hi	4.277e	0.520de	3.7
2	41.237	41.403fg	4.043d	0.487cd	3.6
3	41.187	41.133ef	3.967d	0.48bcd	3.7
4	42.467	42.247i	4.497f	0.537e	3.7
5	40.737	39.203c	3.473abc	0.437ab	3.4
6	40.867	40.207d	3.593c	0.45abc	3.8
7	38.857	37.430a	3.287a	0.420a	3.2
8	41.337	41.593gh	4.130de	0.517de	3.6
9	43.637	43.137j	4.650f	0.537e	3.8
10	41.183	40.877e	3.620c	0.463abc	3.5
11	40,387	39.260c	3.530bc	0.433ab	3.4
12	39.580	38.230b	3.357ab	0.427a	3.2
F Value	0.514ns	150.872***	48.160***	8.060***	1.390ns

As shown in the table, the change in C-amount and pH level based on origin in the pellets studied was not statistically significant, whereas the changes in O, N, and H amounts based on origin were statistically significant. When the values are examined, it is seen that the lowest values in all three elements were obtained in origins 5, 7, 11, and 12. The highest values were obtained at origins 1, 4, and 9.

DISCUSSION

The quality and composition of wood pellets were significantly influenced by the tree species used as feedstock. This study, consistent with prior research (Latterini *et al.* 2022), confirmed that species such as *Eucalyptus*, *Fagus sylvatica* (beech), and *Pinus radiata* tend to yield higher-quality pellets. Notably, beech pellets frequently meet stringent A1 or A2 quality standards. This superior quality extends to their heavy metal profile. The heavy metal concentrations (Cr, Cd, As, Ni, Cu, Pb, Zn) measured in the studied beech pellets were not only generally lower than those reported for pellets from mixed or other wood species (Civitarese *et al.* 2023) but were also often lower than values found in beech pellets from other studies (Pazalja *et al.* 2021; Latterini *et al.* 2022). This suggests that specific growth conditions or processing methods can lead to a favorable low heavy metal load.

The finding that Cd and Ni concentrations varied significantly based on geographic origin is critically important. Both metals are recognized as highly hazardous, carcinogenic, and are listed as priority pollutants by agencies including the EPA and ATSDR (Işinkaralar *et al.* 2022; Key *et al.* 2022). Their threat is amplified when inhaled, as occurs when metals in pellets are released during combustion (Ghoma *et al.* 2022; Koç *et al.* 2025). This link between feedstock origin, metal content, and subsequent airborne emission during use underscores a major environmental health consideration for pellet fuel. Among the populations with the highest Ni and Cd concentrations, Adapazarı Karasu, Bursa İnegöl, Karabük Yenice, and Ordu Akkuş stand out, especially given their proximity to industrial zones. Heavy metals are found in soils in certain proportions and can naturally be released into the air and soil. However, studies show that anthropogenic releases of heavy metals in air and soil concentrations are much higher (Mutlu and Aydın Uncuosmanoglu 2018; Chowdhury and Rahman 2024). Traffic, urban areas, and mining activities, especially industrial activities, cause a significant increase in heavy metal pollution in the air and soil, and, as a result, plants growing in these regions accumulate large quantities (Kulac *et al.* 2025; Sevik *et al.* 2026). In the studies, it was determined that the Cd concentration was very high in the vicinity of the cement factory, recycling facility, and iron and steel factory, and the Ni concentration was very high in the vicinity of the highway side, recycling facility, and yeast factory (Dışbudak 2024; Ash *et al.* 2026). It is noteworthy that these facilities are located in the regions where Cd and Ni concentrations were determined to be high in the present study. In many studies, it is reported that heavy metals adhere to particulate matter after leaving their sources and are transported by wind, resulting in high heavy metal concentrations in plants grown in areas close to polluting sources (Ismail *et al.* 2026; Demirci *et al.* 2026). Therefore, the high levels of Cd and Ni concentrations in some populations in the study can be explained by the presence of industrial facilities and highways in these regions. The fact that the pollution with the lowest content is in Zonguldak supports this inference. The population of Zonguldak is located on the slopes of mountain ranges facing the Black Sea, which cuts off their

connection to industrial facilities in the country's interior. In this case, it is very difficult for heavy metal pollution to reach these populations.

Interestingly, trees themselves are potent tools for phytoremediation, capable of accumulating heavy metals, particularly in woody biomass (Key *et al.* 2023; Şevik *et al.* 2024). This accumulation potential varies by species and individual, influenced by environmental conditions (Erdem *et al.* 2024). Consequently, wood harvested from polluted areas may contain elevated metal levels, creating a paradox where a natural fuel source becomes a vector for air pollution upon combustion. This highlights the necessity of considering the provenance of pellet feedstock.

Furthermore, the study revealed significant variations in elemental composition (O, N, H) based on origin. The highest values for these parameters were observed in populations such as Bursa İnegöl and Karabük Yenice, while the lowest were observed in the Kahramanmaraş Andırın populations. This result is quite remarkable because while beech populations in Turkey extend along the Black Sea strip in the north of the country, there are beech populations in a much more limited area around Kahramanmaraş (Ayan *et al.* 2022; Ertürk *et al.* 2024). As is well known, the phenotypic characters of plants are shaped by environmental conditions and genetic structure, and climate is the most important environmental parameter (Cetin *et al.* 2026; Somaly and Sokra 2026). The population of Kahramanmaraş Andırın, whose C, H, N, and O contents were determined to be at the lowest level, is both far from the northern regions where the species is densely distributed and significantly different in climate. Therefore, this content difference can be related to climate parameters. The measured oxygen and hydrogen percentages were relatively low, while nitrogen content was notably higher compared to values reported by Latterini *et al.* (2022). These differences can affect combustion efficiency, emissions (particularly NO_x from nitrogen), and overall fuel quality, indicating that origin affects not only contaminants but also fundamental fuel properties. Future research should investigate the specific soil and atmospheric factors driving these variations in both heavy metals and elemental composition to enable better sourcing and quality control.

As a result of the study, it was determined that the heavy metal content of the pellets can vary significantly depending on the origins of the wood from which the pellets are produced. In this case, it turns out that to produce quality pellets, it is necessary to select the appropriate tree species and the appropriate origin. According to the study's results, it was determined that the highest quality pellets among the origins studied were those produced from beeches from Andırın, Yazıcık, Gökçebey, and Kalkım, which had both low heavy metal content and low oxygen, nitrogen, and hydrogen content. It is proposed that these origins be given priority in pellet production.

Moreover, it was determined that the concentrations of heavy metals, such as Cd and Ni, which are highly hazardous to human health, carcinogenic, and fatal even at low concentrations, vary significantly based on their origin. These heavy metals can be particularly hazardous if they enter the human body through the respiratory tract. Since pellets are also used for heating, they are burned, and the heavy metals in their bodies can mix with the air, primarily affecting the people in their immediate vicinity. Therefore, people should be made aware of the risks associated with using pellets, and the use of masks should be ensured for individuals who spend a long time in these environments. In a study, the flue gas emissions of two different beech pellets, which were determined to have elemental composition mass ratios of 48.3 to 48.5% carbon, 6% hydrogen, 0.12 to 0.2% nitrogen, 0.02% sulfur, undetectable chlorine, and ash content in the range of 0.46 to 1.2%, were determined. As a result of the study, O₂ was measured between 14.4 and 15.4%,

CO₂ 5.30 to 6.35%, CO 815 to 1150 mL/m³, NO_x 63.9 to 93.7 mL/m³, SO₂ 1.5 to 1.6 mL/m³, and TOC 11.5 to 26.4 mL/m³ in the flue gas of an automatic residential pellet stove (Matijašević *et al.* 2024). In studies conducted on different pellets, NO₂ emissions were found to be 95 ± 28 mg/MJ in spruce wood pellets, 103 ± 28 mg/MJ in willow wood pellets, 282 ± 74 mg/MJ in willow bark pellets, 82 ± 16 mg/MJ in pine wood pellets, 131 ± 28 mg/MJ in pine bark pellets, and 147 ± 30 mg/MJ in oak wood pellets (Sippula *et al.* 2007; Perez-Jimenez 2015; Schmidt *et al.* 2018). According to these values, it can be said that beech pellets have higher NO₂ release values than spruce, willow, and pine wood pellets.

CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

1. The wood species used for pellet production is a primary determinant of pellet quality, with beech (*Fagus sylvatica*) consistently yielding high-quality fuel.
2. Beech pellets generally contain lower concentrations of hazardous heavy metals (Cr, Cd, As, Ni, Cu, Pb, Zn) compared to pellets produced from other or mixed wood species.
3. The geographic origin of the wood feedstock causes statistically significant variation in the concentration of specific, highly hazardous heavy metals, notably cadmium (Cd) and nickel (Ni).
4. The elemental composition (oxygen, nitrogen, and hydrogen content) of pellets is also significantly influenced by the origin of the raw wood material.
5. The combustion of pellets releases inherent heavy metals into the air, meaning that feedstock origin directly impacts potential airborne emissions and associated human health risks during fuel use.
6. Considering both heavy metal contents and C, H, N, and O contents, it can be said that the most suitable populations for pellet production are the Kahramanmaraş Andırın population and Zonguldak Gökçebey and Yazıcık populations. It is recommended to select these populations as sources of raw materials for pellet production.

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