

Article

Energetic Features of Hardwood Pellet Evaluated by Effect Size Summarisation

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Abstract: High-quality pellets are typically produced from coniferous sawdust. However, achieving comparable quality from alternative feedstocks, such as broadleaf wood, often necessitates pre-treatments or additives. Yet, within the framework of small-scale pellet production, local forest enterprises may lack the resources for such treatments and usually produce pellets from the whole trees, including branches, leaves and tops. This can have an impact on the quality of the pellets obtained in this manner. To be classified as high-quality pellets (A1 class), the specific features of the pellet must be higher or fall below the thresholds specified in the EN ISO 17225 standard. In this study, we developed an alternative statistical approach to evaluate pellet quality in comparison to the constant thresholds reported in the technical standard. We applied such an approach to evaluate the quality of pellets produced from the broadleaved species common in the Mediterranean forestry, including European beech (*Fagus sylvatica* L.), Turkey oak (*Quercus cerris* L.), Eucalyptus (clone *Eucalyptus camaldulensis* × *C. bicostata*), and Poplar clone AF6. In particular, we focused on three variables that are generally the most troublesome for the production of high-quality pellets from the broadleaved species, namely bulk density, ash content, and lower heating value. We found that the beech pellets showed satisfactory bulk density (average effect size of -1.2 , with no statistical difference in comparison to the standard's threshold) and ash content (average effect size of about -5 and significantly lower than the standard's threshold), but the heating value was significantly lower than the threshold required by the standard (average effect size of about -3). Conversely, other investigated species exhibited notable deficiencies, with turkey oak pellets displaying acceptable heating values. We found a significant improvement in ash content and heating value with increasing stem age within the same species thus suggesting that material derived from thinning interventions might be preferable over coppice-derived biomass for high-quality pellet production. We suggest that future research on the topic should focus on investigating pellets produced from blends of beech and turkey oak biomass. We further recommend a wider application of the proposed statistical approach, considering that it is clear and easy to interpret, and allows for a statistical comparison of the obtained values against the requirements of the technical standard.

Keywords: broadleaf biomass; fuelwood; small-scale pellet production



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1. Introduction

Enhancing the production and utilisation of renewable energy is among the most important goals of the European Union [1,2]. Solid biomass currently represents the main source of renewable energy in Europe [3]; however, to achieve the target on energy independence, its use should continue to expand [4–6]. Nonetheless, there are several concerns which persist regarding the implementation of efficient biomass supply chains,

mostly as a consequence of the fact that biomass is characterised by a low bulk density, and it is generally scattered on the territory [7–9]. One of the most commonly applied solutions to overcome the problem of the low bulk density of biomass is pelletisation [10–12]. The great advantages of pellets in comparison to other forms of solid biomass are reflected in the impressive growth of pellet production, which has been occurring in the last years, mostly in Central and Eastern Europe [3]. Mediterranean countries, particularly Italy, heavily rely on extensive pellet imports to satisfy the requests of the internal market [13,14].

Pellets are primarily produced from the residues of softwood species, predominantly sawdust [15]. Softwood sawdust is the perfect substrate for pelletisation, considering that it is an unprocessed residue, and that even small traces of pollutants can be removed by debarking and washing the logs before sawing [16]. However, countries that have a forestry system which is less reliant on softwood may face some challenges in producing high-quality pellets. The growing demand for wood pellets and the limited supply of sawmill residues have sparked a great deal of interest in exploring the use of alternative sources [17].

Just as any other biomass supply chains, pellet production can be done on a small scale or industrial basis. To minimise transportation expenses and environmental issues, the industrial manufacturing of pellets necessitates large quantities of readily available feedstocks concentrated in a small geographical area [18,19]. However, recent research has shown how crucial it is to start small-scale pellet manufacture using local raw materials from one or a small number of producers [20]. Small-scale pellet production in rural locations can further help local small agriculture and forestry businesses by increasing their income [21,22].

It is important to underline that high-value pellets are frequently produced on an industrial scale from pure sawdust [23], and other processing stages including pre-treatment and the inclusion of binders are also used [15]. In contrast, pellets made from different feedstocks that contain a significant amount of bark or leaves could result in worse quality [24,25]. Small farmers, owners of sawmills, or other forest enterprises that produce pellets on a small scale cannot afford to further invest time, energy, and financial resources into pre-treating the biomass [26]. Therefore, in the case of small-scale pellet production in the Mediterranean area, the use of a poor-quality feedstock such as hardwood with the presence of bark and leaves is often the only affordable solution. The main issues regarding fuel quality related to the production of pellet from such kind of raw materials are associated to decreased bulk density and heating value, as well as increased ash content [27].

At the international level, pellet quality is assessed according to the standard EN ISO 17225. This standard was released in 2014 and replaced the previous EN 14961. Within EN ISO 17225, the standard EN ISO 17225-1 regards the general quality requirements for pellets, while EN ISO 17225-2 is about wood pellets for both residential and commercial usage, and EN ISO 17225-6 regulates non-woody pellets. Essentially, the standard assigns a quality class to the pellet based on various parameters. For instance, considering pellets for residential use, the top-quality class is A1, followed by A2 and B. The standard provides some threshold constant values for the various parameters, i.e., to be considered a class A1 pellets, the ash content should be $\leq 0.7\%$. This approach is valid for commercial purposes but has some drawbacks concerning the scientific evaluation of pellet quality. The commonly applied statistical analysis techniques, such as the analysis of variance (ANOVA), are constructed to compare different data distributions among others and not one distribution and a constant, as it is in the case of pellet quality standard. Hence, typically in scientific papers addressing pellet quality, there exists either a non-statistical comparison between the average values of the examined pellets and the standard value [28], or a statistical comparison among the data of various pellet types [11]. In both cases, however, the differences between the investigated pellet values and the values reported by the standard are not analysed through an inferential statistic approach.

In this study, we tried to address the above-mentioned issues by proposing an alternative statistical approach to evaluate the quality of pellets. Our aim was to develop an

approach for evaluating pellet quality that elucidates whether the difference between the values of a pellet type and the standard requirements is statistically significant. We applied this method to investigate the effects of different species and stem age on the quality of pellet produced from broadleaved species typical of the Central and Southern Italy forestry context, namely Turkey oak (*Quercus cerris* L.), European beech (*Fagus sylvatica* L.), poplar (*Populus nigra* L. × *Populus* × *Generosa* A.Henry–*Populus* × *Euroamericana* Moench.) and eucalyptus (clone *Eucalyptus camaldulensis* × *C. bicostata*), in an attempt to shed light on the potential combinations of species and management system, in terms of stem age, that can lead to the satisfaction of the quality standards for A1 class, according EN ISO 17225, concerning bulk density, lower heating value, and ash content.

2. Materials and Methods

2.1. Investigated Pellet Types

We considered four species largely present in Central and Southern Italy [29]. For each species, we focused on different management regimes (except for turkey oak) characterised by different stem age at harvesting. As a result, we obtained ten pellet types. The investigated pellet types are reported in Table 1.

Table 1. Investigated pellet types.

Species	Management	Stem Age	Acronym
Beech	Coppice	30	beech30
Beech	High forest	70	beech70
Turkey oak	Coppice	20	oak20
Turkey oak	Coppice	25	oak25
Eucalyptus	Short Rotation Coppice	3	euc3
Eucalyptus	Medium Rotation Coppice	6	euc6
Eucalyptus	Coppice	18	euc18
Poplar	Short Rotation Coppice	3	poplar3
Poplar	Medium Rotation Coppice	6	poplar6
Poplar	Coppice	9	poplar9

2.2. Pellet Preparation and Quality Assessment

All the investigated types were derived from harvesting interventions carried out with the whole tree system, therefore all the base materials for preparing the pellet contained a certain percentage of bark, branches, and leaves. Following chipping, the biomass was refined using a BL-100 shredder fitted with a grid with 6 mm holes. Following reduction, we placed the various biomass types in bins and occasionally exposed them to the sun to speed up the dehydration process until they reached the appropriate moisture level (about 10%). We then proceeded to pelletise the biomass. Pelletisation was carried out at two different sites with two different machines, a 4 kW Bianco Line (Cuneo, Italy) and a 5.5 kW Ceccato (San Giorgio delle Pertiche, Italy). It is worth highlighting that the methods and procedures for producing the pellets were exactly the same in both the sites, only the machine was different. In detail, we reported the technical data for the two pelletizers as follows: maximum production capacity of 60–70 kg/h; 6 mm flat die model for the production of pellets with a length of 30 mm (± 5 mm). Before production, the pelletizers were warmed up to an optimal temperature of 70 °C. Once the optimum temperature was reached, indicated by the outflow of durable pellets, the production of samples started. The production cycles were monitored by maintaining a variable temperature range between 60 and 100 °C.

For the evaluation of pellet quality, we focused on those parameters that generally represent the major challenges for producing high-quality pellets from feedstocks other than softwood sawdust, namely bulk density, lower heating value, and ash content. For all the parameters, we referred to the specific standards for their determination. Bulk density was assessed directly after the pellet production with a 0.005 m³ container, filled

and weighed with a 0.01 precision scale, and 50 replications per pellet type were carried out. Lower heating value was assessed by a calorimeter Anton Paar 6400 (Moline, IL, USA), and 50 measurements per pellet type were carried out. Ash content was assessed using a muffle furnace (Lenton EF11 8B, Hope Valley, UK) at 250 °C for one hour and at 550 °C for two hours; also, in this case, 50 measurements per pellet type were performed.

2.3. Data Analysis

The proposed statistical approach is based on the calculation and further summarisation of the effect size, namely the standardised mean difference expressed as Cohen's *d* [30], calculated as reported in Equation (1).

$$d = (M - C) / \text{St.Dev.} \quad (1)$$

where *M* is the average of the sample, *C* is the constant value to which we want to compare our sample, and St.Dev. is the standard deviation of the sample. A positive *d* value indicates that the mean is larger than the target value *C*. As a rule of thumb, *d* values of 0.5, 1.0, and 2.0 represent a “small”, “medium”, and “large” effect, respectively, while values higher than 10.0 represent a “very large” effect [31].

The formula of *d* was modified by replacing the mean of the sample with the individual measurements; in this way, we obtained 50 effect sizes (*d*) for any pellet type for any investigated variable. We used, as constant value *C*, the threshold reported in the standard for A1 quality pellets, specifically 0.7% for ash content, 600 kg m^{−3} for bulk density, and 16.5 MJ kg^{−1} for lower heating value.

After checking this dataset for normality with the Shapiro–Wilk test, the Linear Mixed-Effects Models (LMMs) fitted by Restricted Maximum Likelihood (REML) was used to calculate the 95% confidence intervals for the effect size and the influence on species, stem age, and pellet type. A mixed-effects approach was used considering that the production of pellets with two different machines could represent a source of data nesting. We therefore indicated in the model the machine used for pellet production (Bianco Line or Ceccato) as a random effect. We fitted an LMM for every single independent variable (bulk density, ash content and lower heating value), indicating the species and stem age as fixed effects with the lme4 [32] package in R 4.3.1 software [33]. Then, we further fitted LMM for every variable indicating the pellet type as fixed effect. We used the packages ggeffects [34] and emmeans [35] to calculate and visualise the marginal response and marginal means representing the mean values of each experimental treatment, assuming a constant level of all other predictors and no random effect (global estimate). Tukey's test was applied as a post hoc analysis to compare the effect sizes for species and pellet type.

This approach allowed us to simultaneously evaluate both the presence of statistically significant differences among the experimental treatments, and the significance of the differences of each treatment in comparison to the threshold value of the standard. It was necessary to verify whether the confidence intervals calculated by REML intersect with the 0 line. If the 95% confidence intervals for the effect size intersect the 0 line, it indicates that the difference from the standard is not significant, as the potential range of standardized mean difference includes 0. Conversely, if the confidence intervals do not intersect the 0 line, the difference is statistically significant. This method of interpreting results mirrors the approach used in any meta-analysis based on standardized mean differences [36–38].

3. Results

3.1. Pellet Bulk Density

LMMs revealed a statistically significant influence of species on bulk density (Figure 1A), whereas pellet age did not show a significant effect (Figure 1B). All species showed an average negative effect size but the confidence intervals for beech do overlap with the 0 line, indicating that the difference with the reference value reported in the standard is not significant (Figure 1A). On the contrary, confidence intervals for oak, poplar, and eucalyptus do not intersect with the 0 line, suggesting a significant difference with the

standard's threshold (Figure 1A). Regarding the outcomes of each pellet type, a positive effect size was detected only for pellets derived from 70-year-old beech and 6-year-old eucalyptus, although the difference with the standard threshold was significant only for the latter pellet type (confidence intervals not overlapping with the 0 line (Figure 1C)). For all the other pellet types, a negative effect size was detected with a significant difference in comparison to the threshold value of the standard (Figure 1C).

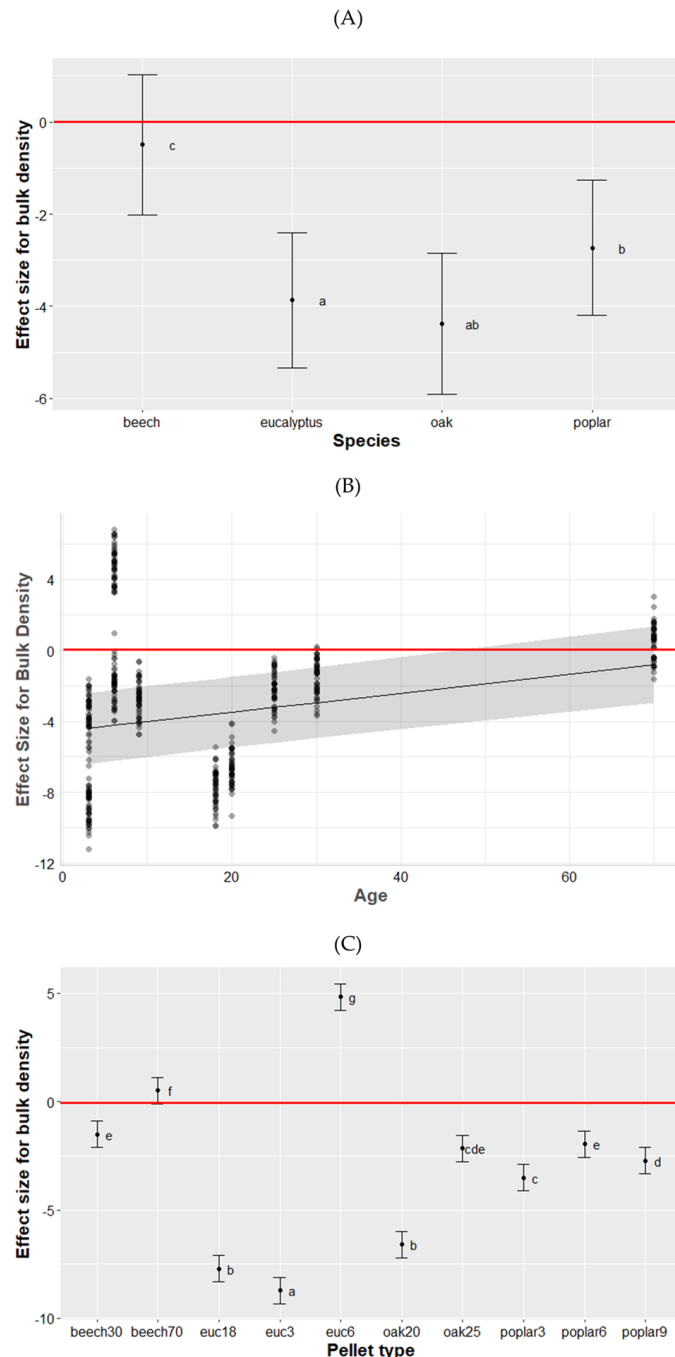


Figure 1. (A) Marginal effects of species on pellet bulk density. (B) Marginal effects of age on pellet bulk density. (C) Specific effect of pellet type on pellet bulk density. In (A,C), the black dots represent the average effect size, while the error bars represent the 95% confidence intervals. Statistically significant differences occur when the confidence intervals do not overlap with the 0 line (in red). In (B) the regression line is represented by the black line, and the grey ribbon represents the 95% confidence intervals. Different lowercase letters indicate homogeneous groups according to Tukey posteriori test.

3.2. Pellet Ash Content

LMM analysis revealed a significant effect on ash content of both species and age (Figure 2A,B). Average effect size was negative (ash content lower than the standard's threshold for A1 pellet) only for the beech pellet, with confidence intervals not overlapping the 0 line and thus suggesting a significant lower values of ash content in the beech pellets (Figure 2A). For oak, eucalyptus, and poplar, the average effect size was positive, with confidence intervals not intersecting with the 0 line and therefore showing a significantly higher ash content than the value of the standard for A1 pellets (Figure 2A); effect size results were particularly high for poplar pellets, which was characterised by a very high ash content (Figure 2A). Increasing the age of the feedstock for pellet manufacturing had a significant beneficial effect on ash content (Figure 2B). This means that, for the same species, increasing age leads to decreased ash content in the produced pellets.

The analysis for the specific pellet type confirmed that beech pellets showed the best ash content (Figure 2C). For both beech30 and beech70, the average effect size was negative, with a significant reduction in comparison to the threshold value for A1 class reported in the standard. In contrast, the average effect size for all the other typologies resulted in positive values and was significantly different from the standard's threshold (Figure 2C). A very strong effect size was detected for poplar 6, poplar 9, and euc6 pellets (Figure 2C). It is worth highlighting that the satisfactory results obtained for beech are probably related to the relatively old age of beech stems used for pellet production in comparison to the other species and their production cycles. For instance, in this case, for the beech wood introduced into the pelletizing process, a percentage of bark varying from 10% to 15% was found, while the other species show percentages varying from 19% to 23%.

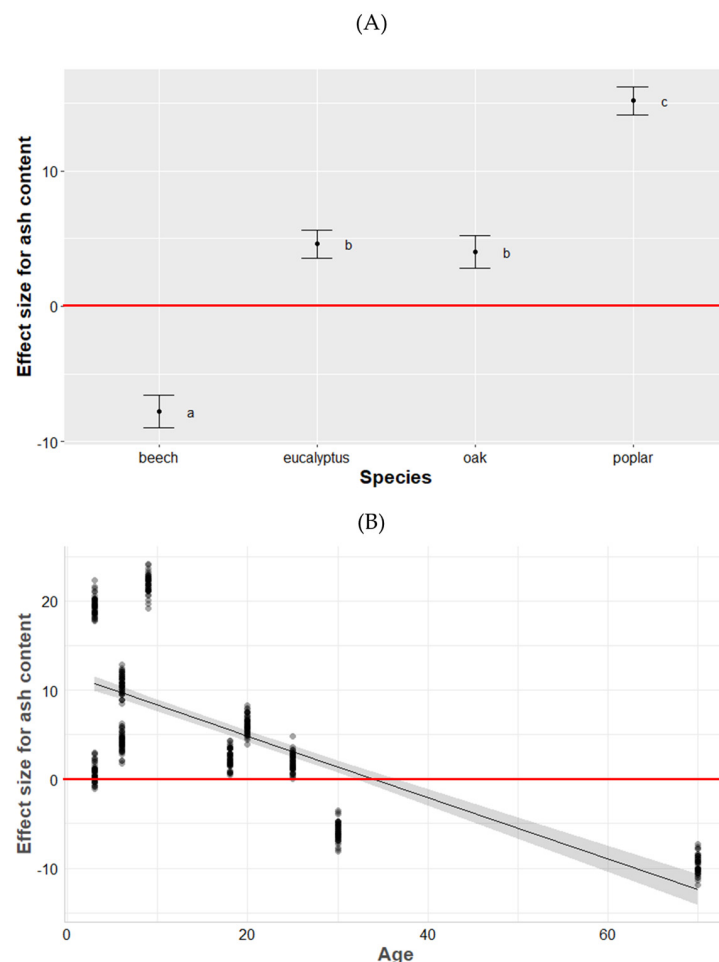


Figure 2. Cont.

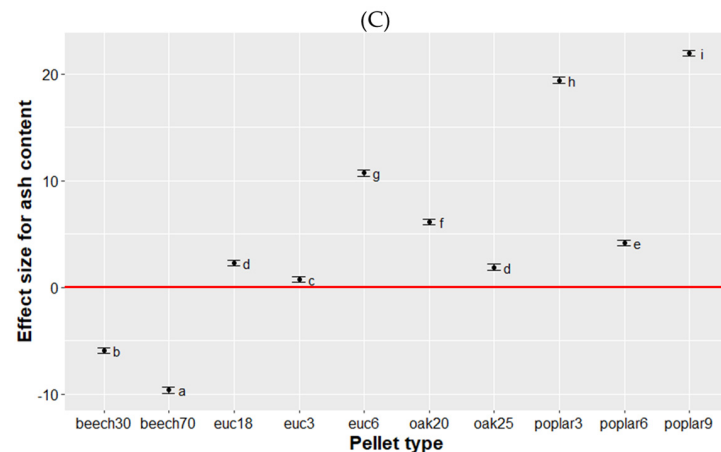


Figure 2. (A) Marginal effects of species on pellet ash content. (B) Marginal effects of age on pellet ash content. (C) Specific effect of pellet typology on pellet ash content. In (A,C), the black dots represent the average effect size, while the error bars represent the 95% confidence intervals. Statistically significant differences occur when the confidence intervals do not overlap with the 0 line (in red). In (B), the regression line and is represented by the black line, while the grey ribbon represents the 95% confidence intervals. Different lowercase letters indicate homogeneous groups according to Tukey posteriori test.

3.3. Pellet Heating Value

LMMs revealed statistically significant effects of both species and age on the lower heating value of pellets (Figure 3A,B). Concerning the effect of the species, oak and poplar showed significantly positive effect size, while beech and eucalyptus showed significantly negative ones (Figure 3A). For the same species, the model results indicated decreasing heating value with increasing stem age; however, the slope of the regression line is almost flat (Figure 3B) thus suggesting a negligible effect of this variable on the lower heating value.

Regarding the specific pellet types, the results largely follow the analysis concerning species marginal effect. Indeed, lower heating value for all oak and poplar pellets resulted in significantly higher values than the standard's threshold, while pellets from eucalyptus and beech showed significantly negative effect sizes (Figure 3C).

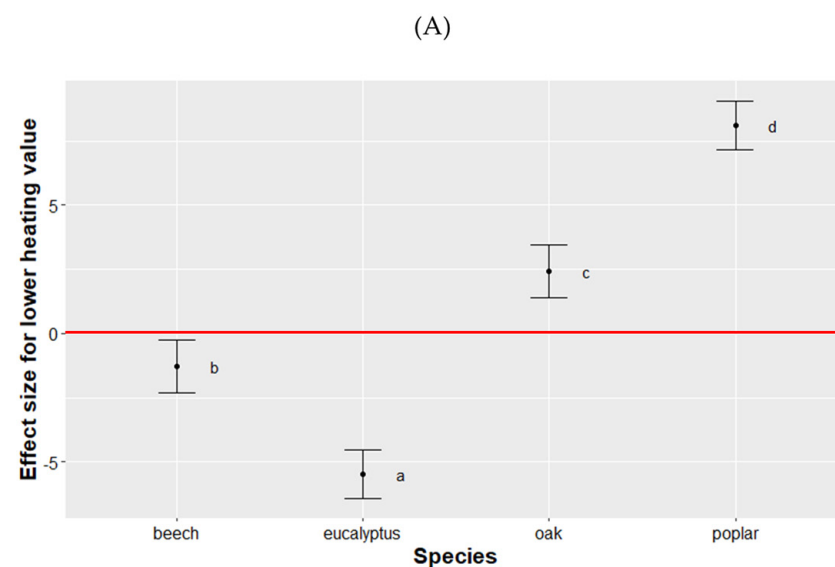


Figure 3. Cont.

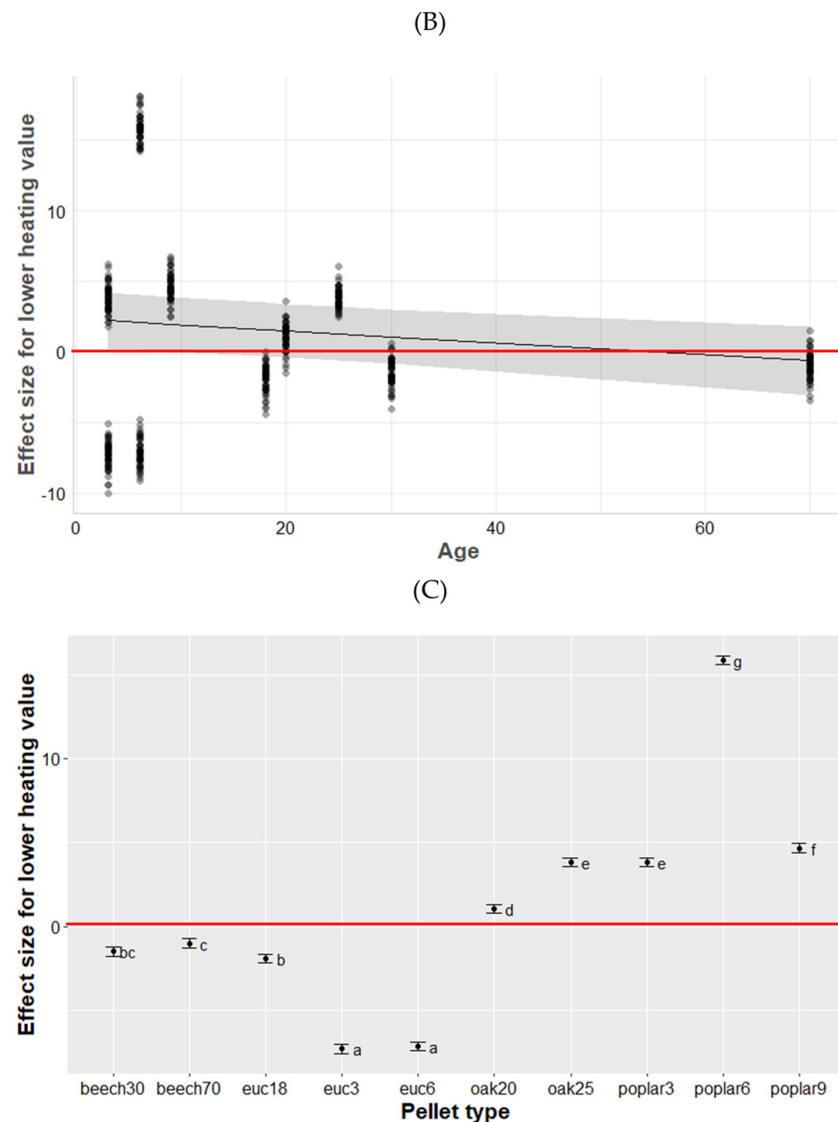


Figure 3. (A) Marginal effects of species on pellet lower heating value. (B) Marginal effects of age on pellet lower heating value. (C) Specific effect of pellet typology on pellet lower heating value. In (A,C), the black dots represent the average effect size, while the error bars represent the 95% confidence intervals. Statistically significant differences occur when the confidence intervals do not overlap with the 0 line (in red). In (B), the regression line and is represented by the black line, grey ribbon represents the 95% confidence intervals. Different lowercase letters indicate homogeneous groups according to Tukey posteriori test.

4. Discussion

This paper aimed to achieve two primary objectives as follows: (1) introducing an alternative statistical approach for evaluating pellet quality and (2) assessing the possibility of small-scale pellet production from material derived from different broadleaved species found in the Mediterranean forestry. Regarding our primary objective, we have validated the effectiveness of the proposed approach. The calculation and summarisation of the effect size were highly suitable to assess pellet quality. This methodology was the most effective as the focus is on the comparison of the value of a given pellet type with the reference standard, rather than the comparison among different pellet types, as typically performed with ANOVA. Effect size based on Cohen's calculation gave an immediate idea of how much the obtained value differs from the standard, and the calculation and visualisation of the confidence intervals represents an immediate and clear method to assess the statistical differences [39,40]. We therefore recommend the application of this approach in studies

conducted on pellet quality. Furthermore, this approach is not only limited to pellets, but to all those cases in which there is the need of comparing the obtained value with a constant threshold, as is the case for wood chips quality [41–43] or wood-based panels mechanical performance [44–46].

Regarding broadleaved pellet quality, we confirmed that bulk density, ash content, and heating value are the most troublesome parameters to produce high-quality pellet from broadleaves species. The previous literature largely confirmed that the thresholds indicated by the standard for these variables can be particularly challenging to be achieved [47,48]. None of the investigated pellet typologies showed fully satisfactory results for all the variables. For instance, beech pellets showed proper bulk density and satisfactory ash content, but the resulting heating value to be significantly lower than the standard's threshold (Figures 1–3). However, oak pellets showed satisfactory heating values, whereas bulk density was low and ash content was too high to be classified as an A1 pellet (Figures 1–3). These results are related to the intrinsic characteristics of the raw materials. Broadleaved wood has lower lignin content than coniferous wood and, considering that lignin is the major binding component for pellet production, this can obviously affect the quality of the pellets [49,50]. Furthermore, the presence of material other than sawdust, as it happens when producing pellet from the whole tree, is another critical aspect that can decrease pellet quality [27]. However, based on the results obtained a possible solution could be blending raw materials from different species. Additional dedicated studies are needed to confirm this [51–53]. Based on our findings, it could be interesting to blend beech (high bulk density and low ash content) with turkey oak (high heating value). These species are widely distributed along the Italian Apennine [54]. Often, they are located in stands very close to each other and with a certain degree of admixture, so this kind of blend could represent an interesting solution [28,55,56]. Eucalyptus and poplar pellets showed excessive shortcomings, making them less preferable as suitable raw materials for small-scale pellet production. These facts confirm that producing high-quality pellet from short and medium rotation forestry is particularly challenging [3,57,58].

Our results showed the significant influence on pellet quality generated by not only the species but also of the stem age, which is a direct consequence of the forest management systems applied, as highlighted in Latterini et al., (2022) [26]. Surprisingly, we did not find a significant influence on pellet bulk density (Figure 1B), but only on ash content (Figure 2B). In particular, the increasing age of the raw material led to an improvement in ash content. This is probably related to an increase in the wood/bark ratio which is generally observed with increasing diameter of the stem [59,60]. Increased ash content is often observed with an increase in the amount of bark [61,62]. The influence of bark on heating value is instead less straightforward and depends on the species intrinsic features; in beech, for instance, bark has a lower heating value than wood [63].

In summary, we applied an innovative statistical approach to evaluate the quality of pellets in relation to the official standards. The applied approach was revealed to be effective and easy to interpret. We recommend that this approach be applied in the sector of biomass quality evaluation. We further confirmed the generally known shortcomings which often occur when producing pellet from broadleaves species, in terms of high ash content, low heating value, and low bulk density. However, we found that increasing the stem age is beneficial for ash content, suggesting that material retrievable from thinning in high forests could be a better feedstock than material from coppice. We further showed that beech pellets demonstrate promising results concerning bulk density and ash content, and that the shortcomings related to low heating value could be addressed by blending with turkey oak biomass. This blend can compensate for the characteristics of turkey oak biomass as it was satisfactory only for the heating value. Thus, we recommend that future trials in the topic should investigate quality of pellets produced by blending beech and oak in the framework of small-scale pellet production.

Among the possible limitations of our study, it is possible to mention that this was a preliminary trial, based on a limited number of species and focused on pellet produced with

small-scale machinery. Future studies should involve more species and more management systems in order to develop models which are even more reliable. Furthermore, modelling the influence of bark percentage on pellet quality can represent an interesting research topic. Most importantly, we obtained promising results concerning beech pellets, but it is important to highlight that the pellets produced from beech were also those with the highest age among the investigated ones. This aspect had for sure an influence on the positive performance of beech pellets. However, it is also true that forest management in beech forests in the Mediterranean context consists mainly in conversion from coppice to high forests or in thinning in high forests. Thus, the logged stands always have an age of higher than 30 years, and our samples were representative of the beech wood which could be retrieved and used for pellet production in the study context.

5. Conclusions

To assess the pellets' quality in comparison to the mandated standards, we used a novel statistical technique. We recommend the application of this approach in the field of biomass quality evaluation given that it has exhibited efficiency, and it is simple to interpret. This approach can be recommended for further application in the sector of biomass quality evaluation to compare different pellet types. We also validated the well-known drawbacks that frequently arise when pelleting broadleaf species, which are associated with a high ash content, low heating value, and low bulk density. We discovered that raising the stem age improves the ash content. This suggests that material which has been recovered through thinning in high forests might provide a better feedstock than material from shorter rotation management systems. Additionally, we demonstrated that beech pellets had encouraging results in terms of bulk density and ash content. We suggest that the poor heating value of the beech pellets could be addressed by combining them with turkey oak biomass, which instead only showed a good heating value. Furthermore, using the wooden materials retrieved from thinning in older stands can provide pellets with higher quality. Therefore, future studies on the subject of small-scale pellet manufacturing in the Mediterranean region should focus on investigating the effects of blending among different broadleaved species on the final pellets' quality.

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