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RESEARCH PAPER

Physical, chemical and mechanical wood properties of *Pinus nigra* growing in Portugal

Alexandra Dias[1] · Ana Carvalho[1,2,3] · Maria Emília Silva[1,4] · José Lima-Brito[1,2,3] · Maria João Gaspar[2,3,5] · Ana Alves[5] · José Carlos Rodrigues[5] · Fábio Pereira[1] · José Morais[1] · José Luís Lousada[1,4]

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Abstract

• ***Key message*** **The wood of *Pinus nigra* populations planted in Portugal, comparatively to *Pinus pinaster*, has higher total extractive content, lower Klason lignin and H/G ratio, and similar mechanical properties, presenting advantages for industrial purposes.**

• ***Context*** *P. nigra* was used in the reforestation of mountainous areas in Portugal, but its wood chemical and mechanical properties were never studied.

• ***Aims*** This work intends to evaluate the chemical and mechanical wood properties of the *P. nigra* populations planted in Portugal, to relate these properties with previously characterised physical features and to compare these data with other European *P. nigra* stands and species, namely, *P. pinaster.*

• ***Methods*** Wood chemical and mechanical properties were analysed in 90 trees from six Portuguese sites, using near-infrared (NIR) spectrometry and the three-point bending test.

• ***Results*** The wood of the *P. nigra* populations planted in Portugal presented average values of total extractive content = 9.4%, Klason lignin = 26.69%, MOR_{Rad} = 14.93 MPa and MOE_{Rad} = 1200.98 MPa. Ring density showed no significant correlation with ring width.

• ***Conclusion*** The *P. nigra* populations planted in Portugal presented qualitative and quantitative properties similar to *P. pinaster* wood, the main resinous species in Portugal. Facing the lack of raw material for wood industry due to frequent forest fires in the Mediterranean region, *P. nigra* could be used to reforest mountainous areas of those regions.

Keywords European black pine · NIR spectrometry · MOE radial and MOR radial · Wood density · X-ray microdensitometry

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✉ José Luís Lousada
jlousada@utad.pt

Alexandra Dias
xana_dias@hotmail.com

Ana Carvalho
anacar@utad.pt

Maria Emília Silva
emil_ms@utad.pt

José Lima-Brito
jbrito@utad.pt

Maria João Gaspar
mjgaspar@utad.pt

Ana Alves
analves@isa.ulisboa.pt

José Carlos Rodrigues
jocarod@isa.ulisboa.pt

Fábio Pereira
fampereira@gmail.com

José Morais
jmorais@utad.pt

Extended author information available on the last page of the article

1 Introduction

Pinus nigra Arnold is used in the reforestation of mountainous areas due to its ability to grow in high altitudes (Naydenov et al. 2006). It is considered a relict species with a broad and fragmented distribution that ranges from the North of Africa, Northern Mediterranean, Eastwards to the Black Sea, Corsica and Sicily islands (Afzal-Rafii and Dodd 2007). Because of the different ecological pressures (Thompson 2005), this species manifests high variation among populations (del Cerro Barja et al. 2009; Rubio-Moraga et al. 2012; Dias et al. 2019), occupying a wide variety of sites (Barbéro et al. 1998; Génova and Cancio 1998).

In Portugal, *P. nigra* was planted in the middle of the twentieth century at the North and Centre (Louro 1982). Although the populations are between 50 and 90 years old, its wood characteristics were just studied in the current years (Dias et al. 2018, 2019).

Wood properties variation is mainly influenced by the growth pattern (Downes et al. 2000) and its biological origin (Zobel and van Buijtenen 1989). There is variation within the tree from pith to bark and within each annual ring from earlywood to latewood (Zobel and Sprague 1998). This large variability poses difficulties on the prediction of the wood performance and therefore, the efficiency of its processing and use (Koga and Zhang 2004). The definition of wood quality is dependent of its properties for specific end-use, with density as the more significant, followed by other features such as chemical composition (the content of cellulose, hemicellulose and lignin) and mechanical properties (modulus of elasticity and rupture) (Zobel and van Buijtenen 1989).

Wood density is the main responsible for the timber strength, pulp yield, ease of drying, machining and hardness (Elliot 1970; Brazier and Howell 1979; Panshin and Zeeuw 1980). This wood property is the result of the ratio between cell size and wall thickness, proportion of earlywood and latewood, and the number of ray cells, vessel elements and chemical content (Zobel and van Buijtenen 1989; Cave and Walker 1994). In what concerns the wood chemical composition (cellulose, hemicellulose, lignin and extractive components) and its variation is vital for a part of the forestry industry, such as the pulp industry. In this case, to achieve high pulp yield and brightness of the bleached paper, it should have high cellulose, low extractive content and lignin (Campbell and Sederoff 1996; Üner et al. 2009). Besides, chemical composition also influences the mechanical properties of particle boards (Üner et al. 2009).

The mechanical properties of wood pose interest in several areas of engineering for the selection and application of wood for specific end-use. This knowledge will allow its mechanical characterisation for comparison with other materials (Santos and Pinho 2004). Two of the properties most commonly measured are the modulus of elasticity and rupture, used for the evaluation of wood quality for structural components (Green et al. 1999).

P. nigra is widely used in the forestry industry due to its aptitude to grow in different environments, with suitable outcoming products (Üner et al. 2009). Also, it is recognised for its mechanical strength for structural refurbishing and construction (Fernández-Golfín Seco et al. 2004). Moreover, the main resinous species in Portugal used for industrial purposes, *Pinus pinaster* Ait., is reducing, increasing the timber demands and importation of raw material (Uva 2015). In this sense, this work aims to answer the following:

- What is the relation found between chemical, mechanical and previously achieved physical properties (density and growth; Dias et al. 2018) of *P. nigra* planted in Portugal?
- Are the wood properties of this species similar to those of other European natural stands and species including *P. pinaster*, the main resinous species used to supply the softwood national demands?

2 Material and methods

P. nigra allochthonous populations were planted mainly in high altitude mountains in the North and Centre of Portugal. Six populations representative of its distribution, with an altitude range of 450 to 1600 m, were sampled (Table 1). More detailed information about the sample sites characterisation can be found in Dias et al. (2018). In each sample plot (0.04 ha), dendrometric measurements were performed in all trees, and a total of 90 dominant and codominant trees (15 per plot) were sampled. In each tree, wood cores of 12 mm from bark to pith to bark were sampled at the breast height. Samples with lower reaction wood were chosen.

It was analysed the chemical composition (macromolecules) with the near-infrared (NIR) spectrometric method and mechanical features by using a three-point bending test. The wood density and growth were studied previously in Dias et al. (2018) and those results were used here in the correlation matrix for the analysis of all the components: density, growth, chemical and mechanical properties.

For the evaluation of the chemical properties per tree, it was used the wood material of the opposite radial strip used in the microdensitometry. The tree samples were milled in a Retsch Ultra Centrifugal Mill ZM 100 with a 1-mm screen sieve for posterior Soxhlet extraction with dichloromethane, ethanol and water. Finally, the extracted material was oven-dried at 45 °C for 2 days. NIR spectra were recorded on a Bruker MPA spectrometer (Bruker Optics, Ettlingen, Germany) equipped with a spinning cup module. The spectra were acquired in diffuse reflectance mode using an integration sphere in the wavenumber range from 12,000 to 4000 cm^{-1}, at a spectral resolution of 8 cm^{-1}, each spectrum resulted from the average of 100 spectra and a zero filling of two was applied (Alves et al. 2006; Schwanninger et al. 2011a). Extractive-free samples were dried at 60 °C

Table 1 *P. nigra* sampled sites and dendrometric data (Dias et al. 2018)

	Paredes de Coura	Caminha	Vila Pouca de Aguiar	Campeã	Manteigas	Vale do Zêzere
Number of individuals	15	15	15	15	15	15
Coordinates	41° 52′ 0.00″ N 8° 36′ 21.00″ W	41° 50′ 15.00″ N 8° 43′ 57.00″ W	41° 31′ 02.72″ N 7° 35′ 31.36″ W	41° 19′ 9.12″ N 7° 53′ 28.35″ W	40° 22′ 47.00″ N 7° 33′ 18.00″ W	40° 19′ 19.00″ N 7° 34′ 26.00″ W
Average age ± SD	57.8 ± 1.1	57.9 ± 1.3	74.7 ± 2.9	58.1 ± 1.5	93.3 ± 2.8	59.1 ± 1.6
Average height (m)	14.8	26.3	26.8	23.1	24.4	15.0
Average diameter at 1.3 m (cm)	21.1	32.6	40.1	37.1	34.1	24.8
Stand density (trees/ha)	975	725	475	650	525	700
Altitude	451	443	908	891	1144	1560

overnight and kept in a desiccator until ready for analysis. The oven-dried and extractive-free Klason lignin content and extractive-free H/G ratio were assessed by NIR-based PLS-R models with software OPUS-Quant (Bruker Optics, Ettlingen, Germany). These models have prediction errors of 0.18/0.18 (RMSEC/RMSECV) for Klason lignin content and 0.002/0.003 (RMSEC/RMSECV) H/G ratio (Alves et al. 2019). These models were similar to the ones applied in *Picea abies* (Schwanninger et al. 2011a, b) and *Pinus sylvestris* (Fernandes et al. 2017).

Concerning the radial mechanical properties, the same strips from the microdensitometric analysis were used, i.e. obtained from the wood cores of 12 mm sampled at the breast height. One pith-to-bark strip was sawn from each core with approximately dimension of 5 mm (tangential) × 3 mm (axial) × stem radius (radial). For each sample, MOE_{Rad} (modulus of elasticity in radial direction) and MOR_{Rad} (modulus of rupture in radial direction) were evaluated through three-point bending tests (Brancheriau et al. 2002; Yoshihara and Tsunematsu 2006; Gaspar et al. 2011), in which it was only necessary to adapt the size and orientation of the wood samples. Before testing, the specimen dimensions (tangential and axial) were measured with a digital calliper (0.01-mm resolution). Bending tests were carried out at room temperature with an electromechanical testing machine (Instron 5848 MicroTester®) with a 0.5-mm/min displacement control and 40 mm span.

3 Results

3.1 Chemical wood properties

In average, the *P. nigra* populations planted in Portugal had a total of extractive content of 9.4%, mainly removed by dichloromethane (5.6%) followed by water (2.2%) and ethanol (1.6%). The Klason lignin was of 26.69%, and the H/G ratio was 0.041.

In terms of total extractive content and dichloromethane extraction solvent, the site that presented higher value was Vila Pouca de Aguiar, while Campeã showed the lowest value. Between the remaining solvents, the differences were not statistically significant ($p > 0.05$). Regarding the Klason lignin, the higher values were observed in Caminha, Campeã and Vale do Zêzere (ranging from 27.02 to 27.38%). In comparison, the remaining sites did not present statistical differences ($p > 0.05$) among them (25.61 to 26.73%). A similar trend was found in the cP/cH, with the highest values in Campeã and Vale do Zêzere but with no significant differences ($p > 0.05$) relative to the remaining sites. In the H/G case, globally, the differences were very reduced and not significant ($p > 0.05$), being noteworthy the higher value presented by Vale de Zêzere (0.044) (Table 2).

Table 2 Mean values (± standard deviation) and results of the comparison test for chemical and mechanical properties. (Dichloro): extractives soluble in dichloromethane (%); (ethanol): extractives soluble in ethanol (%); (water): extractives soluble in water (%); (total): total extractives (%); (Klason): lignin content (%); (H/G): lignin composition (%); (cP/cH): pentose/hexose ratio; (MOE_{Rad}): radial modulus of elasticity (MPa); (MOR_{Rad}): radial modulus of rupture (MPa). Different letters in the same column indicate significant differences ($p < 0.05$) between sampled sites after Duncan's multiple range test

Site	Dicloro	Ethanol	Water	Total	Klason	H/G	cP/cH	MOR_{Rad}	MOE_{Rad}
All	5.6	1.6	2.2	9.4	26.69	0.041	10.07	14.93	1200.98
Paredes de Coura	6.0 bc	1.4 a	2.3 a	9.7 b	26.14 ab	0.040 ab	9.62 a	14.15 a	1258.25 ab
Caminha	4.7 ab	1.4 a	2.1 a	8.2 ab	27.38 c	0.040 a	9.46 a	13.44 a	1216.76 ab
Vila Pouca de Aguiar	8.1 c	2.0 b	2.7 a	12.9 c	25.61 a	0.040 ab	9.40 a	13.95 a	1068.56 a
Campeã	3.2 a	1.4 a	2.0 a	6.6 a	27.24 c	0.042 ab	10.74 b	17.49 b	1235.78 ab
Manteigas	5.9 bc	1.7 ab	2.0 a	9.6 b	26.73 bc	0.040 ab	9.99 a	12.47 a	1137.65 ab
Vale do Zêzere	5.8 b	1.5 a	2.0 a	9.3 b	27.02 c	0.044 b	11.24 b	17.47 b	1288.85 b

3.2 Mechanical wood properties

The average MOR_{Rad} and MOE_{Rad} obtained for all sites were 14.93 MPa and 1200.98 MPa, respectively. Globally, the differences among sites were small. In MOR_{Rad}, the higher values were detected in Campeã and Vale do Zêzere (17.49 MPa and 17.47 MPa, respectively), while the differences among the remaining sites (ranging from 12.47 to 14.15 MPa) were not significant ($p > 0.05$). Regarding the MOE_{Rad}, it is only worth to mention the higher value shown by Vale do Zêzere (1288.85 MPa) and the lower one of Vila Pouca de Aguiar (1068.56 MPa), with no significant differences ($p > 0.05$) among the remaining sites (1137.65 to 1258.25 MPa) (Table 2).

4 Discussion

4.1 Wood density and growth properties

To consider the main *P. nigra* components that will be correlated and discussed in Section 4.4, a brief resume of the results obtained by Dias et al. (2018) concerning the density and growth components are here mentioned.

The wood of the allochthonous *P. nigra* populations planted in Portugal presented similar RD values found in European stands of the same species. However, upon comparison to other European conifers (*Pinus sylvestris*, *Pinus radiata*, *Pinus brutia*, *Picea abies* and *Abies balsamea*), the wood density values was higher, with few minor exceptions (Dias et al. 2018). The heterogeneity index (HI), which confers ring uniformity and homogeneity to the final product (Louzada and Fonseca 2002; Louzada 2003), was similar to the values achieved in *P. pinaster* and *P. sylvestris* growing in Portugal. On the same study, the growth component RW was higher compared to the values obtained in European *P. sylvestris* and *P. abies*, but lower than *L. decidua* of the Czech Republic and in Portuguese *P. sylvestris*, *Pinus pinea* and *P. pinaster* trees.

Regarding the influence of the growth rate on density in the *P. nigra* growing in Portugal, Dias et al. (2018) showed that the RD is accompanied by higher RW values, except in Paredes de Coura stand, possibly due to site restrictions.

4.2 Chemical wood properties

Extractives are one of the main wood components, along with cellulose, hemicelluloses and lignin (Vainio-Kaila et al. 2017). The extractives variation is mainly influenced by the species, but also by its growth conditions, climatic and geographic location, age and genetics of the tree, among others. Nevertheless, in each species, the extractive content varies within specific limits (Hafizoglu 1983). The comparison of our results with other studies should be analysed with attention because of the different tree ages and methodologies used in the extraction procedures, which may result in different outcomes.

Pinus nigra populations planted in Portugal presented a total of extractive content of 9.4% (dichloromethane, ethanol and water extraction). These values were higher in comparison to the literature review on the subject, which refers that softwoods average values range from 2 to 5% (Sjöström and Alén 2013). Other studies on the same species reported lower average values, 7.77% (Uner et al. 2009), 4.65% (cyclohexane extraction) (Uçar and Balaban 2002), 4.88% in variety *pallasiana* and 4.94% in variety *pyramidata* (ciclohexane followed by ethanol extraction) (Uçar and Fengel 1995) and 3.2% (petroleum benzene extraction) (Yildirim and Holmbom 1978). Higher values were found by Uner et al. (2009) in Turkey on *P. nigra* variety *pallasiana* where the extractive content ranged from 4.30 to 13.0% and in the Portuguese *P. sylvestris*, with 10.72 to 15.41% (dichloromethane, ethanol and water extraction) (Fernandes et al. 2017). In the Portuguese *P. pinaster*, the total extractive content was lower, ranging from 5.5 to 9.6% (Reva et al. 2015). Other studies in species of younger age (absent or reduced heartwood) revealed lower values in *P. sylvestris* (2.9%, 27 years old trees) (Sable et al. 2012), *P. pinaster* (4.2%, 11 years old trees) (Fernandes 2006); 4.8%, 10 years old trees (Da Silva Perez et al. 2007); 6.1%, 11 years old trees (Gaspar et al. 2011) and *P. brutia* (7.7%, 17 to 25 years old) (Üner et al. 2011). Usually, younger trees present lower extractive content, which increases rapidly with age (Gomide et al. 2005; Fernandes et al. 2017). This fact is due to the extractives appearance in high quantity in the heartwood, which only develops in mature wood. Therefore, we can conclude that the extractive content of *P. nigra* in Portugal showed, in general, higher values when compared with other species. Still, these values were similar in the Portuguese *P. sylvestris* (Fernandes et al. 2017) also growing in high altitudes.

In the present study, the extractives were mainly removed by dichloromethane (5.6%), followed by water (2.2%) and ethanol (1.6%). Research in Portuguese *P. sylvestris* pointed out that dichloromethane was also the main solvent (7.59 to 12.41%), although in this case followed by ethanol (2.18 to 2.29%) and water (0.53 to 0.96%) (Fernandes et al. 2017). In *P. pinaster* studies, the main solvent was water, followed by dichloromethane and ethanol, respectively 3.21%, 1.69% and 1.20% (Fernandes 2008); 1.8%, 1.6% and 1.2% (Gaspar et al.

2011); 5.33%, 3.32% and 0.25% (Reva et al. 2015); 2.0%, 1.6% and 1.2% (Da Silva Perez et al. 2007).

The Klason lignin content is variable within and among species, influenced by the tree's age and the existence of compression wood, which is related to more lignin and less cellulose (Tsoumis 1991). Concerning to the present study, the *P. nigra* populations planted in Portugal attained a value of 26.68%, which complies with the reference values for pine species, ranging from 26 to 30% (Zobel and van Buijtenen 1989). Also in *P. nigra*, Uner et al. (2009) reported values between 14.3 and 34.5%. In other species similar values were presented: *P. sylvestris* 26.9 to 27.8% (Fernandes et al. 2017), 27.1% (Sable et al. 2012) and 18.8 to 26.6% (Toivanen and Alén 2006), *Pinus monticola* 25% and *Pinus palustris* 30% (Campbell and Sederoff 1996), *P. radiata* 25.2 to 47.6% (Cruz et al. 2018), *P. pinaster* 30.7% (Da Silva Perez et al. 2007), 27.9% (Fernandes 2008), 28.1% (Gaspar et al. 2011) and *Pinus caribaea* 26.4 to 28.6% (Godoy et al. 2007).

Very few are still known about the structural lignin composition and its H/G ratio (*p*-hydroxyphenyl/guaiacyl) in pine species, due to the chemical methods normally used (Godoy et al. 2007). The use of the Klason method along with the NIR spectrometric method is a nondestructive and more informative approach (Alves et al. 2006). In this work, the H/G ranged from 0.040 to 0.044. Similar results were obtained in *P. sylvestris* (0.042 to 0.048) (Fernandes et al. 2017), *P. radiata* (0.019 to 0.052) (Nanayakkara et al. 2015) and *P. caribaea* (0.047 to 0.053) (Godoy et al. 2007). In contrast, slightly higher values were reported in *P. pinaster* (0.041 to 0.111) (Da Silva Perez et al. 2007).

Regarding the differences among the six Portuguese sites, the total extractives ranged from 6.6% in Campeã to 12.9% in Vila Pouca de Aguiar, which are geographically near but represent the lowest and the maximum values. The Klason lignin was lower in Vila Pouca de Aguiar (25.61%) and higher in Caminha (27.34%), followed by Campeã (27.24%). As for the H/G ratio, which is expected to vary just a few within species (Sjöström and Alén 2013), the values were similar among sites. The lowest value of 0.040% was detected in Paredes de Coura, Caminha, Vila Pouca de Aguiar and Manteigas, and the maximum (0.044%) in Vale do Zêzere. Thus, it is possible to conclude that although there is no high distance among sites, there was no consistent tendency detected in terms of its geographic location.

4.3 Mechanical wood properties

P. nigra MOR_{Rad} and MOE_{Rad} values obtained for all sites were 14.92 MPa and 1204.90 MPa, respectively. The MOE_{Rad} results were similar to *P. pinaster* and *P. sylvestris* with values ranging from 1100 to 1370 MPa (Fernandes 2008; Gaspar et al. 2011; Fernandes et al. 2017). Regarding the MOR_{Rad}, the values were similar to *P. pinaster* wood ranging from 13.7 to 14.1 MPa (Fernandes 2008; Gaspar et al. 2011), although much lower than the value of 28.11 MPa obtained by Fernandes et al. (2017) in *P. sylvestris.* In a study performed on younger *P. radiata* trees, lower MOR_{Rad} values (7.3 to 7.8 MPa) were found (Ohbayashi et al. 2001). Regarding the Portuguese sampled sites, the highest MOR values were found in Campeã (17.49 MPa) and Vale do Zêzere (17.47 MPa), while the lowest value was detected in Manteigas (12.47 MPa). The highest MOE values were obtained in Vale do Zêzere (1288.85 MPa) and Paredes de Coura (1258.25 MPa) and the lowest one, in Vila Pouca de Aguiar (1068.56 MPa). In terms of the spatial distribution, it was not detected any trend from North to South, with the highest MOR and MOE values found both in the North and South, which does not seem to reflect any tendency. Also, in terms of altitude, no effects were detected.

4.4 Correlations among wood features

Table 3 shows the correlation among all wood features: physical (achieved by Dias et al. 2018), chemical and mechanical properties (this work), computed at the tree level based on the original data (Dias et al. 2020).

Among the extraction solvents, the correlations were positive, with the total extractives higher correlated with dichloromethane (0.940), than with water and ethanol (0.459 and 0.411, respectively). Also, between the solvents ethanol and water, there was a highly significant correlation (0.412). Similar results were found by Reva et al. (2015) and Fernandes et al. (2017), with a higher correlation between the total extractives and dichloromethane. Fernandes et al. (2017) also found a high correlation between ethanol and water. Klason lignin is highly significantly correlated with H/G (0.666), cP_cH (0.700) and strongly correlated with both (0.829). A similar finding was detected in *P. sylvestris* that showed a high significant correlation between Klason and H/G (Fernandes et al. 2017). Considering the correlations between the chemical (Klason lignin, H/G and cP_cH) and mechanical properties (MOR and MOE), all were very low and statistically not significant. Identical behaviour was found between Klason lignin and the wood density components, where globally the correlations were low and not significant. The exception occurred between Klason and EWW (0.239). Fernandes et al. (2017) did not find correlations but Gaspar et al. (2011) detected in *P. pinaster* a negative correlation between Klason (lignin content) and latewood (LWW and LWP), previously documented in *P. abies* (Hannrup et al. 2004). The correlation between cP_cH and the wood density components was, in general, negative, and in some cases

Table 3 Pearson's correlation matrix between wood density components and chemical and mechanical properties, computed at tree level (100 observations). Significance level (100 obs.): highly significant ($r > 0.337$), very significant ($r > 0.267$), significant ($r > 0.205$)

	Dic	Etan	H2O	Total	Klas	H_G	cP_cH	MOR	MOE	RD	EWD	LWD	HI	RW	EWW	LWW	LWP
Dic	1.000	0.157	0.173	0.940	− 0.149	0.039	0.025	− 0.092	− 0.021	0.101	0.150	0.071	− 0.072	− 0.182	− 0.189	− 0.102	0.010
Etan		1.000	0.412	0.411	− 0.140	0.100	− 0.033	0.017	0.068	− 0.013	0.040	− 0.036	− 0.086	− 0.133	− 0.107	− 0.136	− 0.027
H2O			1.000	0.459	− 0.242	0.065	− 0.025	0.090	0.288	0.123	0.167	0.051	− 0.120	− 0.102	− 0.109	− 0.051	0.048
Total				1.000	− 0.212	0.066	0.009	− 0.056	0.062	0.117	0.180	0.070	− 0.107	− 0.203	− 0.206	− 0.123	0.015
Klas					1.000	0.666	0.700	− 0.013	− 0.064	− 0.218	− 0.244	− 0.188	0.005	0.198	0.239	0.069	− 0.105
H_G						1.000	0.829	0.031	− 0.029	− 0.219	− 0.114	− 0.226	− 0.179	− 0.108	− 0.011	− 0.249	− 0.238
cP_cH							1.000	0.210	0.069	− 0.393	− 0.192	− 0.424	− 0.356	− 0.057	0.115	− 0.351	− 0.446
MOR								1.000	0.662	0.311	0.217	0.391	0.174	0.307	0.407	0.016	0.411
MOE									1.000	0.437	0.394	0.448	0.172	0.073	0.092	0.010	0.119
RD										1.000	0.884	0.858	0.150	− 0.044	− 0.274	0.393	0.733
EWD											1.000	0.612	− 0.288	− 0.198	− 0.317	0.079	0.498
LWD												1.000	0.571	0.181	− 0.025	0.503	0.515
HI													1.000	0.356	0.207	0.522	0.188
RW														1.000	0.942	0.786	− 0.133
EWW															1.000	0.534	− 0.430
LWW																1.000	0.456
LWP																	1.000

highly significant (RD: − 0.393; LWD: − 0.424; HI: − 0.356; LWW: − 0.351 and LWP: − 0.446).

The correlation between the wood mechanical properties MOR and MOE was positive and highly significant (0.662). A similar result was reported by Gaspar et al. (2011) and Fernandes et al. (2017). This high correlation common to different studies and species allows the evaluation of the strength parameter (MOR) through the stiffness parameter (MOE). Both mechanical properties are also positively and globally highly correlated with the wood density components (RD, EWD and LWD), a fact that was also observed in several species (Niklas 1992; Chave et al. 2009; Gaspar et al. 2011; Missanjo and Matsumura 2016; Fernandes et al. 2017). Similarly to Fernandes et al. (2017) and Gaspar et al. (2011), it was possible to verify that the correlations were higher with MOE (0.394 to 0.448) than with MOR (0.217 to 0.391). Although compared to MOE, MOR presented a lower correlation with the density components, also showing high positive correlations with some of the growth components RW (0.307), EWW (0.407) and LWP (0.411). An identical behaviour was found in *P. sylvestris* (Fernandes et al. 2017). Likewise, in *P. nigra*, Amarasekara and Denne (2002) found that the correlation between the mechanical properties and RW was also higher in MOR than in MOE, despite negative.

Regarding the wood density components, RD showed a similar high positive correlation with EWD (0.884), LWD (0.858) and LWP (0.733), similar to what was found previously by different authors (Koubaa et al. 2000; Louzada 2003; Gaspar et al. 2008; Peltola et al. 2009; Fernandes et al. 2017).

RD showed very significant and negative correlation with EWW (− 0.274) (Fig. 1a), which is compensated by the positive and highly significant correlation that was found with LWW (0.393) (Fig. 1b). Thus, RD with RW presents no significant correlation (− 0.044) (Fig. 1f), similar to what was obtained by Pritzkow et al. (2014), Fernandes et al. (2017) and Louzada (2003), which might reflect that wood density is not negatively influenced by higher radial growth. On the other hand, other authors found a higher negative correlation between wood density and growth rate in other softwood species (Zhang and Morgenstern 1995; Zhang 1995; Zhang et al. 1996). Nevertheless, this diversity of results can be observed within the same species. In *P. radiata*, it was found cases of positive correlation (Fielding and Brown 1960), negative correlation (Bannister and Vine 1981; Cown and McConchie 1981) or no correlation at all (Nicholls and Fielding 1964; Bamber and Burley 1983). This fact may be also due to the chosen silvicultural management, which can influence the relationship between wood density and growth rate (Zobel and van Buijtenen 1989) and to the environmental conditions of the site (Zhang and Morgenstern 1995). Moreover, it should be taken into account that the analysis and comparison should be performed within similar age classes due to the distinct wood properties of RW with age. Larger rings with low density are characteristic of juvenile wood, while narrow rings with high density are typical of mature wood (Zobel and van Buijtenen 1989). Also, it was observed a strong correlation of RW with EWW (0.942) (Fig. 1c) and LWW (0.786) (Fig. 1d), similar to the findings of Peltola et al. (2009) and Fernandes et al. (2017). Distinct results are reported by Koubaa et al. (2000). The authors found a very low correlation of RW with LWW, which in this case, the higher radial growth was caused by the earlywood augment. There is no significant correlation between LWP and RW (− 0.133) (Fig. 1e), similar to what was previously reported by Guller (2007), while a negative correlation was found in Koubaa et al. (2000), Peltola et al. (2009) and Fernandes et al. (2017), contrarily to a positive correlation observed by Louzada (2003). LWP showed high significant correlations, negative with EWW (− 0.430) and positive with LWW (0.456), which means that both components influence the LWP similarly, i.e. with the LWW increases and EWW decreases. Identical outcomings were found by Peltola et al. (2009) and Fernandes et al. (2017), despite in these cases, the EWW had a stronger negative correlation. Similarly, in Koubaa et al. (2000) and Gaspar et al. (2008), there was a strong negative correlation of LWP with EWW, although in LWP with LWW, the positive correlation was stronger.

Concerning the HI, it was possible to verify that was better correlated with LWD (0.571) than with EWD (− 0.288), i.e. the increase of HI is more related with the augment of the latewood density than with the decrease of the earlywood density. Identical behaviour was observed by Louzada (2003) and Fernandes et al. (2017).

5 Conclusion

In what concerns to the chemical analysis, this species presented higher values of extractive content and similar Klason lignin content when compared to the reference values for softwood species. In addition, the H/G ratio was similar to the performed studies but slightly lower than *P. pinaster*.

The mechanical properties, MOR and MOE, tend to present similar values compared to other conifers. Moreover, these mechanical properties were not related to the geographic location (latitude and altitude).

Regarding the relationships between the chemical properties of wood, the higher correlation was found between total extractives and dichloromethane, as well as between ethanol and water, which is in agreement with other studies conducted in different pine species present in Portugal. Klason lignin was highly correlated with H/G and cP_cH, and the latter two were strongly correlated between them as well.

The correlation between the two radial mechanical properties of wood, MOR and MOE, was highly significant, as expected, and both were significantly correlated with the wood

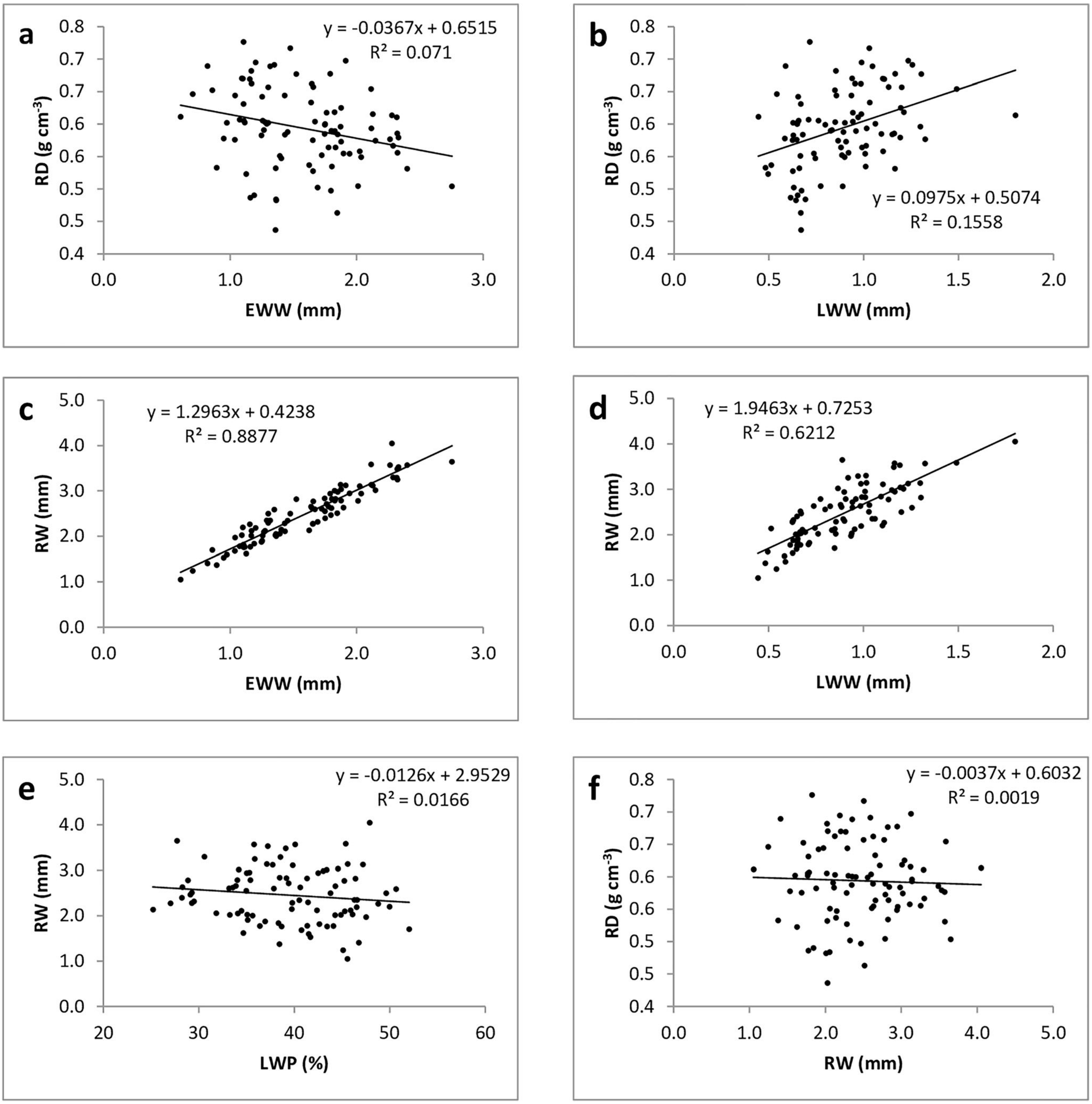

Fig. 1 Linear regression between ring density and ring width components

density components, similar to other studies. The relationship with the wood growth components was lower, but a higher correlation between MOR and RW, and EWW and LWP was found.

As to the correlation of the wood density components, RD presented similar high correlation to EWD and LWD. Concerning the radial growth, it showed no significant correlation with RD, reflecting that wood density is not negatively influenced by growth. HI is more correlated with LWD (positively) than EWD (negatively).

Facing the reduction of the *P. pinaster* forest area that constitutes the main species used for industrial purposes in Portugal, as well as the increasing timber demands and importation of wood, *P. nigra* could be used for the reforestation of mountainous areas. These areas are widely deforested and are not suited for *P. pinaster* reforestation. Therefore, *P. nigra* could constitute an alternative and essential source to supply the Portuguese forestry industry. Besides, as revealed with this work, the *P. nigra* wood, compared to *P. pinaster* with similar age, showed identical or slightly higher wood density components, similar growth rate, higher total extractive content, lower Klason lignin and H/G ratio and similar mechanical properties.

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Data availability The datasets generated during and/or analysed during the current study are available in the figshare repository [https://doi.org/10.6084/m9.figshare.12185223]

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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Affiliations

Alexandra Dias[1] • **Ana Carvalho**[1,2,3] • **Maria Emília Silva**[1,4] • **José Lima-Brito**[1,2,3] • **Maria João Gaspar**[2,3,5] • **Ana Alves**[5] • **José Carlos Rodrigues**[5] • **Fábio Pereira**[1] • **José Morais**[1] • **José Luís Lousada**[1,4]

[1] Center of Research and Technology of Agroenvironmental and Biological Sciences (CITAB), University of Tras-os-Montes and Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal

[2] Biosystems & Integrative Sciences Institute, University of Trás-os-Montes and Alto Douro (BioISI - UTAD), Quinta de Prados, 5000-801 Vila Real, Portugal

[3] Department of Genetics and Biotechnology, University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal

[4] Department of Forestry Sciences and Landscape (CIFAP), University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal

[5] Forest Research Centre (CEF), Instituto Superior de Agronomia (ISA), University of Lisbon, Lisbon, Portugal