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A review on properties and variability of *Pinus Pinaster* Ait. ssp. Atlantica existing in the Landes of Gascogne

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Abstract

Pinus Pinaster Ait. is a softwood species indigenous of the South West of Europe, broadly spread alongside the Mediterranean Sea and present worldwide. *Pinus Pinaster* Ait. (ssp. *Atlantica*) is largely used in industrial applications including construction and buildings in the Southwest of France as it has widely grown across the whole area. However, very often, *Pinus Pinaster* Ait.-based product design strategies make use of properties of generic softwood species due to the lack of a proper database (or review) on the topic. This review article aims to exhaustively present the consistent scientific literature on *Pinus Pinaster* Ait. properties focusing on its physical, hygrical, thermal and mechanical properties. Indeed, a vast literature exists, laid out across a wide range of years and countries.

Keywords *Pinus Pinaster* Ait., Xylology, Physical properties, Variability

Introduction

The forestry and wood industry have become significant sectors of interest following the new environmental considerations highlighted by the rising energy challenges inside the construction industry. Indeed, wood is a natural, renewable, and eco-material which can reduce structures environmental footprints and help reach the sustainable development goals (SDGs) laid down by the United Nations. It is of the utmost significance to promote and master local wood species, especially softwood, to lessen global energy consumption. Several species like scots pine (*Pinus sylvestris* L. 1753) or Norway Spruce (*Picea abies* (L.) H. Karst 1881) have been thoroughly studied and widely used by Western and Northern European Countries such as Germany and Sweden. In the South West of France, maritime pine (*Pinus Pinaster* Ait. 1789) is a dominantly present species broadly used in many domains and economically essential.

From the end of World War II, the use of *Pinus Pinaster* Ait. has changed from simple resin extraction to production of timber and paper in the Southwest of France with a rotation period of around 40 years [1]. In the Landes of Gascogne, the volume harvested stays important (1.424 millions m^3 in 2019) despite a large diminution provoked by the consequences of wind and fire damages (2.148 millions m^3 in 2013) [2]. Nowadays, the local forest industry is separated between first pulpwood production destined to the paper industry, then lumber production for wood packaging, furnitures, wood construction, and finally pellet or residues intended for fuelwood [2]. Several construction applications are visible in the Landes of Gascogne, testimony of the utilisation of *Pinus Pinaster* Ait. throughout the years: from pine bards, remnant of the agropastoral farming system of the 19th century, to private and public buildings [3]. The rise of interest for wood in construction can be attributed to an increase demand for processed wood products such as cross-laminated timber and glued laminated timber (glulam) allowing a wide range of shape and dimensions. Wood

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distortions issued from thermo-hygric variations can be considerably reduced in glulam by assembling a disparity of lamellae typology [4]. This advantage is noticeably reduced when using *Pinus Pinaster* Ait. timber compared to other softwood species. Several studies work on the overall amelioration of *Pinus Pinaster* Ait. glulam properties. Balmori et al. proposed to upgrade the properties of duo beams with an internal glass fibre-reinforced polymer whilst Clouet attempted to estimate the shape stability of multiples configurations of glulam finger-jointed with green wood [5, 6]. In spite of the fact those studies require specific data on *Pinus Pinaster* Ait., the vast majority of studies uses classical softwood properties [7].

To deal with this issue and to make data on *Pinus Pinaster* Ait. more easily accessible to improve analyses on its industrial applications, the main purpose of this article is to propose a bibliographic review on physical properties of *Pinus Pinaster* Ait. The available literature on the topic is not easily accessible, it is written in languages other than English and the available data sometimes require further processing. Therefore, a review on physical properties of *Pinus Pinaster* Ait. seems necessary to gather and improve knowledge on this local richness, destined to be used as a renewable eco-material and more studied in the near future. Hereby, the present work reviews general information of *Pinus Pinaster* Ait. considering multiple provenance and subspecies. Wood properties of industrial interest and their variability will be then exhaustively presented. This work is focused on *Pinus Pinaster* Ait. subspecies Atlantica for his importance in the Southwest of France. The properties of the species *Pinus Pinaster* Ait. are additionally briefly compared to the properties of others softwoods such as *Picea abies* and *Pinus sylvestris* for their global importance in the wood European industry and *Pinus nigra* Arn. 1785, *Pinus pinea* L. 1753, *Pinus radiata* D. Don 1836, and *Pinus taeda* L. 1753 for their geographic proximity with *Pinus Pinaster* Ait.

General information on *Pinus Pinaster* Ait.

Taxonomy

Pinus Pinaster Ait. is a conifer (*Pinophyta* division) in the *genus Pinus*. This species was first legitimately referenced by W. Aiton in 1789 in the *Horthus Kewensis* [8]. Even though its correct name is *Pinus Pinaster* Ait., it is sometimes erroneously referred (*nomen illegitimum*) as *Pinus Pinaster* Soland or *Pinus maritima* and is commonly called maritime pine or cluster pine. Two main subspecies exist that differ by their geographical location. The first one is *Pinus Pinaster* ssp. *Pinaster*, which is commonly called *Pinus mesogeensis* or mesogean pine, and the second one is *Pinus Pinaster* ssp. *Atlantica*, also known as Atlantic pine [9]. On the one hand, mesogean pine is mainly present on the occidental shores of the Mediterranean Sea across several provenances like Spain, South and South East of France, Northwest of Italy, Corsica, Sardinia, and Maghreb [10]. On the other hand, Atlantic pine is present in the Iberian Peninsula (especially Portugal and Galicia) and the Southwest of France (particularly in the Landes of Gascogne) [11, 12].

History of population

Pinus Pinaster Ait. is originated from the Southwest of Europe. Archaeological discoveries found traces of *Pinus Pinaster* Ait. in the South of France dated from the Paleolithic [13]. Thanks to anthracological studies, the presence of individuals has also been found during the Late Prehistory and Protohistory in Northwestern Portugal and in Northeastern Portugal dated from the Mesolithic [14, 15]. In the Late Iron Age (5th to 1st century B.C.), it was well-settled in this area and the Southwest of the Iberian Peninsula and vastly used in settlement construction [16, 17]. These observations led to the main theory that the species was autochthonous of these regions in the early Holocene and survived as monospecific stand or mixed with oaks (*Quercus*) ubiquitous in the area. Last, artificial forest (plantation) for wood or resin exploitation has proven unlikely in central Spain [18].

Forest dynamics are greatly influenced by several events, called disturbances, leading to modifications on forest ecosystems, referred to as succession [19]. These disturbances can be natural events (fire, storm, landslide, volcanic activity, insects, fungi), animal-caused events (grazing), or anthropogenic disturbances (warfare, pollution, tree crops). During the Antiquity to the beginning of the Middle Age, forests including *Pinus Pinaster* Ait. in the Iberian Peninsula were considerably modified by natural, climatic, and anthropogenic events [20]. Several alternations of humid and arid periods (like the Iberian-Roman Humid Period in Spain) and natural disasters (fire) alternated the vegetation.

Nonetheless, the most critical modification was bought by human activities starting from the Late Iron Age and, particularly, during the Roman Empire (1st century B.C. to 5th century A.D.) and the Visigothic Kingdom (5th to 8th century A.D.). Indeed, the development of agriculture and pastoralism, construction of settlements and roads, or cultivation of favoured species (chestnut and olive) provoked vast campaigns of woodland clearings especially by fire [20].

Fire-related reproductive traits (pyrophyte) explain the proliferation of *Pinus Pinaster* Ait. during the second part of the Middle Age (7th to 15th) marked by a combination of intensifying fire regime [21].

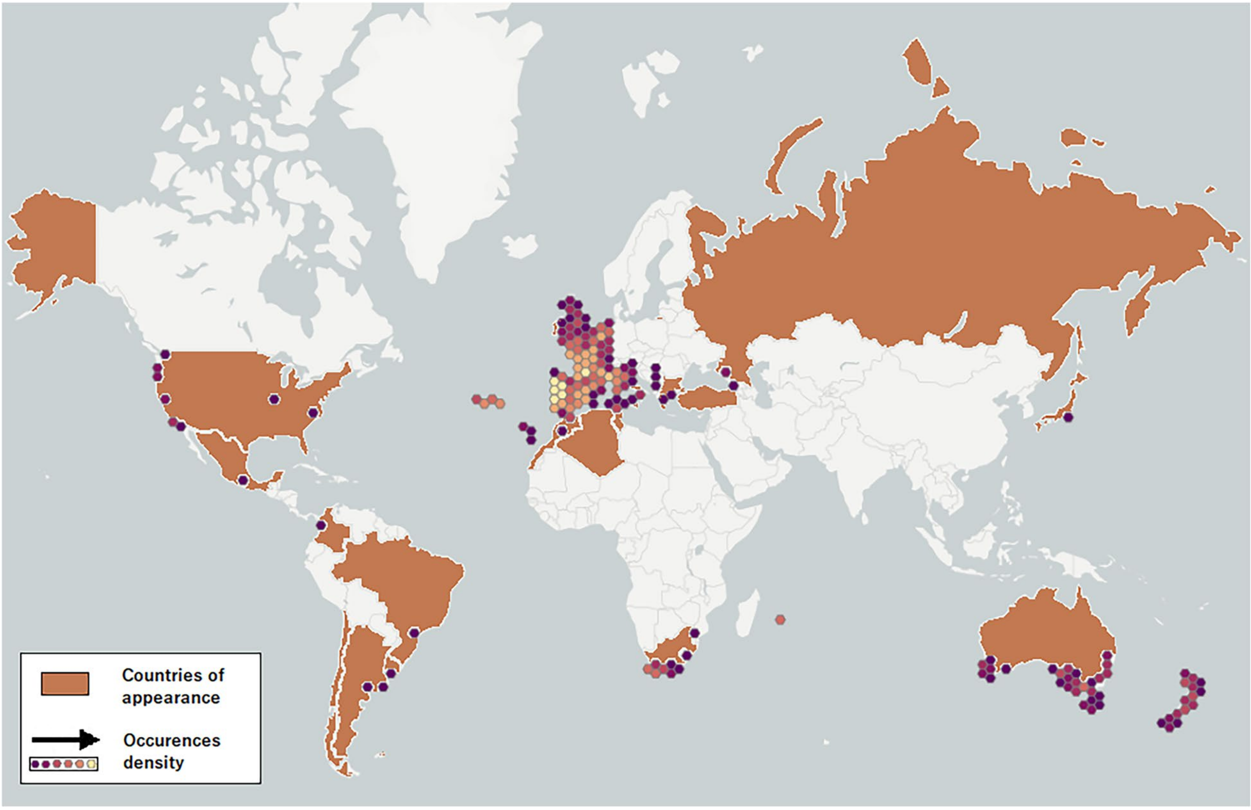

Fig. 1 *Pinus Pinaster* Ait. worldwide distribution adapted from GBIF (Commonwealth Agricultural Bureau International) maps [161, 162]

The beginning of the Early Modern Period (15th–16th centuries) showed a high rate of deforestation and, particularly, *Pinus Pinaster* Ait. in Southwestern Europe because of its uses in naval construction, buildings construction, charcoal demand, and exportation with a peak around the beginning of the Late Modern Period (18th–19th centuries).

Since then, specific French legislation was approved to protect forests. Broad reforestation campaigns impacted both public and private sectors. Reforestation of mountains area and stabilisation of coastal dunes promoted the plantation of *Pinus Pinaster* Ait. because of its ability to grow on low productivity and fertility soils (sandy, acidic soils, rich in silica or sandstone, and granitic arenas). In the Landes of Gascogne, its implementation had the initial purpose of rehabilitating the land for later agrarian activities. However, in a second time, pine-wood exploitation started participating significantly in the rural economy. Many products such as firewood, charcoal, tar, resin, pitch, turpentine, or rosin that were widely used in a large number of industries were produced using and exploiting *Pinus Pinaster* Ait. proliferation [22]. Nowadays, *Pinus Pinaster* Ait. is mainly processed in three major industries: wood production and exploitation, resin extraction, and papermaking.

As a last remark concerning other countries, from the end of the 17th century, as shown in Fig. 1, in the Southern Hemisphere like in Uruguay (1890), Argentina and Chile, South-Africa (1690), Australia (1920) and New Zealand, lacking fast-growing softwood species able to grow in harsh environment, decided to introduce *Pinus Pinaster* Ait. into their territory on infertile or sandy soil [23–25]. Subsequently, it has been considered as an invasive species in South Africa, Australia and New Zealand [26].

Current population of *Pinus Pinaster* Ait.

The worldwide area covered by *Pinus Pinaster* Ait. is approximately 4.4 million hectares, from which 4.2 million are situated in the countries *Pinus Pinaster* Ait. originated from, as shown in Fig. 1. The remaining 200×10^3 hectares are located in other areas where *Pinus Pinaster* Ait. was imported. It represents 51% of the total forest area in Aquitaine (with respectively 84% and 75% in the Landes and Gironde departments), 23% in Portugal, and 23% in Galicia [3, 27]. However, recent natural disasters caused important damages to the local *Pinus Pinaster*

Ait. population in these two French departments such as two storms, respectively Lothar and Martin in 1999 (24 millions m^3) and Klaus in 2009 (37 millions m^3) [1], and the forest fires of the few last years and especially 2022 (30790 hectares according to EFFIS's data [28]). Numerous other threats affect *Pinus Pinaster* Ait. such as insect attacks (*Dioryctria sylvestrella, Rhyacionia buoliana, Thaumetopoea pityocampa*), fungal attacks, inter-individual competition, and drought [9, 29–31]. Studies showed the vast importance of mixed stands compared to monospecific ones involving *Pinus Pinaster* Ait. on the resilience of forests to drought and more generally climate change impacts across Europe [32, 33]. Nonetheless, climate change could lead to extend the suitable area for *Pinus Pinaster* Ait. in the Iberian Peninsula in comparison to other species [34], as the species evolved originally in a pre-Mediterranean tropical-like environment [35], and is more fire adaptable than some of the other softwoods (*Pinus nigra* and *Pinus pinea*) in the area [36].

Xylology of *Pinus Pinaster* Ait.

Variability and structure of wood

Wood is a highly heterogeneous and anisotropic natural composite whose constitution results from layers accumulation through cambial activity responsible for the diametrical growth of trees. A local orthotropic coordinate system to describe the trunk geometry can be defined by three planes of orthogonal symmetry: the transversal plan RT, the longitudinal radial plan LR, and the longitudinal tangential plane LT. Three preferential directions can be distinguished: the longitudinal direction L of the stem, the radial direction R corresponding to the direction of diametrical growth, and the direction T tangential to the growth rings [37].

Cambium division is primarily influenced by external conditions such as characteristics of the biotope, interactions with the biocenosis, climatic environment, silviculture, tree height, and tree ageing, which affect the cambium division capability and variability of wood properties at different levels: between species, between provenances, inter-tree, intra-tree, inter growth rings, and intra growth rings.

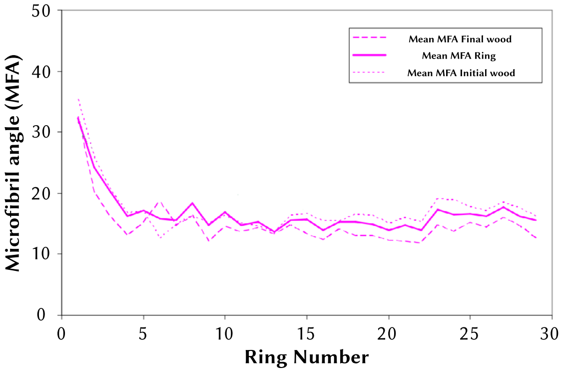

Fig. 2 Example of the evolution of the mean microfibril angle as a function of the ring number of a 30-year-old specimen measured, adapted from [39]

Anatomy of *Pinus Pinaster* Ait.

At the microscopic scale, wood is composed by tracheids which are longitudinal elements constituting 90% of softwood cells. They are formed by cells organised in different layers. The cell walls are natural fibrous composites composed of microfibrils of cellulose (46.37%) in a matrix of hemicellulose (24.21% and lignin (28.99%) with additional extractive contents in the case of *Pinus Pinaster* Ait. [38]. Close to no information exists in the case of *Pinus Pinaster* Ait. on the layers geometry except for the second sub-layer of the secondary cell wall. The sub-layer S_2 represents an important part of the secondary layer (75%–85% of the final thickness) and has an organisation of microfibrils in parallel lamellæ and inclined compared to the cell axis (10°–30° and can reach around 40° in reaction wood (RW) and in juvenile wood in the case *Pinus Pinaster* Ait. [39]. The orientation of this secondary sub-layer, defined by the angle of micro-fibrils (MFA), and its importance in terms of total mass and thickness are responsible for the mechanical behaviour of the wood cell wall. Limited literature does exist in the case of *Pinus Pinaster* Ait. for the MFA, especially as a function of the distance to the pith. Brémaud et al. found values for *Pinus Pinaster* Ait. (average with two other softwood species) of 22.4° at 6.9 cm [40] from the pith (corresponding to a cambial age of 8 years) whilst Lundqvist et al. provided the evolution of MFA for a few sample of *Pinus pinaster* Ait.) with ring number [39], as illustrated in Fig. 2. For other softwood species, Donaldson provided mean ring MFAs data for *Pinus radiata* ranging between 9° and 55° [41] and Auty et al. found values ranging from 5° and 35° for MFAs in the case of *Pinus sylvestris* [42]. The additive manufacturing of tracheids cells resulting from cambial activity is responsible for the tree diametrical growth. Tracheid geometries are defined by several parameters such as number of cells, lumen width or radial–tangential fibre width, radial and tangential cell wall width (total width of constituting layers) and tracheid length. Typical values for these anatomic parameters in the case of *Pinus Pinaster* Ait. are reported in Table 2 [38, 39, 43–47]. The anatomy of *Pinus Pinaster* Ait. cells is particularly dependent of the climatic conditions affecting the cambial activity and can endure important modifications during an annual growing season, as illustrated in Fig. 3. *Pinus Pinaster* Ait. tracheids are mostly divided into three different types, i.e., initial wood of important

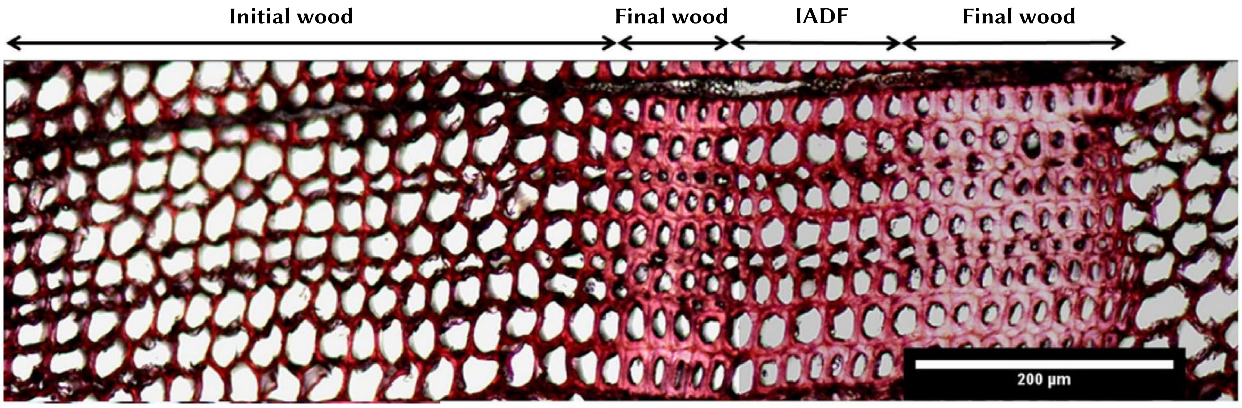

Fig. 3 Light microscope images showing the anatomical differentiation of *Pinus Pinaster* Ait. cells in a complete growth ring [43] with the different parts of initial wood, final wood, and inter-annual density fluctuation (IADF)

lumen diameter and thin cell wall width, final wood of narrower lumen and thicker cell wall, and zones of inter-annual density fluctuation (IADF) which corresponds to the apparition of initial wood-like cells in the final wood zone, which can be explained as a defense mechanism against drought period [43]. Several focus on the influence of climatic environment (solar radiation, temperature, water availability, and evapotranspiration) and characteristics of the biotope (altitude, soil properties) on the anatomy of the species *Pinus Pinaster* Ait. Bogino and Bravo showed a 60.8% of the total variance of radial growth of *Pinus Pinaster* Ait. samples from the Iberian Peninsula with climate environment and especially precipitation and temperature [35] and found a good correlation between radial growth, temperature, and altitude. Carvalho et al. linked the variability of lumen diameter and cell wall thickness with soil moisture content and temperature, respectively [44]. Ballesteros et al. studied the modification of cell anatomy of *Pinus Pinaster* Ait. after wounds obtained by flash foods [48]. Riesco Muñoz and Barrio Anta studied the modification of anatomical parameters of *Pinus Pinaster* Ait. cells with gravitropic modification inducing the apparition of compressive wood [49]. In the case of IADFs, Wilkinson et al. found a strong correlation between the apparition of IADFs in the final wood with precipitation events following summer drought [43]. Campelo et al. and Vieira et al. found an increased frequency of apparition of IADFs in specimens of *Pinus Pinaster* Ait. with larger diameters [50] and in young trees [51], respectively. Moreover, Nabais et al. observed a strong species-dependent influence of IADFs apparition by studying the differences arising between two softwoods, i.e. *Pinus negra* and *Pinus Pinaster* Ait. [52]. The influence of the climate environment on the anatomy and the growth response is distinctly variable according to softwood species. Hernández-Alonso et al. showed that *Pinus Pinaster* Ait. is the species the most impacted by temperature in comparison to *Pinus negra* and *Pinus sylvestris* much more impacted by water availability [53]. Häusser et al. found temperature of growth initiation colder for *Pinus nigra* in comparison to *Pinus Pinaster* Ait. provoking a 1 month time shift in the period of growth initiation [54]. Finally, Olivar et al. studied the differences in the historic of precipitation on growth response and IADFs between *Pinus Pinaster* Ait., more impacted by the preceding winter and spring of growing season, and *Pinus sylvestris*, impacted by mostly by summer precipitation [55].

Growth-influencing mechanisms

The presence of heterogeneous factors in the growth environment leads to curvature and stem reorientation (also called tropism) of the plant, i.e. modifications of cross-section shape and size, eccentricity of the pith. Tropisms are mainly divided into phototropism, gravitropism and thigmotropism (reorientation due to external contact stress) [56]. *Pinus Pinaster* Ait. of the Landes situated in coastal dunes is particularly influenced by strong prevailing winds (anemotropism) [57].

Regarding anemotropism, Polge et al. analysed the inclination of trunks of *Pinus Pinaster* Ait. population of Landes of Gascogne according to the preferential west to east wind flow directions [58]. Berthier et al. highlighted several phenomena resulting from wind effects (static) such as the inclination of the stem, imbalance of the crown, eccentricity, non-circularity of the sections, pre-existing constraints on the trees root system, and presence of RW, as shown in Fig. 4 [59]. The same authors presented the action of wind turbulence on the geometric shape of the trunk with the reduction of stem lengths,

Fig. 4 Impact of wind solicitations on the inclination of trunks and transverse section shape of *Pinus Pinaster* Ait. trees planted in coastal dune regions [59]

more comprehensive sections combined with meplat (non-circular trunk), and eccentricity of the pith [59].

Genetics has also an important influence on growth. Several studies on genetic modifications of *Pinus Pinaster* Ait. have been carried out to improve the growth and straightness of *Pinus Pinaster* Ait. stems considered as "bad" for the timber industry due to their eccentricity [57, 60]. The genetic characteristics of *Pinus Pinaster* Ait. and the possibility of genetic selection were first inquired between 1930 and 1950 [61]. An extensive breeding program was then performed since 1960 to genetically improve the properties of this specie with two main goals: to genetic gain in growth and stem straightness as well as to preserve diversity in the breeding populations [62]. An improvement ranging between 15% and 30% was measured from the first bred generation to the early 2000s population whilst the second purpose was less studied in spite of its major importance [60, 63].

Last, silviculture has a substantial impact on tree growth. Indeed, variables such as population density, thinning regimes, and rotation forestry duration exploit response mechanisms aforementioned and influence the growth and properties of trees for aesthetic or economic purposes [37, 57, 64]. The current rotation duration used for *Pinus Pinaster* Ait. silviculture is considered short and ranges between 20 and 40 years [1].

Physiological properties

Juvenile and adult wood

An analysis of wood properties allows establishing an age limit between juvenile and adult wood located far from the pith. This boundary can vary according to tree height, ring density and fibre length [65]. Moreau et al. proposed a method for identifying the juvenile wood–adult wood limit that uses delimitation techniques successfully performed on other softwood species such as Douglas fir or Scots pine [1]. This method is based on linear regressions on final wood density measurements inside growth rings. This method can be used in the case of *Pinus Pinaster* Ait. because of the abrupt limit between juvenile and adult wood [66]. The usual limit found is approximately 12 years for *Pinus Pinaster* Ait. and can reach 9 years, as schematically illustrated by Fig. 5 [1]. For *Pinus sylvestris*, Sauter et al. found a mean limit of 22-year old with a standard deviation value comprised between 5- and 7-year old [67].

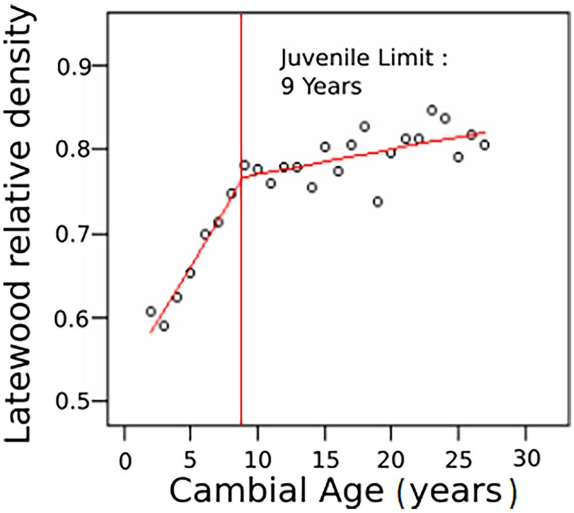

Fig. 5 Juvenile wood limit identification by an intersection method relying on linear regressions of final wood relative densities as a function of the cambial age for *Pinus Pinaster* Ait. [1]

Heartwood and sapwood

Heartwood is characterised by a colour change with respect to sapwood that, in the case of *Pinus Pinaster* Ait., takes a "darker red" colouring, as illustrated Fig. 6. In the case of *Pinus Pinaster* Ait., there is no

Fig. 6 Illustration of *Pinus Pinaster* Duramen characterised by a "darker red" colouring [1]

fundamental differences between longitudinal modulus of elasticity of sapwood and heartwood [68]. An hypothesis seems to link the formation of heartwood to the tree general energy consumption. Heartwood being composed by dead cells, its formation could optimise sapwood surface area to adjust the energy inflow according to the leaf sap demand [69]. This phenomenon has been explained by the Pipe Model Theory [70, 71] which was demonstrated for *Pinus Pinaster* Ait. [68]. Further studies have shown the influence of internal parameters on heartwood formation such as genetics [72] and cambial age, and external parameters such as environment and silviculture [69, 73]. Knapic and Pereira showed an initial heartwood formation in *Pinus Pinaster* Ait. around 21 years followed by constant annual development rates dependent on cambial age of 0.5 and 0.7 rings/year for a cambial age inferior and superior to 50 years, respectively [74]. Gjerdrum found a similar relationship in *Pinus sylvestris* with a rate of formation of 0.5 rings/year for a cambial age of 50 years up to a rate of 0.8 rings/year at 200 years [75].

The surface percentage of heartwood, relative to total surface, in the transverse plane varies along the longitudinal direction of the tree. Taylor et al. described the general heartwood surface percentage profile in the longitudinal direction of the tree as an irregular cone [69]. This conical profile is not found in the case of *Pinus Pinaster* Ait. Indeed, an increasing heartwood surface percentage was found up to an height of 3–6 m followed by a constant decrease in *Pinus Pinaster* Ait. The specific height was estimated around 35% of the total height for 20 trees of *Pinus Pinaster* Ait. [1, 73, 74, 76]. Giroud et al. found a similar profile for *Betula papyrifera* [77]. The lower water conductivity at the tree base for *Pinus Pinaster* Ait. could explain this particular profile. Indeed, the duraminisation would slow down to compensate the conduction loss [78].

Variability in the transverse heartwood profile also exists. A quasi-circular shape of the heartwood surface up to an average height of 10 m in certain individuals of *Pinus Pinaster* Ait. has been found [76]. Variation of heartwood percentage or shape can occur because of pith eccentricity, meplat (elliptical shape of the trunk), crown influence, or presence of RW resulting from external mechanical solicitations (wind, snow). The number of *duramen* rings is greater on the compression side, as schematically represented in Fig. 7 [68, 79]. Mechanisms of increased heartwood formation induced by compression wood (CW) presence are still relatively unknown [72].

Reaction wood

The reorientation of the stem is ensured by the formation of RW which has different property when compared to normal wood (NW) [80]. In softwoods, RW is also referred as CW and occurs in the wood region under compression (e.g., downwind), as illustrated in Fig. 7(b). In CW, the transition between initial and final wood is progressive for species where this anatomical transition is usually abrupt, which is the case for *Pinus Pinaster* Ait. [58]. Radi and Castéra present the CW distribution of two *Pinus Pinaster* Ait. trunks that show a consequent reorientation induced by basal rectification (tilted ground) or reorientation by phototropism [64]. The average CW percentages in the two individuals are 3.89% and 5.97%, respectively, despite a greater basal inclination in the first case. In the French *Pinus Pinaster* Ait. industry, the presence of CW is neglected because of its difficult identification.

Geometric properties

Height and diameter

The species *Pinus Pinaster* Ait. is a fast-growing softwood that reach around 23–26 m in height for a diameter at breast height ranging between 415 mm and 470 mm and tree age between 35- and 48-year old [81, 82] in comparison with the most popular industrial softwood species in Europe, i.e. *Picea abies*, that reach height of approximately 18–24 m for a diameter at breast height ranging between 150 mm and 300 mm and tree age between 36- and 43-year old (in Lithuania) [83] and a locally relative species, i.e. *Pinus nigra*, that reach height of approximately 15–27 m for a diameter at breast height ranging between 200 mm and 400 mm and tree age between 58- and 93-year old (in Portugal) [84]. Typical values for height increment, tree height, and diameter at breast height for *Pinus Pinaster* Ait. are reported in Tab. 3 [81, 82, 85–87]. Radial growth and height increment are two geometric parameters widely influence by the climatic environment, particularly precipitation and temperature historic (duration, season of occurrences). The impact of drought is more important on height increment and basal radial growth than radial growth on the upper part of the stem [87]. The annual height increment comprises between

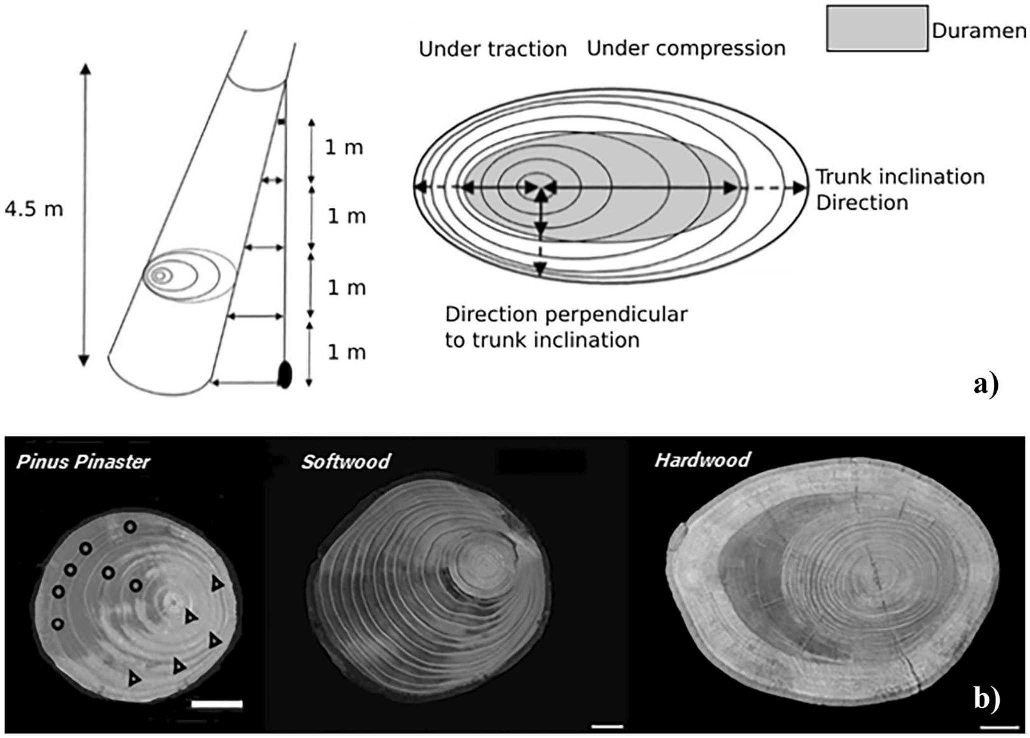

Fig. 7 **a** Elliptical *Duramen* formation induced by the presence of compressive wood under trunk inclination in *Pinus Pinaster* Ait. [79], **b** transverse section of *Pinus Pinaster* Ait. containing compressive wood in comparison to softwood and hardwood transverse section [40]

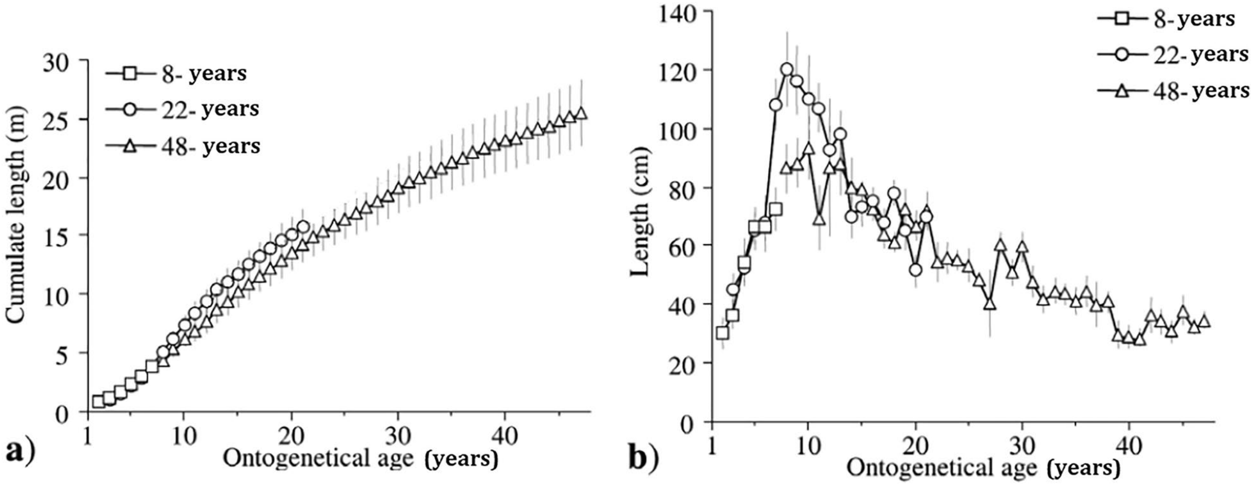

Fig. 8 **a** Cumulate length of the stem and **b** length increment to the stem per year for 32, 20, and 10 samples of 8-, 22-, and 48-year-old *Pinus Pinaster* Ait. trees, respectively, as a function of the ontogenetical age [82]

20 and 180 cm for 10 samples of *Pinus Pinaster* Ait. dominant trees from Soria in Spain in [87] and 30 to 120 cm for 62 samples of *Pinus Pinaster* Ait. dominant trees ranging between 8-, 22-, and 48-year old from Bordeaux in France in [82]. In dominant trees of *Pinus Pinaster* Ait., where the influence of resource competition is minimum, the height increment increases rapidly in the early ages of a tree until around 10-year old followed by a constant decline with ontogenetical age, as illustrated in Fig. 8.

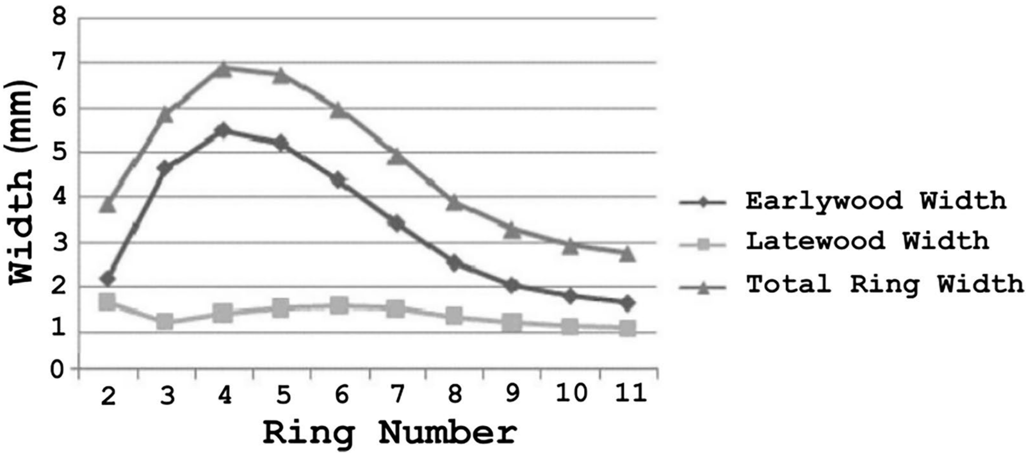

Fig. 9 Inter-ring values for earlywood, latewood, and total ring width as function of ring number for the first 12 rings of a Portuguese (Leiria) *Pinus Pinaster* Ait. [89]

Ring width

The ring width is the geometric parameter the most reflecting of the climatic condition undergone by *Pinus Pinaster* Ait. during the growing season. Except for tree species growing in harsh environments, ring width is not a constant.

Ring width decreases along the diametrical direction from the pith to the bark for a given height, with a pronounced decrease in the juvenile wood, from a value of around 8–12 mm to an asymptotic value of around 2 mm. An exception exists in the first rings because of the growing difficulties (competition, climatic hazards) experienced in the younger stages of a tree [57]. In the case of *Pinus Pinaster* Ait., an increase in ring width in the first rings (up to the first 5–9) and then a constant decrease for a sample of eight 83-year-old pines was found [88]. This tendency can also be observed with samples measurements, as illustrated in both Figs. 9 and 10 [89, 90]. In the case of other softwoods, Dias et al. found a constant decrease of mean ring width with cambial age from a value of around 5–6 mm to an asymptotic value around 1 mm reached around 40 years in the case of *Pinus nigra* [84].

Typical values of the ring width for the *Pinus Pinaster* Ait. are reported in Table 4. The measuring techniques can be very different: Nicholls measures ring widths at the green state with a low-power objective lens engraved with a precision scale of 0.1 mm, Burgers uses an "Absolute Digital Metric Indicator" at 12% moisture content with a precision of 0.02 mm, Gaspar and Louzada measure this property at a conditioned 12% moisture content with X-rayed images (no information about the used instrument is given) [89–94].

The proportion of initial wood is higher in the upper part of the tree than in the lower part (70% to 83%). The width of initial wood is always greater than final wood one in *Pinus Pinaster* Ait. Therefore, a larger ring width in the top of the trunk is explained by juvenile wood presence. These observations are in agreement with the general theory of ring width variations [57].

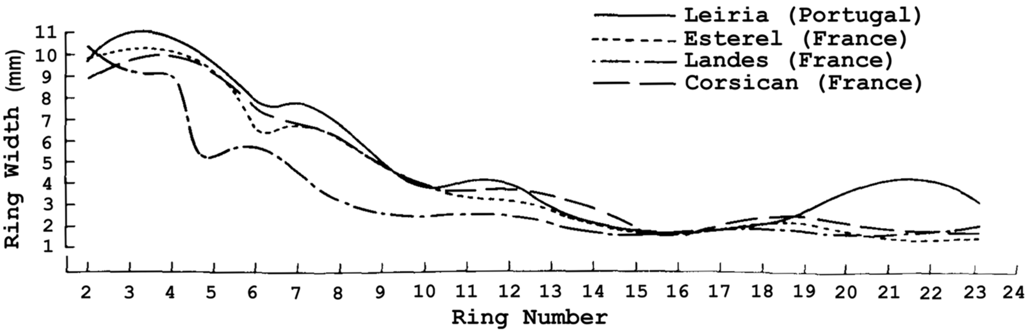

Fig. 10 Inter-ring values for total ring width as function of ring number for the first 23 rings of specimens of *Pinus Pinaster* Ait. originating from several provenances [90]

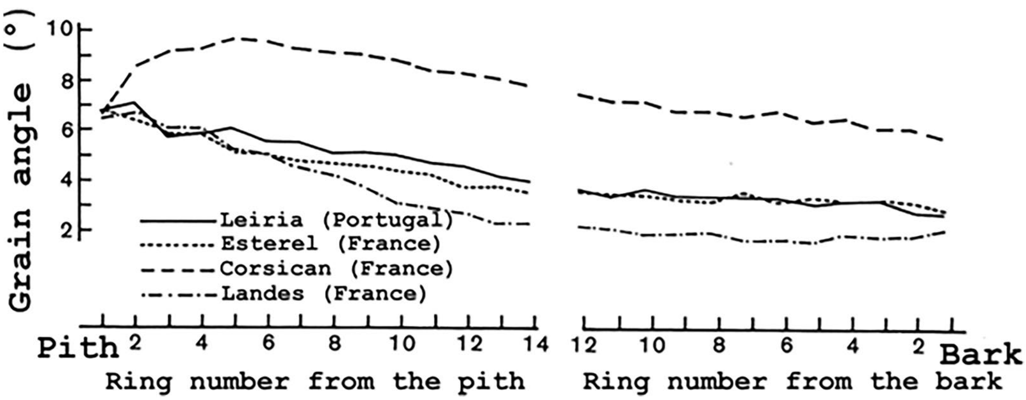

Fig. 11 Inter-ring values for wood grain angle as function of ring number for the first 27 rings of specimens of *Pinus Pinaster* Ait. originating from several provenance [163]

Grain angle

The grain angle is the angle between the direction of the wood fibre and the longitudinal direction in the LT plane. In the case of *Pinus Pinaster* Ait., the grain angle can rise up to 8° around the first few rings before gradually decreasing with cambial age, as illustrated in Figs. 11 and 12. High intra-tree variability of the grain angle (between −1.8° and +10.4° with a coefficient of variation of 88%) using a radioactive tracer to facilitate measurements is observed [95]. The tendency for the grain angle to increase in the first few rings close to the pith and then to decrease gradually with ring number is common to other softwood species, where the grain angle can rise to values up to 12° in the case of *Pinus radiata* [96] and *Picea abies* [97] before decreasing to reach values down to −12° in the case of *Picea abies* [97].

In the vertical direction of the tree, at a given distance from the pith, the wood grain angle seems to increase gradually from the basal area to the top of the tree, as shown in Fig. 12. This phenomenon can be explained by the increasing proportion of juvenile wood along this direction [57]. Density, straightness, and the presence of RW do not seem to impact the wood grain angle [1].

Physical properties: density

Wood density is an important physical parameter because of its influence on the mechanical properties, its ease of measurement, its use as a wood quality criterion [60], and its reflection of the growing season climate conditions.

Intra-ring density

In softwoods, such as *Pinus Pinaster* Ait., the ratio final wood density to initial wood density belongs to the range $(2, 4)$ [91]. Density variations within a ring have been linked to anatomic variations due to cambial activity. The common density profile for a ring composed of initial and final wood in the case of *Pinus Pinaster* Ait. is shown in Fig. 13. The intra-ring relative density values are usually comprised between 0.2 and 0.9 for *Pinus Pinaster* and are similar to the one obtained for *Picea abies* where the values are usually comprised between 0.3 and 0.9 [98].

This initial–final wood structure is an essential source of density variation at the microscopic level [99]. This differentiation is produced by a change in the water supply/demand balance during the growing season and hence is deeply related to climatic conditions [78, 100]. The proportion of final wood in a ring in the case of *Pinus Pinaster* Ait. is highly variable and it depends upon several parameters, like climatic conditions, RW and ring age, see Fig. 14. Typical values of intra-ring density and proportion of latewood

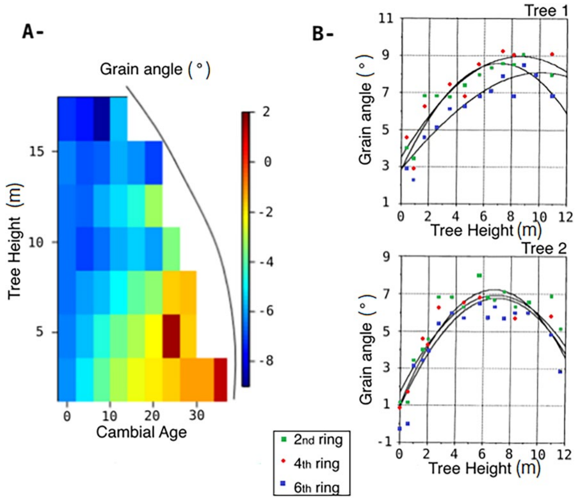

Fig. 12 Height influence on grain angle for *Pinus Pinaster* Ait. obtained **A**—in [1] (values should be read with opposite sign) thanks to a calibrated inclinometer and **B**—two trees obtained in [64] by measuring the direction of crack propagation in splitting tests

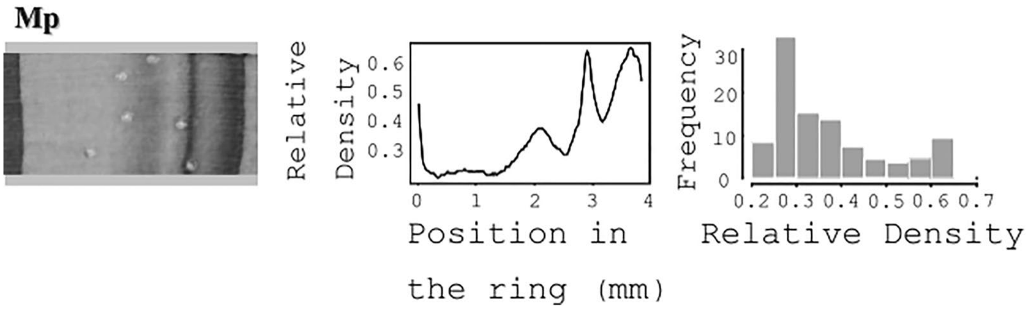

Fig. 13 **a** Evolution of intra-ring relative density as a function of the position in the ring studied (mm) and **b** corresponding relative densities frequency apparition for *Pinus Pinaster* Ait. [164]

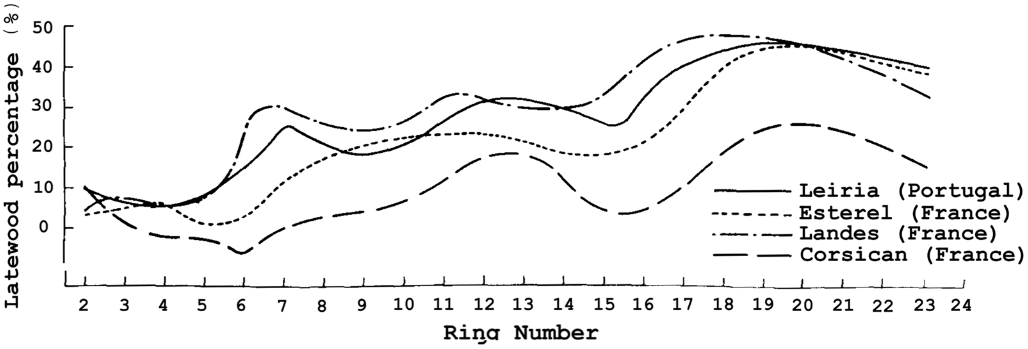

Fig. 14 Latewood percentage evolution as function of ring number for specimens of *Pinus Pinaster* Ait. originating from several provenance [90]

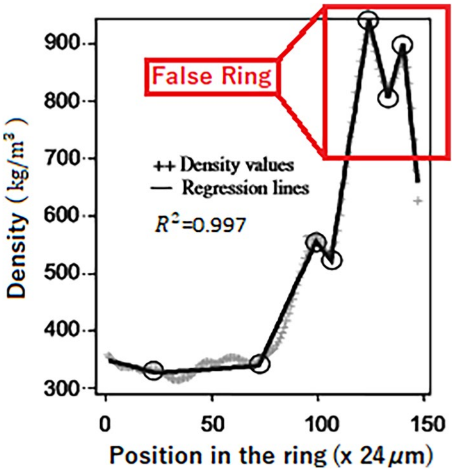

Fig. 15 Highlighting of the False Ring or IADF phenomenon in *Pinus Pinaster* Ait. thanks to the study of intra-ring density as a function of position in the ring [101]

for the *Pinus Pinaster* Ait. are reported in Table 5. Most of studies obtain density values using a microdensitometric analysis on X-rayed images (samples conditioned at 12% moisture content) [1, 89, 93, 101–103]. They compute densities from anatomical data on cell walls [43].

Furthermore, particular climatic conditions (succession of rainfall after severe drought) can trigger cambial reactivation and unique occurrences such as the appearance of additional density peaks in the final wood [104]. This phenomenon is called “false ring” and is quite frequent in juvenile wood of *Pinus Pinaster* Ait. more impacted by the climatic conditions, as shown in Fig. 15.

Inter-ring density

Variations in inter-ring density, although smaller than variations in intra-ring density, are significant in softwoods (20–25% of mean variation). Two studies provide inter-ring density data for *Pinus Pinaster* Ait. [89, 90]. A microdensitometric analysis on samples dried at 12% moisture content is used [89]. In the meanwhile, Nicholls claim to measure basic specific gravities (ratio of oven-dry mass to green volume) by drying samples at 103°C during 4 h [90]. However, the study never provides the relative humidity needed to estimate the resulting equilibrium moisture content (EMC).

In the case of *Pinus Pinaster* Ait., a decrease in the mean relative density was observed in the first few rings close to the pith followed by a general increase until

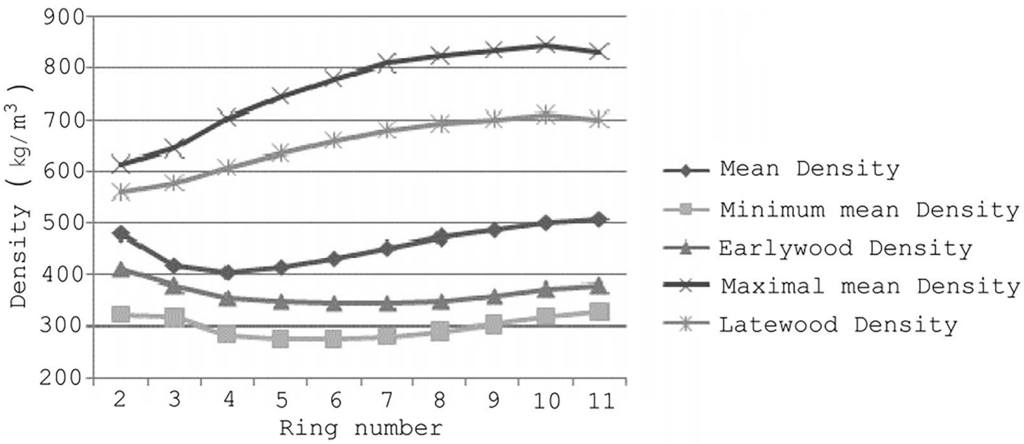

Fig. 16 Evolution of inter-ring mean relative densities as a function of ring number for 552 specimens of *Pinus Pinaster* Ait. originating from Leiria-Portugal [89]

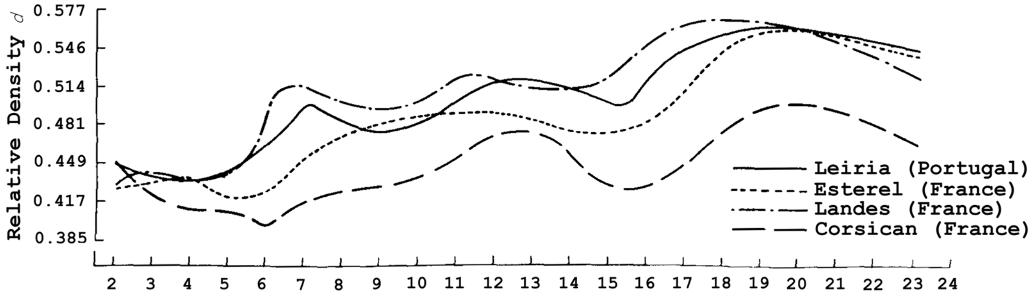

Fig. 17 Evolution of inter-ring mean relative densities as a function of ring number for the first 23 rings of specimens of *Pinus Pinaster* Ait. originating from several provenance [90]

the 11th to 15th ring, see Figs. 16 and 17 [89, 90]. The value of mean ring relative density is generally lower in the juvenile wood compared to mature wood where it reaches an asymptotic value and is negatively correlated with ring width. A density limit value of around 0.55 is reached in the mature wood zone, as illustrated in Fig. 17 [90]. In the case of *Pinus radiata*, the asymptotic value is roughly similar to *Pinus Pinaster* Ait. [96], whilst its value is closer 0.6 in the case of *Pinus nigra* [84], and closer to 0.45 in the case of *Picea abies* [105].

A correlation can also be found between latewood relative density and ring width. At a given cambial age, as ring width increases, the latewood relative density decreases, as shown in Fig. 18.

Hygric and thermal properties of *Pinus Pinaster* Ait.

Moisture transfer model and hygric properties

Water content

A stabilisation of moisture content for *Pinus Pinaster* Ait. logs stored for several months under immersion of 190% for sapwood rings and 60% for *duramen* rings was presented [106]. This moisture content gradient is important and can induce high stresses at the sapwood–heartwood transition zone [107]. Water content seems constant in the *duramen* but variations in moisture content exist

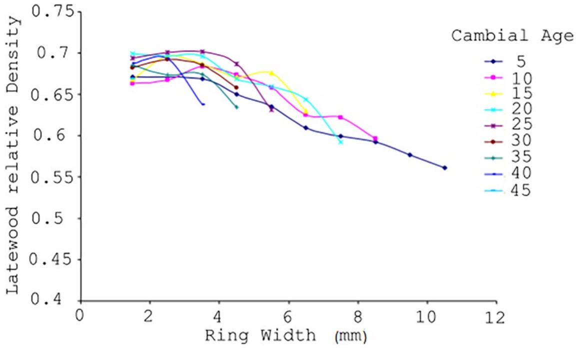

Fig. 18 Evolution of latewood relative density as a function to ring width and cambial age obtained experimentally for specimens of *Pinus Pinaster* Ait. [1]

in the sapwood with additional variations between initial and final wood (up to 4 times). Furthermore, supplementary variations have been registered up to 50% along the height of the tree for softwoods [57]. *Pinus Pinaster* Ait. is usually dried up to 12% for its industrial uses. Indeed, French standard indicates that the measurements of deformations must be carried out after drying with a moisture content of 12% [108]. Annex A denotes that in case of unknown service class, the moisture content must be limited to 16% [109]. Annex B states that for an unheated carpentry structure, the moisture content must belong to the range 12%–19% outside and 12%–16% inside [110]. For heated structures, it should belong to 9%–13%. It specifies that for service classes 1, 2 and 3, the water content must be equal to 12%, to 12%–16% and possibly higher than 18%, respectively [111]. The anhydrous mass is obtained when the wood has been dried at 103 °C until the difference in mass between two successive measurements taken 2 h apart is less than 0.1%, according to the French norm [112].

Sorption–desorption isotherm and equilibrium moisture content

For a given temperature and air relative humidity, wood reaches an EMC. For a given temperature, one can trace sorption isotherms that link air relative humidity to the equilibrium water content of the wood. These isotherms are quite independent of the species (unlike the sorption kinetics, which strongly depends on density and anatomical structure) [113]. The FSP is the wood water content (about 30% for *Pinus Pinaster* Ait.) corresponding to a saturation of cell walls by bound water [40]. Above this point, free water fills the cell cavities by capillarity and its maximum content depends on the porosity of the wood (up to 200% water content) [6]. The wood sorption isotherms depend on the history of thermo-hygric variations.

Pinus Pinaster Ait. sorption model

Several analytical modelling laws exist to express the wood water content H as a function of temperature T and relative humidity h. These models seem to be valid for a temperature range between 0 °C and 100 °C [114]. In the case of *Pinus Pinaster* Ait., a semi-empiric relationship for adsorption isotherm based on experimental results originated from the Landes region is proposed [113]:

$$\mathrm{EMC} = \frac{\log(Q)}{100\ \log(B')}, \tag{1}$$

where Q is defined as

$$Q = \frac{C^{'}}{A^{'}} - \log h, \tag{2}$$

whilst parameters $A^{'}$, $B^{'}$ and $C^{'}$ depend upon the temperature as follows

$$\begin{aligned} A^{'} &= -2.86\ 10^{-5}\ T^2 - 1.075\ 10^{-2}\ T + 10.238, \\ B^{'} &= -5.414\ 10^{-4}\ T + 1.0134, \\ C^{'} &= 4.976\ 10^{-6}\ T^2 - 2.667\ 10^{-3}\ T + 0.3546. \end{aligned} \tag{3}$$

Whilst established thanks to experimental data on *Pinus Pinaster* Ait., this semi-emperic relationship is not well-adapted to predict the EMC of *Pinus Pinaster* Ait. and more accurate models such as Hailwood-Horrobin [115] for softwoods can be used.

Hygric transfer model

The physical phenomenon of moisture transfer in wood can be separated into two parts: above and below the FSP. Above FSP, the physical behaviour of water transfer is not yet fully understood. It is generally acknowledged that in this phase, wood presents an evaporation plane. This evaporation divides wood into a wet zone towards the centre and a dry zone towards the exterior of the material. Below the FSP, the material is situated in the hygroscopic range. The water transfer is completely controlled by the diffusion of bound water and water vapour transport. The coefficients of these two types of transfer can be combined into a total diffusion coefficient [116, 117].

One of the most common water transfer model is the transient total diffusion model. This model is based on Fick's diffusion laws [118, 119]. It provides sufficient accuracy below the FSP (30% in *Pinus Pinaster* Ait.) contrary to a linear diffusion model. The transient total diffusion model is based on water transport induced by a water content gradient. Clouet used this model in the case of *Pinus Pinaster* Ait. to describe the stress state developing in several configurations of glulam manufactured at green state [6]. Two parameters govern this model: the surface-emission coefficient (SEC) s and the diffusion coefficient D. The estimation of these parameters is fundamental to match experimental results [120]. The coefficient s reflects the external resistance against moisture transport and is influenced by temperature, velocity, viscosity, wood density, moisture content and surface condition [121]. The diffusion coefficient D is function of wood anatomy, temperature and moisture content.

Considering a given volume V of wood characterised by a total external surface S and subject to a given moisture flow $\mathbf{q}$. The Fick's first law can be written as

$$
\begin{aligned}
\mathbf{q} &= -\mathbf{D}\nabla H, \\
\dot{\mathbf{q}} &= -\dot{\mathbf{D}}\nabla H - \mathbf{D}\nabla \dot{H},
\end{aligned}
\tag{4}
$$

with $\mathbf{D}(H)$ the diffusivity matrix as a function of moisture content H and defined by three diffusion coefficients $D_a(H)$ along the orthotropy directions $a = L, R, T$ and $\bar{\nabla} H$ moisture gradient vector. Those terms are expressed in the local orthotropic coordinate system [122].

The strong formulation of Fick's second law reads:

$$
\frac{\partial H}{\partial T} = \vec{\nabla} \cdot \left(\mathbf{D}\overrightarrow{\nabla H} \right) + Q, \tag{5}
$$

where $\frac{\delta H}{\delta t}$ is the rate of moisture variation and Q the moisture content given to the body per time unit. The boundary conditions associated to the above formulæ are usually expressed as

$$
q_n = s(H) \times (H - H_0), \tag{6}
$$

with $s(H)$ the SEC, which depends on the moisture content H, whilst $(H - H_0)$ is the initial difference in moisture content between the external surface S and the surrounding environment and q_n the normal flux towards the exchange surface.

For *Pinus Pinaster* Ait. $D_a(H) \in [5; 10] \times 10^{-10}\, m^2.s^{-1}$ with $a = R, T$ and $s(H) \in [6; 8] \times 10^{-8}\, m.s^{-1}$ was experimentally found [6].

Hygroscopic deformation

Hygroscopic deformation is induced by moisture content variations below FSP whose value is approximately 30% (29%–31% for *Pinus Pinaster* Ait.) [91]. Consequently, the wood swells or shrinks during absorption or desorption phases. Above the FSP, changes in moisture content do not influence the dimensional variations (uncoupled with mechanical behaviour) of wood [123]. Due to the wood orthotropic symmetry, shrinkage and swelling due to moisture content variations strongly depend upon the symmetry axes L, R, T. These hygroscopic deformations ε_H are governed by shrinkage/swelling coefficients α_i in %/%, which describe the dimensional variations S_i in % along the directions $i = L, R, T$ for a 1% water content loss under the FSP:

$$
\begin{aligned}
\alpha_i &= \frac{S_i}{\text{FSP}}, \\
\dot{\boldsymbol{\varepsilon}}_{\mathbf{H}} &= \alpha \dot{H}, \\
\boldsymbol{\alpha}^T &= [\alpha_L \;\; \alpha_R \;\; \alpha_T \;\; 0 \;\; 0 \;\; 0].
\end{aligned}
\tag{7}
$$

The shrinkage coefficients are always estimated as a relative differences between the dimensions of the anhydrous (0% moisture content) and the green state (30% moisture content). Although the distribution of the shrinkage/swelling coefficients is quite heterogeneous, as reported in Table 6, very often constant coefficients have been used on *Pinus Pinaster* Ait. studies [6]. The range of values of transverse shrinkage coefficient of $\alpha_R = 0.05$–0.20 and $\alpha_T = 0.15$–0.35 for *Pinus Pinaster* Ait. [124] are similar to the ones obtained for *Pinus radiata* in [96] and different from the ones obtained for a sample of two trees of *Picea abies* which are $\alpha_R = 0.10$–0.25 and $\alpha_T = 0.25$–0.40 in [125].

Shrinkage properties are deeply influenced by several wood parameters. A strong correlation for a linear relationship between infra-density and transverse shrinkage (α_R and α_T) properties was showed [124]. For *Pinus Pinaster* Ait., significant variations in the juvenile wood zone for the longitudinal coefficient with some impossible negative values between −0.003 and 0.003 were observed [90]. In CW, despite an increase in density, α_R and α_T remain lower than in NW with a decrease of about 50% [40]. Whereas α_T increases in CW up to a value of 0.09, α_L can reach values around 1%/% in juvenile wood and CW [57]. This shrinkage value cannot be negligible for specific lengths considered in construction. However, CW is rarely identified in the industries for the volumes processed. Along the longitudinal direction, an increase of 14.9% from top to base of the stem for α_T, regardless of tree individuals were presented [124].

Mechanical properties of *Pinus Pinaster* Ait.

Several models are available in the literature to describe the behaviour of wood subjected to coupling of mechanical loads and climatic variations [6, 126–131]. In the case of *Pinus Pinaster* Ait., only the mechanical and failure properties are presented in the following of the article.

Elastic properties

Hooke's Law

Wood is an orthotropic material defined by three main orthotropy R, T, and L axes. The planes RT, TL and LR are planes of orthogonal symmetry for the wood material. Its elastic behaviour is modelled through Hooke's law whose compliance matrix for wood is uniquely defined via 9 independent elastic constants: three Young's moduli of elasticity E_i, $(i = R, T, L)$, three shear moduli G_{ij} $(i, j = R, T, L)$, and three Poisson's ratios ν_{ij}.

To evaluate softwood mechanical properties at the microscopic scale, a two-scale homogenisation method to determine the constant elastic properties of the cell wall layers from the properties of its constituent polymers before computing wood cell wall lamella properties at 12% moisture content is used [132]. At the macroscopic scale (tree scale), several studies presented their experimental results for *Pinus Pinaster* Ait. elastic properties: some of these data are reported in Table 7. Cariou et al. presented elastic properties issued from tensile and shear tests on specimens visually chosen with a straight grain angle, constant spacing growth rings, high radius of curvature, and without knots [133]. The shear mechanical properties from clear wood specimens extracted from a 74-year-old *Pinus Pinaster* Ait. tree were measured [134, 135]. The properties are evaluated through three different shear tests: the Iosipescu test, the off-axis test, and the Arcan test. Santos et al. presented the Young's moduli and Poisson's ratios as results of tensile test [136]. The radial modulus of elasticity thanks to 3-point bending tests was evaluated [137]. The longitudinal Young's modulus and Poisson's ratios for several specimens of clear wood, with variability in density and growth rings width, obtained from tensile and compression tests parallel and transversal to the grain, shear tests and flexural tests were also evaluated [138]. Finally, an anisotropic-based method resting on digital image correlation and tensile tests to evaluate elastic properties in the transverse plane of specimens was used [139].

In comparison with other softwood species, the Young's moduli of *Pinus Pinaster* Ait. are similar to the properties of *Pinus radiata* [96], whilst the longitudinal Young modulus ((11.4, 17.8) GPa in Table 7 in the case of *Pinus Pinaster* Ait.) is lower in the case of *Pinus sylvestris* and is comprised between 7.4–7.9 for samples between 30- and 60-year old [140] and in the case of *Picea abies* with values comprised between 11.0 and 15.0 GPa [141]. In the case of the shear moduli of elasticity, the properties of *Pinus abies* are much lower than the ones of the species *Picea pinaster* Ait., with properties equal to $G_{RT} = 33.4$ MPa, $G_{TL} = 681$ MPa, and $G_{LR} = 702$ MPa [142].

Variability of elastic properties

As all natural materials, *Pinus Pinaster* Ait. is characterised by a a significant variability of elastic properties which is most prominent intra-tree [143]. A model was established for predicting the elastic properties of hardwood and softwood species as a function of their density d [7]. The following equations describe the elastic properties (MPa) of standard softwoods.

$$
\begin{aligned}
&E_L = 13100 + 41700(d - 0.45),\ \frac{E_R}{\nu_{RT}} = 20250 + 5280(d - 0.45),\ G_{RT} = 83.6 + 228(d - 0.45),\\
&E_R = 1000 + 2370(d - 0.45),\ \frac{E_L}{\nu_{LR}} = 34200 + 117000(d - 0.45),\ G_{LT} = 745 + 989(d - 0.45),\\
&E_T = 636 + 1910(d - 0.45),\ \frac{E_T}{\nu_{LT}} = 30800 + 101000(d - 0.45),\ G_{LR} = 861 + 2080(d - 0.45).
\end{aligned}
\tag{8}
$$

In the case of *Pinus Pinaster* Ait., relationships between infra-density G_b and shear modulus (MPa), albeit with relatively low coefficients of determination R^2 were introduced [134, 135]. For instance, the shear moduli is given as a function of $G_b \in [0.53; 0.63]$ through the following empirical formulæ[134]:

$$
\begin{aligned}
G_{LR} &= 2402G_b \text{ with } R^2 = 0.711,\\
G_{LT} &= 2072G_b\ with\ R^2 = 0.255,\\
G_{RT} &= 495G_b\ with\ R^2 = 0.307.
\end{aligned}
\tag{9}
$$

Further relationships were derived with $G_b \in [0.57; 0.69]$ [135]:

$$
\begin{aligned}
G_{LR} &= 500G_b + 1020 \text{ with } R^2 = 0.050,\\
G_{LT} &= 960G_b + 500\text{with } R^2 = 0.056,\\
G_{RT} &= 600G_b + 160 \text{ with } R^2 = 0.108.
\end{aligned}
\tag{10}
$$

The elastic properties are also influenced by variations of moisture content below the FSP. Above this threshold, it is considered that variations in moisture content do not influence the elastic properties [126].

Water content influence on wood elastic properties is directly derived from polymers' behaviour composing the cell walls of wood [6]. A state of the art is provided: variations of 15%–20% for elastic properties have been recorded for a variation in water content of 12%–20% [144]. The evolution of elastic and shear moduli over a wide range of water content was analysed [7]. Between 0% and 6% of water content, all moduli undergo a slight increase around 5% before decreasing linearly for water content increasing from 6% to 20%. Finally, a stabilisation of elastic properties occurs around the FSP. An empirical formulæfor computing the elastic E_i^H and shear moduli G_j^H (MPa) as a function of water content H (%) was proposed [7].

Finally, temperature also influences elastic properties. A decrease in elastic moduli when the temperature was increased from 20 °C to 50 °C was observed [145]. Moreover, mechanical properties depend on the position of the sample in individuals of softwoods [141]. Along the radial direction, elastic properties tend to increase with the distance from the pith r. In the case of *Pinus Pinaster* Ait., an increase in elastic moduli of 99% between samples at 10% and 90% of total distance from the pith for 50-year-old trees which can be explained by the

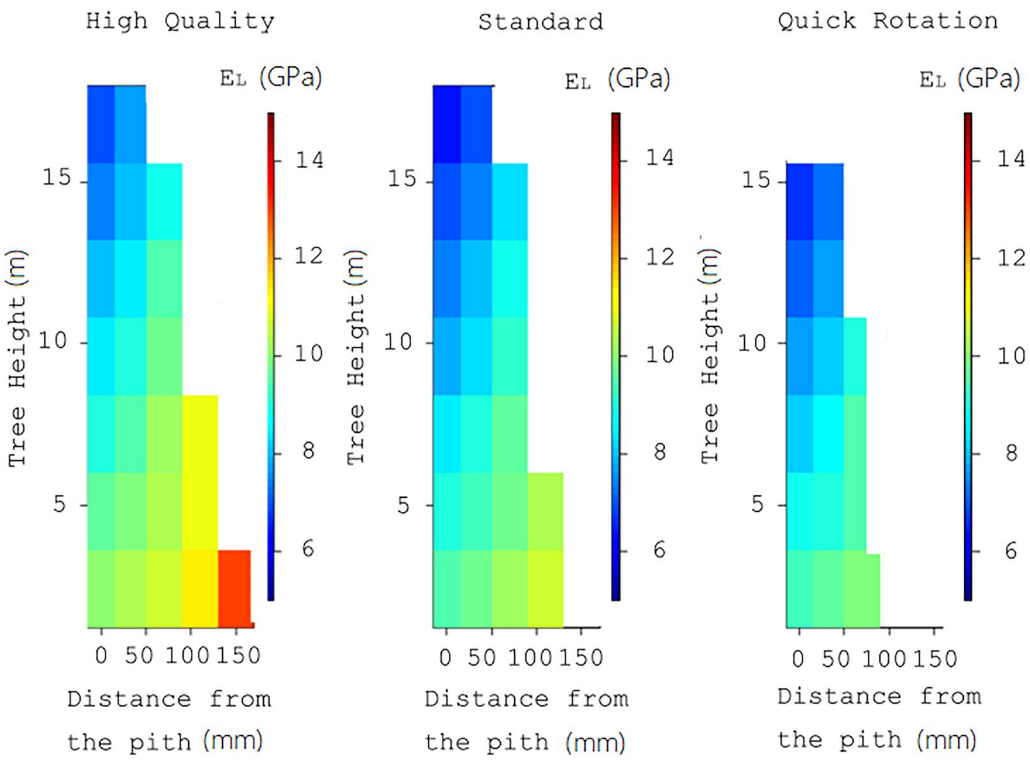

Fig. 19 Intra-tree experimental evolution of the longitudinal modulus of elasticity as a function of tree height, distance from the pith, and silviculture options for *Pinus Pinaster* Ait., adapted from [1]

presence of juvenile wood in the first rings closer to the pith was recorded [1, 146]. Variations between 55% and 65% in longitudinal Young's modulus between juvenile and mature wood without defects were observed [3]. In the *duramen*, no consequent variations have been measured between heartwood and sapwood in *Pinus Pinaster* Ait. [68].

Regarding the longitudinal direction, a decrease in elastic moduli with tree height for two softwood species was observed [141]. As for *Pinus Pinaster* Ait., a decrease in longitudinal Young's modulus of elasticity with tree height was noted [1]. It can be mostly explained by the juvenile wood higher proportion in the highest part of trees at the proximity of the living crown and branches, as shown in Fig. 19.

The defects such as RW and knots strongly influence the elastic properties. Singularities, like knots and resin pockets play inclusion roles because their properties are different from the wood matrix, as reported in Table 1. Silviculture plays an important role in the wood growth and properties, as illustrated in Fig. 19. The effect of different silvicultural scenarios on *Pinus Pinaster* Ait. elastic properties was presented [1]. The three scenarios are a high-quality scenario with long rotation and moderate growth, a traditional rotation scenario and a short rotation scenario with clear-cuts [1]. For example, decreasing rotation time leads to an increase in the proportion of juvenile wood and thus to a decrease in elastic properties. In the case of growth rate variation in softwoods, species with an abrupt transition between initial and final wood, such as *Pinus Pinaster* Ait., do not show changes in their elastic properties.

Strength properties

Definition

The mechanical properties most commonly used to evaluate wood failure are the limit stress in bending, ultimate stress values in compression, tension and shear strength parallel and perpendicular to the wood grain [147]. Wood strength is different in tension and compression. This difference is explained by the distinct behaviour of the tubular elements constituting the wood microstructure: they show micro-buckling in compression and brittle failure in traction. Table8 regroups the *Pinus Pinaster* Ait. strength properties at the macroscopic scale available in the literature and expressed in terms of modulus of rupture (MOR); ultimate axial stress $\sigma^{u}_{i,\tau}$ $(i = R, T, L)$ in both traction $(\tau = t)$ and compression $(\tau = c)$; limit shear stresses in the three characteristic planes, i.e. LR,

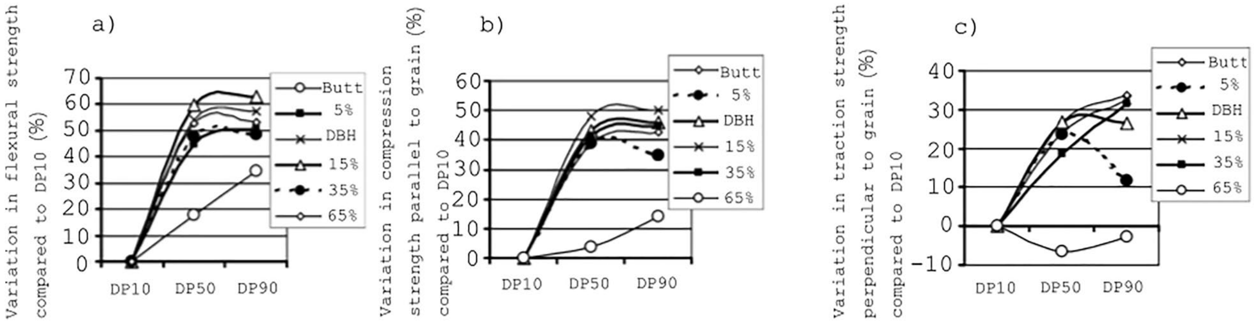

Fig. 20 Variation of **a** flexural strength, **b** compression strength parallel to grain, and **c** traction strength perpendicular to grain relative to properties measured at 10% of total radius DP10 as a function of radius from the pith and percentage of total height for *Pinus Pinaster* Ait., adapted from [146]

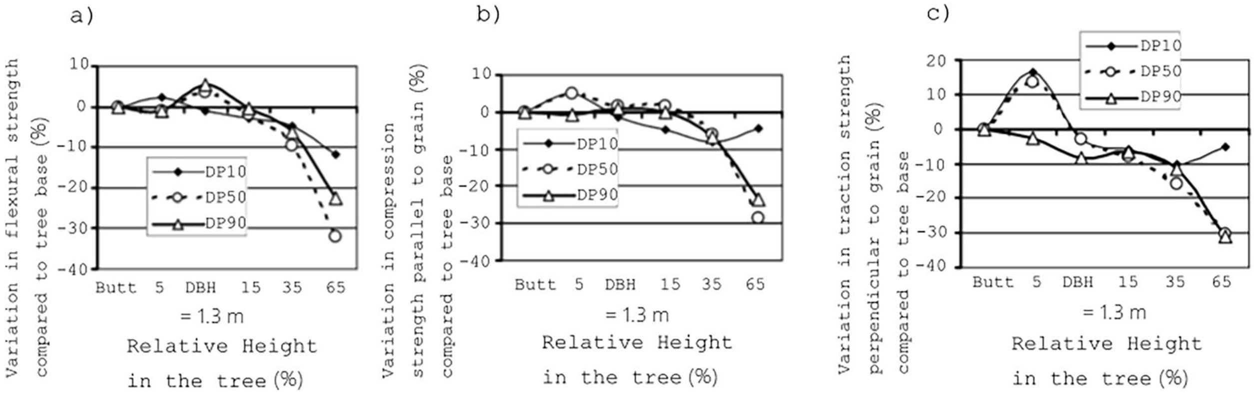

Fig. 21 Variation of **a** flexural strength, **b** compression strength parallel to grain, and **c** traction strength perpendicular to grain relative to properties measured at tree base "butt" as a function of percentage of total height and radius from the pith for *Pinus Pinaster* Ait., adapted from [146]

Table 1 Knots elastic properties of *Pinus Pinaster* Ait. [37]

Transverse Elastic Moduli (MPa)	$E_R = E_T = 400$
Poisson's Ratio	$\nu_{RT} = 0.4$
Transverse Shear Modulus (MPa)	$G_{RT} = 143$

LT and RT, in terms of stress level at which the first crack onset occurs, i.e., $\sigma_{s,co}$, of the ultimate shear stress, i.e., $\sigma_{s,u}$, and of the shear strength, i.e. $\sigma_{s,s}$.

Experimental results were obtained through

Table 2 *Pinus Pinaster* Ait. mean anatomical parameters issued from several references

Sources	Origin	Nb of samples	Max Cambial Age (years)	Sampling height (m)	Nb of cells per ring	Lumen diameter (µm)	Fibre width (µm)	Cell wall thickness (µm)	Fibre length (mm)
[43]	Bordeaux, France	/	24–35	1.3	40–70	5–50	/	3–9	/
[44]	Tocha, Portugal	10	/	/	20–60	5–45	/	3–9	/
[39]	/	2	16–30	/	/	/	25–35	1–6	/
[45]	Tocha, Portugal	33	/	1.3	24–30	/	/	3.5–7	/
[46]	Tuscany, Italie	/	/	1.3	/	/	/	2–8	/
[47]	Tronquats, France	960	14	/	/	/	42.5	/	1988
[38]	Aquitaine, France	186	15	/	/	/	27.43	/	1990

Table 3 *Pinus Pinaster* Ait. tree height and diameter for issued from several references

Sources	Origin	Type of sample	Nb of samples	Cambial Age (years)	Age Standard deviation	Tree Height (m)	Tree Height Standard deviation	Diameter at breast height (DBH) (mm)	Diameter Standard deviation
[81]	Gnangara Australia	Dominant Trees	4	10.25	0.5	9.90	0.4	136.2	13
[81]	Gnangara Australia	Dominant Trees	4	16	0	16.05	0.4	241.6	7
[81]	Gnangara Australia	Dominant Trees	4	35.75	0.5	23.32	0.8	416.6	31
[81]	Gnangara Australia	Dominant Trees	4	37.5	0.3	23.28	0.3	465.3	26
[82]	Bordeaux France	Dominant Trees	32	8	/	4.7	/	73	/
[82]	Bordeaux France	Dominant Trees	20	22	/	16.6	/	253	/
[82]	Bordeaux France	Dominant Trees	10	48	/	25.5	/	470	/
[81]	Pinjar Australia	Dominant Trees	4	8	0	8.64	0.4	147.8	3
[81]	Pinjar Australia	Dominant Trees	4	20.25	0.3	17.05	0.5	310.4	6
[81]	Pinjar Australia	Dominant Trees	4	30.25	0.3	19.75	0.4	411.1	22
[85]	Asturias and Galicia Spain	/	14339	20.3	8.3	11.7	3.8	181	68
[86]	Portugal	/	1698	5	/	1.6	1.0	/	/
[86]	Portugal	/	1234	10	/	4.7	1.5	/	/
[86]	Portugal	/	1217	15	/	7.8	1.7	/	/
[86]	Portugal	/	1186	20	/	10.7	1.9	/	/
[86]	Portugal	/	1090	25	/	13.2	1.9	/	/
[86]	Portugal	/	941	30	/	15.4	2.0	/	/
[86]	Portugal	/	695	35	/	17.1	2.0	/	/
[86]	Portugal	/	395	40	/	18.9	2.0	/	/
[86]	Portugal	/	235	45	/	20.5	2.2	/	/
[86]	Portugal	/	157	50	/	21.8	2.6	/	/
[86]	Portugal	/	128	55	/	23.1	2.9	/	/
[86]	Portugal	/	89	60	/	24.0	2.8	/	/
[86]	Portugal	/	25	65	/	24.0	1.7	/	/
[86]	Portugal	/	4	70	/	24.9	0.1	/	/
[87]	Spain	Dominant Trees	10	/	/	17.7	0.9	484	18

Table 4 *Pinus Pinaster* Ait. (ssp. Atlantica) ring width issued from several references

Sources	Origin	Nb of samples	Max Cambial Age (years)	Sampling Height (m)	Mean value (mm)	Standard deviation	Range of values (mm)	Limit Value (mm)
[91]	Occitania, France	4	/	/	5.5	/	2–13	/
[92]	Portugal	/	70	/	4.8	/	/	2.2
[93]	Bragado, Portugal	180	6	1.3	7.34	1.12	4.50–10.80	/
[93]	Bragado, Portugal	180	10	1.3	5.86	0.83	3.50–8.80	/
[94]	Bragado, Portugal	180	13	1.3	5.13	0.73	3.10–7.80	/
[90]	Landes, France	10	24	1.04–1.94	/	/	2–10	2
[89]	Leiria, Portugal	552	17	2	4.224	0.901	2.5–8.6	2.5

- modified Arcan test [148];
- vibratory ranking method [143];
- 4-points bending tests which rely on French standards [1, 149–153];
- axial compression tests [91].

Cruz et al. extracted the strength properties from the Portuguese norm [154, 155]. Balmori et al. referred to the European norm and to two Spanish norms [5, 156–158].

Table 5 *Pinus Pinaster* ssp. *Atlantica* intra-ring relative density (air dry density—the ratio of mass to volume of wood conditioned to a moisture content of 12% relative to water density) for earlywood and latewood. Mean relative density *d*; Latewood *LW*; Earlywood *EW*; Latewood relative density d^{LW}; Earlywood relative density d^{EW}; Standard deviation for Latewood relative density $\sigma_{d^{LW}}$; Standard deviation for Earlywood relative density $\sigma_{d^{EW}}$; Latewood percentage $\%^{LW}$; Standard deviation for latewood percentage $\sigma_{\%^{LW}}$

Sources	Origins	Nb. of samples	*d* range	Max Cambial Age (years)	d^{LW}	$\sigma_{d^{LW}}$	d^{EW}	$\sigma_{d^{EW}}$	$\%^{LW}$ (%)	$\sigma_{\%^{LW}}$
[101]	Gironde, France	/	0.3-0.9	/	/	/	/	/	/	/
[89]	Leiria, Portugal	552	0.207-0.917	17	0.618	0.034	0.386	0.026	38.2	16.93
[93]	Bragado, Portugal	180	0.215-0.889	6	0.651	0.033	0.397	0.029	21.4	6.700
[93]	Bragado, Portugal	180	0.228-0.933	10	0.684	0.036	0.404	0.031	24.1	6.000
[93]	Bragado, Portugal	180	0.240-0.921	13	0.687	0.035	0.411	0.031	25.9	6.100
[43]	Gironde, France	/	0.2-1.2	29-41	/	/	/	/	/	/

Variability of strength properties

Strength properties fluctuate similarly to the elastic properties depending on the position of the sample in the log and the climatic conditions. As far as the radial direction is concerned, variations of strength properties follow the same tendencies as elastic properties [1, 141]. For *Pinus Pinaster* Ait., an increase of strength properties proportional to distance from the pith was registered [146]. Notably, from samples extracted from 10% to 90% of total radius, an increase of 50% to 60% has been observed for bending strength and an increase of 39% to 48% for compression strength parallel to the grain with a stabilised constant reached for both properties at 50% total radius. Finally, for the tensile strength perpendicular to the grain, a first increase of 23% has been measured between 10% and 50% total radius before a second increase of 33% between 50% and 90% total radius, as illustrated in Fig. 20.

Strength properties also vary along the longitudinal direction [141]. A reduction of strength properties in the higher portions of a tree was confirmed [1]. Reductions of 12%, 32% and 23% for bending strength on samples extracted, respectively, from 0% to 65% of the total tree height and at a distance of 10%, 50% and 90% of total radius from the pith were registered [146]. They found reductions of 29% and 24% for the compression strength parallel to the grain and 30% for the tensile strength perpendicular to the grain at the same height for sampling distance from the pith of 50% and 90% of the total radius, as shown in Fig. 21.

In the juvenile wood, strength properties are lower compared to adult wood in softwood species. This degradation of mechanical strength in juvenile wood could be explained by a lower cell wall thickness and bigger micro-fibril angles. In *Pinus Pinaster* Ait., average variations of 30% in bending strength, 20% in compression parallel to the grain and 15% in tension strengths perpendicular to the grain, with respect to adult wood were reported [146].

In CW, tensile and impact strengths are reduced [37]. Knots and resin pockets greatly influence the tree mechanical strength and quality. The geometrical characteristics of a knot (size and position) and the deviation of the grain slope imply a decrease in the bending strength of wood beams [148].

Table 6 *Pinus Pinaster* Ait. shrinkage properties (tangential α_T, radial α_R, longitudinal α_L) issued from several references

Sources	Origins	Nb of samples	Sample tree age (years)	α_T (%/%)	α_R (%/%)	Mean Ratio α_T/α_R	α_L (%/%)
[160]	Galicia (Spain)	22	10-15	0.18-0.27	0.09-0.22	1.68	0.000-0.170
[124]	Gironde (France)	862	10-15	0.15-0.35	0.05-0.20	1.6	/
[91]	Gard (France)	57	/	0.21-0.41	0.11-0.26	2.12	/
[40]	Gironde (France) Mean of 3 softwoods	14	/	0.28	0.14	2	0.007
[6]	Numerical simulation	/	/	0.26	0.13	2	0.000

Table 7 Mean reference elastic properties, i.e. Young's moduli E_L, E_R, and E_T, shear moduli G_{RT}, G_{TL}, and G_{LR}, and Poisson's ratios ν_{RT}, ν_{TL}, and ν_{LR} in the local cylindrical reference system for *Pinus Pinaster* Ait. as a function of several corresponding relative densities d and moisture content of measurement H [%] extracted from several studies

Sources	E_L (GPa)	E_R (GPa)	E_T (GPa)	G_{RT} (MPa)	G_{TL} (MPa)	G_{LR} (MPa)	ν_{RT}	ν_{TL}	ν_{LR}	d	H (%)
[133]	11.4	0.94	0.70	200	1615	1350	0.58	0.03	0.32	0.49-0.54	11.8-13.5
[136]	15.1	1.91	1.01	280	1340	1480	0.586	0.051	0.471	/	/
[137]	/	1.1	/	/	/	/	/	/	/	/	/
[134] Iosipescu Test	/	/	/	286	1220	1410	/	/	/	0.578-0.589	10-12
[134] Off-axis Shear Test	/	/	/	/	1040	1110	/	/	/	0.538-0.582	10-12
[135] Arcan Test	/	/	/	239	1090	1330	/	/	/	0.608-0.660	11
[138] Measure 1	13.2	/	/	/	/	/	/	/	0.46	0.46	/
Measure 2	15.7	/	/	/	/	/	/	/	0.35	0.60	/
Table 4.25	16.11-17.77	/	/	/	/	/	/	/	/	0.635-0.725	/
[139]*	/	1.4-2.6	0.4-1.5	110-333	/	/	0.53-0.95	/	/	0.58	/
[57]	3-15	/	/	/	/	/	/	/	/	/	/

*Anisotropic based method

In the case of strength properties oriented differently from the main orthotropic directions of the material, an improved version of the Hagen–Hankinson–Kollman's formula, which estimates strength properties for *Pinus Pinaster* Ait. oriented differently from wood grain angle was presented:

$$R_\theta = \frac{R_0 R_{90}}{R_0 \sin\theta^n + R_{90} \cos\theta^n}, \tag{11}$$

Table 8 Reference strength properties expressed in terms of modulus of rupture (MOR); ultimate axial stress $\sigma^u_{i,\tau}$ ($i = R, T, L$) in both traction ($\tau = t$) and compression ($\tau = c$); limit shear stresses in the three characteristic planes, i.e., LR, LT and RT, in terms of stress level at which the first crack onset occurs, i.e., $\sigma_{s,co}$, of the ultimate shear stress, i.e., $\sigma_{s,u}$, and of the shear strength, i.e., $\sigma_{s,s}$ for *Pinus Pinaster* Ait. extracted from several studies

Sources	MOR (MPa)	$\sigma^u_{L,t}$ (MPa)	$\sigma^u_{R,t}$ (MPa)	$\sigma^u_{T,t}$ (MPa)	$\sigma^u_{L,c}$ (MPa)	$\sigma^u_{R,c}$ (MPa)	$\sigma^u_{T,c}$ (MPa)	σ_{LR} (MPa)	σ_{LT} (MPa)	σ_{RT} (MPa)
[136]	/	97.5	4.20	7.93	/	/	/	/	/	/
[148]	/	85-95	3-7	3-7	/	/	/	7-12	7-12	/
[143]	17.2-37.2	/	/	/	/	/	/	/	/	/
[91]	/	/	/	/	44.8	/	/	/	/	/
[1]	23-82	/	/	/	/	/	/	/	/	/
[134] Iosipescu Test	/	/	/	/	/	/	/	15.9 ($\sigma_{s,co}$) 16.9 ($\sigma_{s,u}$)	15,9 ($\sigma_{s,co}$) 18.1 ($\sigma_{s,u}$)	2.38 ($\sigma_{s,co}$) 4.35 ($\sigma_{s,u}$)
[134] Off-Axis Test	/	/	/	/	/	/	/	14.1 ($\sigma_{s,u}$) 16.5 ($\sigma_{s,s}$)	14.0 ($\sigma_{s,u}$) 16.6 ($\sigma_{s,s}$)	/
[135] Arcan Test	/	/	/	/	/	/	/	15.1 ($\sigma_{s,co}$) 15.9 ($\sigma_{s,u}$)	11.7 ($\sigma_{s,co}$) 15.2 ($\sigma_{s,u}$)	4.6 ($\sigma_{s,co}$)
[3]	62.0-151.9	46-162	/	/	34.0-68.5	/	/	/	/	/
[57]	7-80	/	/	/	/	/	/	/	/	/
[149]	69.3	/	/	/	37.7	/	/	/	/	/
[150]	82.7	/	/	/	40.9	/	/	/	/	/
[136]	/	93.7	/	/	51.9	/	/	/	/	/
[5]	54.75	71.04	/	/	42.50	/	/	/	/	/
[155]	18-35	11-21	0.4	0.4	18-25	6.9-7.3	6.9-7.3	/	/	2.0-3.4

where R_θ is the generic strength property oriented at θ with respect to the wood fibre [37, 56, 159]. n is an empirical coefficient, whilst R_0 and R_{90} are the strength properties parallel and perpendicular to the wood fibre direction, respectively. The values of n and of the ratio $\frac{R_{90}}{R_0}$ for different strength properties of *Pinus Pinaster* Ait. are not available in literature. As well, the influence of variations in moisture content on strength properties of *Pinus Pinaster* Ait. is not available in literature.

Finally, density and temperature also influence the strength properties. Few information is available in the case of *Pinus Pinaster* Ait.. An affine relationship between relative density and tensile strength along the fibre direction was presented [3]. As well, relationships between the infradensity G_b and shear strengths (MPa) with relatively low coefficients of determination R^2, which apply for values of $G_b \in (0.57, 0.69)$ were introduced [135]:

$$\begin{aligned} \sigma_{LR} &= 0.57G_b + 15.44 \text{ with } R^2 = 0, \\ \sigma_{LT} &= 44.09G_b + 15.02 \text{ with } R^2 = 0.274, \\ \sigma_{RT} &= 8.39G_b + 0.80 \text{ with } R^2 = 0.212. \end{aligned} \tag{12}$$

Conclusions

This literature survey regroups a wide variety of information extracted from the scientific literature on the properties of one species deeply rooted into the Landes of Gascogne: *Pinus Pinaster* Ait. (ssp. Atlantica). First, by presenting the propagation of this species throughout History to regroup only the information related to the particular “Atlantica” subspecies. Then, by displaying the multi-scale organisation and natural variability of wood to expose its complexity. Finally, by regrouping the thermal, hygrical and mechanical properties needed to model wood behaviour. This review aims to enhance accuracy of future research works on *Pinus Pinaster* Ait. and draw a distinction with others softwoods. Moreover, this work highlights the lack of information of several properties of *Pinus Pinaster* Ait. especially about variability at the macroscopic scale (intra-tree). It is of enormous significance in both industrial domain and ecological interest to provide sufficient cognizance in xylology and properties of *Pinus Pinaster* Ait. To improve our understanding and master this local richness, experimental and numerical studies should be held to further estimate and deepen our knowledge of *Pinus Pinaster* Ait. properties at several scales.

Abbreviations

SDGs	Sustainable development goals
RW	Reaction wood
CW	Compression wood
MFA	Angle of micro-fibrils
IADF	Inter-annual density fluctuation
NW	Normal wood
EMC	Equilibrium moisture content
SEC	Surface-emission coefficient
MOR	Modulus of rupture

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