

## SOMMARIO

L'area rurale della Piana di Gioia Tauro è una zona importante per il tessuto economico della provincia di Reggio Calabria. Nei 33 comuni che ricadono in quest'area, sono presenti numerose ma piccole aziende agroforestali che operano nella fornitura di assortimenti legnosi e nella prima e seconda trasformazione del legno stesso. Queste aziende utilizzano non solo essenze forestali, come il faggio e il castagno, tipiche della zona, ma anche l'olivo, specie che caratterizza il paesaggio agrario. In alcune aree della Piana di Gioia Tauro, infatti, esistono dei veri e propri "Boschi di olivo", definizione piuttosto appropriata e ampiamente utilizzata per identificare la tipologia, la maestosità e la densità di questi alberi. Per quanto riguarda la disponibilità di risorse forestali, il versante tirrenico dell'Aspromonte si presenta piuttosto variegato: castagneti; pinete di pino calabro; faggete, e talvolta formazioni miste con abete bianco. Per questo motivo, è evidente che le diverse aziende che operano nell'area all'interno della Filiera foresta-legno hanno bisogno di un supporto per migliorare le loro attività lavorative, piuttosto limitate, con modeste innovazioni nel processo di raccolta e lavorazione del legno. Gli obiettivi, quindi, di questo progetto sono:

- i) analizzare la produttività di queste macchine forestali specializzate che operano nei boschi calabresi;
- ii) ampliare la conoscenza del legno d'olivo;
- iii) definire una serie di azioni volte a favorire lo sviluppo di nuovi e innovativi processi produttivi nelle varie fasi di raccolta e lavorazione del legno.

Per raggiungere i suoi obiettivi, la ricerca triennale si è concentrata sull'analisi della filiera foresta-legno nella Piana di Gioia Tauro e sulla valorizzazione dei prodotti legnosi.

La ricerca si è articolata in cinque obiettivi specifici di ricerca (OSR):

- OSR1. Analisi della produttività di due macchine forestali specializzate;
- OSR2. Studio dell'anatomia del legno di due cultivar di olivo;
- OSR3. Approfondimento della conoscenza delle due cultivar di olivo attraverso varie prove fisico-meccaniche su tronco e rami di entrambe le cultivar;
- OSR4. Valutazione della possibilità di introdurre la vaporizzazione del legno di olivo come metodo alternativo di stagionatura o per altri usi;
- OSR5. Analisi delle rese di segazione, con tre specie diverse, di una segheria di medie dimensioni.

I risultati di questi obiettivi specifici di ricerca sono stati sviluppati nella tesi.

## ABSTRACT

The rural area of the Plain of Gioia Tauro is an important area for the economic fabric of the province of Reggio Calabria. In the 33 municipalities falling within this area, there are numerous but small agroforestry companies operating in the supply of wood assortments and in the first and second transformation of the wood itself. These companies not only use forest essences, such as beech and chestnut which are typical of the area, but also the olive tree which is a species that characterizes the agricultural landscape. In fact, in some areas of the Plain of Gioia Tauro, there are real "Olive Woods", a rather appropriate definition widely used to identify the type, majesty and density of these trees. On the other hand, with regard to the availability of forest resources, the Tyrrhenian side of Aspromonte Mountain is quite varied: chestnut wood; Calabrian pine wood; beech wood, and sometimes mixed formations with silver fir. For this reason, it is clear that the various companies operating in the area within the Forest-Wood Chain need support to improve their rather limited work activities, with modest innovations in the wood harvesting and processing process. The objectives, therefore, of this project are to:

- i) Analyse the productivity of these specialized forestry machines operating in Calabrian forests;
- ii) Broaden knowledge of olive wood;
- iii) To define a series of actions aimed at fostering the development of new and innovative production processes in the various phases of wood harvesting and processing.

To achieve its objectives, the three-year research focused on the analysis of the forest-wood sector in the Plain of Gioia Tauro and the valorization of wood products. The research was divided into six specific research objectives (SROs):

- SRO1. Analysis of the productivity of two specialized forestry machines;
- SRO2. Study of the wood anatomy of two olive cultivars;
- SRO3. Deepening knowledge of the two olive cultivars through various physical-mechanical tests on trunk and branches of both cultivars;
- SRO4. Evaluation of the possibility of introducing steaming of olive wood as an alternative method of seasoning or for other uses;
- SRO5. Analysis of sawing yields, with three different species, from a medium-sized sawmill.

The results of these specific research objectives were developed in the thesis

Angelo Mammoliti

Study of the forest-wood supply chain for the enhancement of local wood resources in the rural area of the plain of Gioia Tauro

Angelo Mammoliti

# STUDY OF THE FOREST-WOOD SUPPLY CHAIN FOR THE ENHANCEMENT OF LOCAL WOOD RESOURCES IN THE RURAL AREA OF THE PLAIN OF GIOIA TAURO

Ph.D. Thesis







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In copertina  
*Vista sulla Piana di Gioia Tauro*

Innanzitutto, vorrei esprimere la mia riconoscenza ai coordinatori del mio corso di dottorato Proff. Marco Poiana e Leonardo Schena. Grazie per aver fornito una guida preziosa e per aver creato un ambiente di studio stimolante e ricco di opportunità. Le vostre preziose direttive e il supporto costante sono stati fondamentali per il mio successo accademico. Un sentito ringraziamento va al mio Tutor Prof. Andrea Rosario Proto e alla CoTutor prof.ssa Michela Zanetti che mi hanno accompagnato lungo questo percorso con pazienza, dedizione e competenza: il loro supporto ha contribuito ad arricchire il mio bagaglio culturale e il mio lavoro di ricerca. Un pensiero a mio fratello Rocco e a mio padre (a cui dedico il mio percorso) che non essendoci più, hanno contribuito insieme a mia mamma e a mio fratello Francesco a motivarmi a non mollare e a raggiungere tutti i miei obiettivi e a superarli guardando al futuro. Un ringraziamento va alla mia dolce metà: Camila. Compagna di vita con cui ho condiviso tutto e che mi ha supportato in tutto.

Note biografiche

Finiti gli studi superiori ad indirizzo informatico, ho continuato gli studi universitari nel settore forestale. Con la tesi triennale ho approfondito la conoscenza in zootecnica. In contemporanea ho svolto gli studi universitari in musica (tromba). Come esperienza lavorativa, ho svolto supplenze di docenza presso gli istituti di istruzione pubblica.





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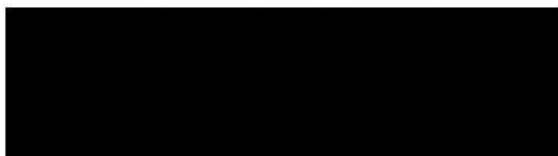
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# Abstract/Sommario

The rural area of the Plain of Gioia Tauro is an important area for the economic fabric of the province of Reggio Calabria. In the 33 municipalities falling within this area, there are numerous but small agroforestry companies operating in the supply of wood assortments and in the first and second transformation of the wood itself. These companies not only use forest essences, such as beech and chestnut which are typical of the area, but also the olive tree which is a species that characterizes the agricultural landscape. In fact, in some areas of the Plain of Gioia Tauro, there are real "Olive Woods", a rather appropriate definition widely used to identify the type, majesty and density of these trees. On the other hand, with regard to the availability of forest resources, the Tyrrhenian side of Aspromonte Mountain is quite varied: chestnut wood; Calabrian pine wood; beech wood, and sometimes mixed formations with silver fir. For this reason, it is clear that the various companies operating in the area within the Forest-Wood Chain need support to improve their rather limited work activities, with modest innovations in the wood harvesting and processing process. The objectives, therefore, of this project are to:

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To achieve its objectives, the three-year research focused on the analysis of the forest-wood sector in the Plain of Gioia Tauro and the valorization of wood products. The research was divided into six specific research objectives (SROs):

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L'area rurale della Piana di Gioia Tauro è una zona importante per il tessuto economico della provincia di Reggio Calabria. Nei 33 comuni che ricadono in quest'area, sono presenti numerose ma piccole aziende agroforestali che operano nella fornitura di assortimenti legnosi e nella prima e seconda trasformazione del legno stesso. Queste aziende utilizzano non solo essenze forestali, come il faggio e il castagno, tipiche della zona, ma anche l'olivo, specie che caratterizza il paesaggio agrario. In alcune aree della Piana di Gioia Tauro, infatti, esistono dei veri e propri "Boschi di olivo", definizione piuttosto appropriata e ampiamente utilizzata per identificare la tipologia, la maestosità e la densità di questi alberi. Per quanto riguarda la disponibilità di risorse forestali, il versante tirrenico dell'Aspromonte si presenta piuttosto variegato: castagneti; pinete di pino calabro; faggete, e talvolta formazioni miste con abete bianco. Per questo motivo, è evidente che le diverse aziende che operano nell'area all'interno della Filiera foresta-legno hanno bisogno di un supporto per migliorare le loro attività lavorative, piuttosto limitate, con modeste innovazioni nel processo di raccolta e lavorazione del legno. Gli obiettivi, quindi, di questo progetto sono:

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Per raggiungere i suoi obiettivi, la ricerca triennale si è concentrata sull'analisi della filiera foresta-legno nella Piana di Gioia Tauro e sulla valorizzazione dei prodotti legnosi. La ricerca si è articolata in cinque obiettivi specifici di ricerca (OSR):

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I risultati di questi obiettivi specifici di ricerca sono stati sviluppati nella tesi

**Keywords:** Forest Operations; Wood Technology; Olive wood; Steaming treatment; Sawing yield.

## 1. STATE OF THE ART OF THE RURAL AREA OF THE PLAIN OF GIOIA TAURO

The rural area of the Plain of Gioia Tauro is an important area for the economic fabric of the province of Reggio Calabria. The plain is located on the Tyrrhenian side of the Aspromonte massif and comprises 33 municipalities, with a total extension of approximately 500 km<sup>2</sup>. Almost 30% of the territory falls within the Aspromonte National Park (Figure 1).

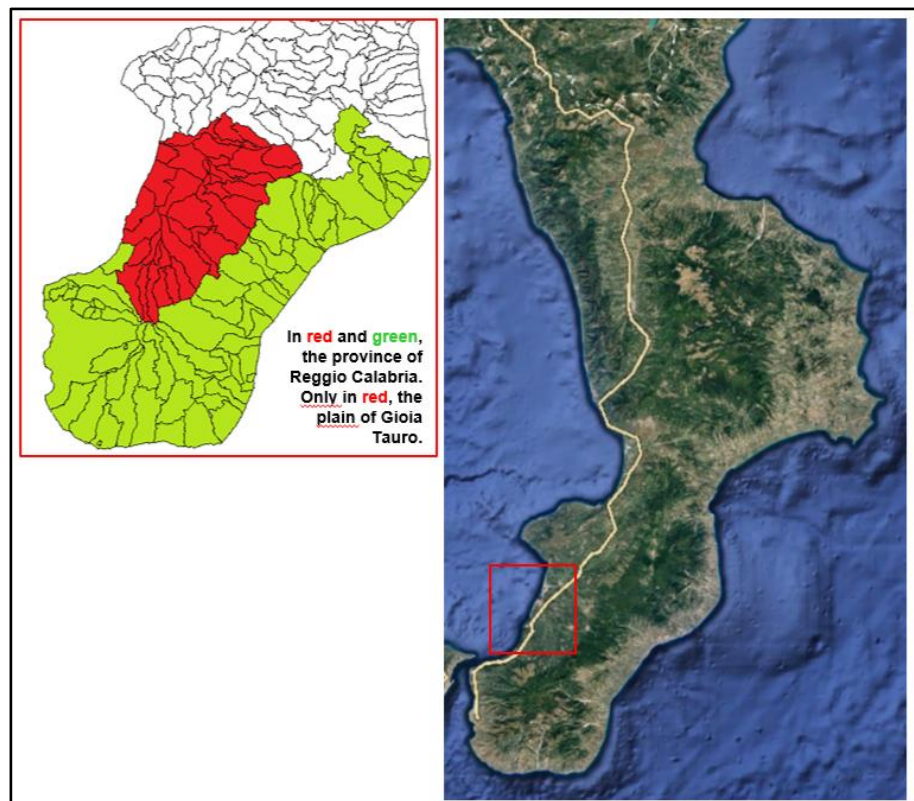


Figure 1. Location of the Plain of Gioia Tauro

The Plain of Gioia Tauro has a Mediterranean climate (Cs according to the Köppen climate classification). Winters are rather mild with mostly rainfall, and frost is rare. Summers are rather dry with little precipitation. The average

annual temperature is around 16.6 °C. The annual rainfall is 633.2 mm, distributed mainly between the months of October and April (Figure 2).

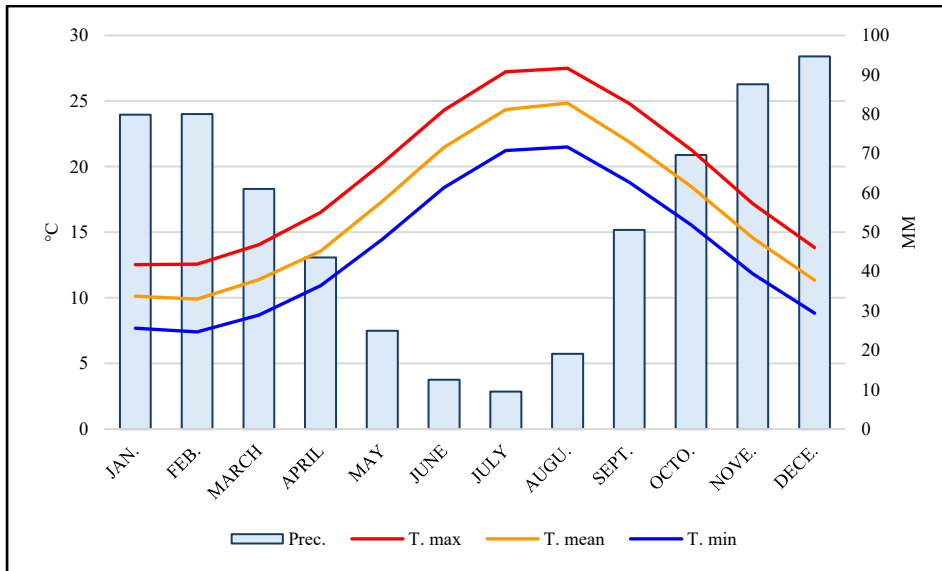
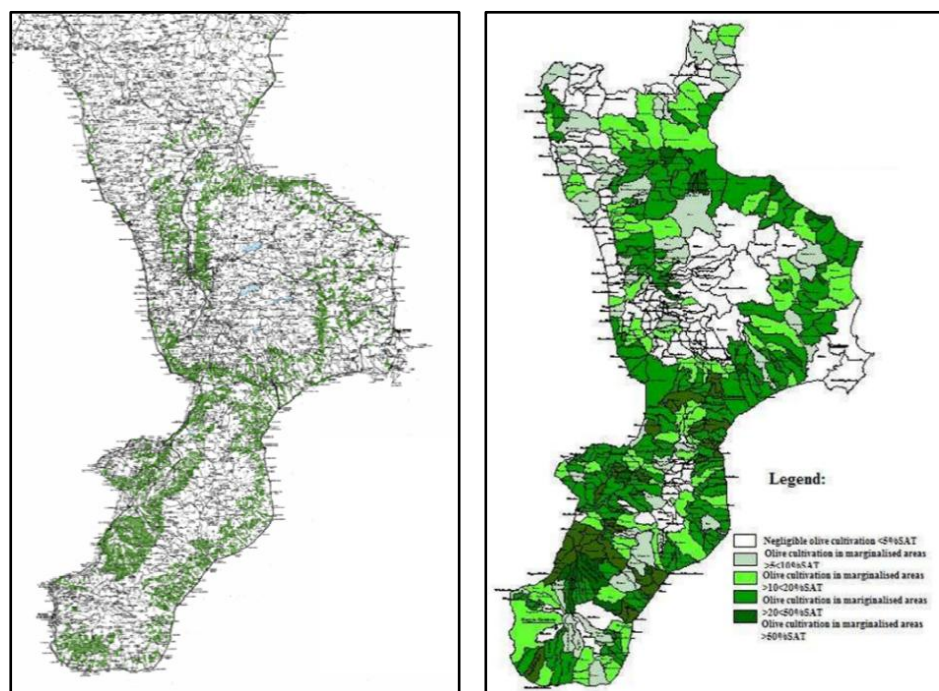


Figure 2. Climogram of the plain of Gioia Tauro

Barreca et al. [1] assert that the current appearance of the Plain of Gioia Tauro began to take shape in the second half of the 18th century and is the result of a series of natural, political and social events that, in a short period of time, radically altered the territory's landscape. Gradually, the villages perched on the foothills of Aspromonte were abandoned and moved towards flat areas. Thus, in a short time (through the removal of vegetation and various clearing operations), the forest formations typical of the Plain of Gioia Tauro (such as cork forests (*Quercus suber* L., 1753), oaks (*Quercus* spp.), poplars (*Populus* spp.), willows (*Salix* spp.), alders (*Alnus* spp.) and other Mediterranean species) were replaced by the species that was to become the most distinctive of the entire area: the olive tree. In 1985, Placanica [2] states that olive growing became one of the main sectors of the rural economy in Calabria at the dawn of the 19th century. This was possible thanks to the various land reclamation operations carried out in the lowland areas [2].

Furthermore, Barreca et al. [1] states that the territory occupied by olive groves in the Plain of Gioia Tauro can be divided into two areas with different characteristics. The first area is constituted by the internal piedmont strip, located between 350 and 650 meters above sea level. The second area consists of the coastal strip up to 350 meters above sea level. The most productive sector in the Plain of Gioia Tauro is agriculture. Among these sectors, the olive sector is of great importance, both at provincial and regional level. The lower part of the Plain is characterized by the agricultural scenario, but it is in most of the municipalities of the hinterland that the olive sector is the main, if not the only productive sector (figure 3). The cultivation of olive trees spans over 20,000 hectares.



**Figure 3.** Effective soil usage, Olive trees distribution (left)– Municipalities with significant presence of olive cultivation according to incidence on SAT (right) [3]

The plantations are characterized by secular trees with an exceptional growth

th of 20 - 25 meters, which makes the olive-growing landscape of the plain the most unique in the world: they form a true 'olive forest' (*Olea europaea* L., 1753) (Figure 4) [4]. The most common varieties of olive trees are 'Sinopolese' and 'Ottobratica': accounting for almost 90%.



Figure 4. Olive trees

In the lower part of the plain, there is a very low density, with a small number of plants per hectare (50-70); arriving in the hill and pre-mountain areas with a higher density: they exceed 100 plants per hectare. In the hill and pre-mountain areas, they also occupy territories with a high slope. In this case, they represent the only productive form in territories that would otherwise be destined for abandonment. Barreca et al. [1] states that the lower part of the plain is characterized by homogeneous stands (of the same age) with fairly regular and homogeneous planting distances. Furthermore, in the hilly and pre-hill areas, olive groves are made up of trees of different ages. This is due to the replacement of each tree when it dies or when production decreases

significantly. Finally, the distribution of trees on the ground is totally random in marginal areas: characteristics linked to the morphology of the terrain.

The citrus sector (*Citrus* spp.) follows, in order of importance, the olive sector.

Citrus fruits are destined for fresh consumption and, secondarily, for processing. The citrus fruit sector, mainly oranges (*Citrus x sinensis* (L.) Osbeck, 1765) and clementines (*Citrus x clementini* Yu. Tanaka, 1954), is mainly located in the northern area of the Plain of Gioia Tauro (municipalities of Candi-doni, San Ferdinando and Rosarno). In other areas they are found near water-courses, up to altitudes of 200 metres above sea level. Citrus cultivation is mainly present in the lower part of the Plain, in some cases merging with olive groves and then disappearing at higher altitudes (figure 5). The most commonly used citrus species in association with olive trees are the lemon trees (*Citrus x limon* (L.) Osbeck, 1765). According to ARSAC's 2020 report on agriculture [5], this sector is going through a deep crisis due to multiple causes.



**Figure 5.** Olive trees and lemon trees intercropping

In the fruit-growing sector, an important role is played by the kiwi (*Actinidia chinensis* Planch., 1847): in the last 10 years, the area under kiwi has more than tripled. According to ARSAC [5], the area has increased from 632 hectares to over 2000 hectares. This is also due to the fact that the kiwi is a very profitable species. Another fruit species of sufficient interest is the pomegranate (*Punica granatum* L., 1753) (both for juice and fresh consumption): cultivated mainly in the lower part of the Plain. Apple (*Malus domestica* (Suckow) Borkh, 1803) and cherry (*Prunus avium* (L.) L., 1755) orchards also of sufficient interest.

Other production sectors present in the Plain of Gioia Tauro are horticulture and cereal growing. The livestock sector is mainly made up of beef breeding (45%), followed by lamb and goat breeding (both account for 31%).

As far as the forestry sector is concerned, starting from the hill-mountain altitudes, the olive-growing sector gives way to the chestnut-growing sector (*Castanea sativa* Mill., 1768) and the coppice or high woods of oak (especially holm oak (*Quercus ilex* L., 1753)). Mediterranean scrub is also present. Lastly, in the mountainous area, pure beech woods (*Fagus sylvatica* L., 1753), sometimes mixed with silver fir (*Abies alba* Mill., 1759), dominate. In addition, there are reforestations of conifers, especially Calabrian pine (*Pinus nigra* J.F. Arnold subsp. *laricio* Palib. ex-Maire). Analysing specifically:

- The chestnut woods represent an important economic resource (Figure 6). The woods are coppice-governed.
- Pure holm oak coppice forests are found between 500/600 and 800/900 metres above sea level (Figure 7).
- Beech forests represent the most important forest category in terms of both area and production, as well as silvicultural landscape (Figure 8). In general, pure beech forests are found from 900-1000 metres above sea level: in some cases they are also found at lower altitudes in conjunction with holm oaks.

- Mixed beech and silver fir forests occur most frequently at altitudes between 1300 and 1500 metres above sea level.
- In the coniferous reforestations, carried out with the implementation of the I Special Law of Calabria (1177/55) [6], the most important species are calabrian pine (Figure 9) and secondarily Douglas fir (*Pseudotsuga Menziesii* (Mirb.) Franco). The reforestations are located at altitudes of approximately 900-1100 metres.



**Figure 7.** Pure holm oak coppice forests in the Plain of Gioia Tauro (Municipality of Cittanova)



**Figure 8.** Pure beech forest in the Plain of Gioia Tauro (Municipality of Delianuova)



**Figure 9.** Calabrian pine reforestation in the Plain of Gioia Tauro (Municipality of Oppido Mamertina)

## **1.1 WOOD SUPPLY CHAIN IN THE PLAIN OF GIOIA TAURO**

The forest-wood sector deals with the processes within the supply chain, starting from forest management up to the valorization of the wood product.

In the Plain of Gioia Tauro, the forest-wood chain is divided into four sectors:

1. AGRO-FORESTRY. This sector deals with the supply of wood material from the various felling (in the forest), grubbing and pruning (in the countryside).
2. FOREST ENTERPRISES. This sector is made up of forestry companies that carry out felling, grubbing and pruning operations. They also carry out the initial processing of timber.
3. FIRST PROCESSING (sawmills). This sector provides for the sawing of roundwood into planks and/or beams, seasoning of wood material, and the general production of semi-finished products.
4. SECOND/THIRD PROCESSING. This sector is made up of second/third transformation companies, including carpentry, furniture factories, etc.

In 2023, Papandrea [7] states that the forest-wood supply chain (Figure 8) applies the concepts of logistics and supply chain management to the forestry sector, in particular to logging and transport operations. The forest-wood supply chain can be seen as a set of processes through which forest resources are converted into products and services. The various processes are not separated into individual processes, but are interconnected and interact with each other, creating a whole and complete system to supply wood from the forest to the sawmill in a planned manner.

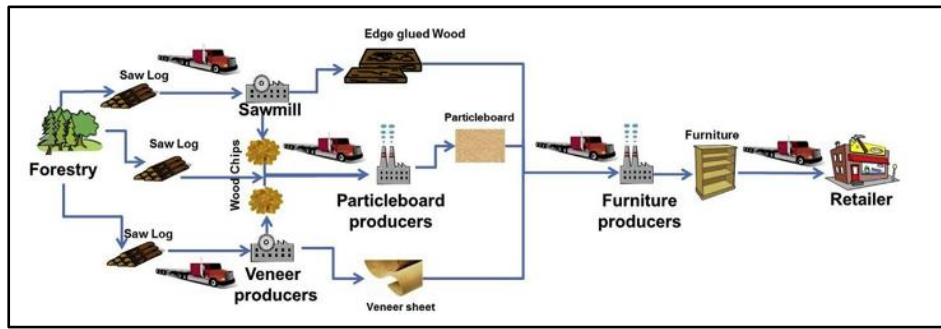


Figure 10. Wood supply chain

In the Plain of Gioia Tauro, the most widely used species is olive wood. It is followed, in terms of importance, by chestnut, holm oak and beech, various conifers and other types of broad-leaved trees. In the Plain of Gioia Tauro, the olive wood used is obtained from the uprooting of olive groves intended for crop conversion. Another source of supply is the various extraordinary prunings. In the latter case, it creates additional economic support for farms. In old plantations, given the considerable size of the trees, pruning is carried out at very long intervals (10 years on average). Around the supply of olive wood gravitate numerous but small companies operating in the area.

Pruning and grubbing are regulated at regional level: Regional Law No. 48 from October 30th, 2012 [8]. The law is aimed at protecting and enhancing the olive-growing heritage of the Region of Calabria. The law regulates: extirpation and replanting, extraordinary pruning; disposals and relocations. In addition, Regional Law No. 47 from December 7th, 2009, established the Register of Monumental Olive Trees [9].

The olive tree goes to create a circuit, first of all at a local level; as, it goes to support small local realities: landowners, user companies, first and second transformation companies. Given the impressiveness of the plant in a circumscribed area, it goes to create the character of exclusivity of a product that is also in demand internationally.

### 1.1.1. Mechanization level and wood harvesting systems

In the Plain of Gioia Tauro, the level of mechanization in harvesting can be described as being at an early stage of mechanization [10]. This level of mechanization in agro-forestry utilization is due to multiple factors, including: the characteristics of the site, the preponderance of firewood and/or biomass production as opposed to round wood, and the small size of many forest enterprises.

The various pruning and extraction operations are carried out using chainsaws, which are the most common machinery for cutting timber [10]. Cut-to-length (CTL system) is the most commonly used working system: this system consists of felling, limbing and sectioning trees into logs of specific lengths to the stump. Subsequently, the timber is extracted to the loading areas and transported to the primary processing industries by trucks equipped with cranes for loading and unloading the timber (Figure 9).



Figure 11. Truck equipped with a crane for transporting the logs.

The most widely used machine for timber extraction, both in agriculture and forestry, is the farm tractor equipped with forestry equipment (forestry winches and grapples) [11]: a trend also found in other regions of central-southern Italy [12] (Figure 10). To a lesser extent, timber is extracted by tractors with a trailer or skip [13]. In recent years, forestry machines (such as forestry skidders and tower yards) have begun to appear that are capable of increasing productivity and safety at work.



**Figure 12.** Timber extraction, with farm tractor equipped with forestry winch

In the agricultural sector, some wood from pruning and grubbing operations is also coming onto the market for energy purposes: wood chips (in recent years) and firewood. Agro-forestry companies carry out the various utilization operations, extract the wood and transport it to a storage yard on their own property for retail sale. In forestry, by contrast, the timber obtained mainly goes for further processing.

The various agro-forestry companies mainly sell timber locally, a large proportion of sales are to the regional and southern Italian market.

As far as round wood is concerned, it comes from both the forestry and agricultural sectors, with most companies transporting it to the primary processing companies. However, in some cases, the latter companies have trucks used to take the round wood to the utilization sites.

Due to increasingly restrictive laws for lighting fires, companies are shifting to the production of wood chips for use in biomass power plants for energy production. Branches and species with low economic value are destined to become wood chips. In addition, due to the small size of the companies, which often cannot cover the expenses for the purchase of a chipper, third-party companies specializing in wood chipping are used (Figure 13).



Figure 13. Wood chipper

Moreover, the rational management of these plants is problematic due to

the particularly laborious and physical effort required for the cultivation operation. Of these, the resulting pruning operations are particularly complex, affecting the quality of the product and its high cost. Traditional pruners, who are less well equipped than modern 'tree climbers', climb trees up to and over 20 metres, using only billhooks and ropes, to carry out the pruning (Figure 14 and Figure 15). The dangerous conditions of pruning and the high cost of the operation has resulted in a scarcity of skilled labour and a tendency to minimise this practice (and in some cases even abandoned altogether). This practice is usually carried out at very prolonged intervals with drastic cuts and considerable removal of wood mass [4].

Branches with a diameter of more than 20 centimetres and a length of at least 130 centimetres are treated as saw logs (Figures 16).



Figure 14. Pruning operation



Figure 15. Extraordinary olive pruning



Figure 16. Loading olive tree trunks for first processing.

### 1.1.2. Sawmill processing and performance measures

The material obtained from the various utilizations in both the agricultural and forestry sectors are destined for the district's primary processing industries (Figure 17).



Figure 17. Stack of olive tree toppings from extraordinary pruning

In 2013, Reyes [16], defines sawmill as the transformation of logs into sawn timber of various squaring. Furthermore, he states that various resources, including machines and operators, must be combined to achieve this transformation. For sawing logs into sawn timber, certain techniques are used related to the machinery and the sawing forms of the raw material; these are called conventional techniques or modern sawmill techniques.

Almost all the sawmills in the Plain of Gioia Tauro do not have a harvesting crew. Therefore, they purchase timber from the various agro-forestry com-

panies operating in the area.

The majority of sawmills in the Plain of Gioia Tauro are family-owned. Most of the plants are more than 20 years old; only a few have been built recently.

Plant employees are mainly general workers which on average consists of 11 employees. The employees specialise in very specific skills over the years. The choice of operators to operate the various machines is of real importance: operators are constantly making decisions on factors that interfere with the proper functioning of the machines and affect the performance of the industry.

Zimbalatti G. et al. [15] state that sawmills require large areas for the storage of logs and sawn timber to be seasoned (Figure 18): moreover, almost half of the companies have chambers for the artificial seasoning of wood (Figure 19). The typical surface area of a sawmill is approximately 5830 square metres, of which 63.5% is yards. Sawmills are medium-sized: they process an annual volume of approximately 5000 cubic metres of timber.



**Figure 18.** natural seasoning of semi-finished products



**Figure 19.** Sawn-boards placed inside the drying plant

The sawmills in the area do not have debarking facilities which is due to the characteristics of the processed timber. The transformation process starts directly from the end saw.

In 2015, Zimbalatti et al. [15], discovered that most sawmills have multi-blade vertical reciprocating saws. In fact, considering the technical characteristics of the machines and the cutting resistance of the different wood assortments, many companies have adopted different processing lines, suitable for the different timber qualities. Vertical band saws are quite common: some companies even have more than one unit.

Forklifts, silos and vacuum units are present in almost every company. The transport of roundwood from the storage room to the sawing hall, and of sawn timber, is carried out by forklift trucks in almost all companies.

Wood is a material that generates a significant amount of waste during production flows, including: residues, slabs, sawdust, shavings. At first, these residues are considered as a process, but they can certainly leave the sawmill as raw material for the production of pulp, panels and organic compounds, as well as for the energy self-sufficiency of the industry itself [16].

According to Badejo [17], the factors that influence the yield and value of timber are: quality and size of timber, types of converting and processing machines, machine maintenance culture, and operator experience. In addition, Hochheim & Martin [18] state that log quality influences the production process of the sawmill, as all cutting decisions are made based on the visual quality presented by the logs, with consequences on the yield and speed of the production product flow. Finally, Rocha [19] states that the yield of each log is influenced by:

- Type of saw used: the thicker the saw, the higher the percentage of waste, thus reducing the yield;
- Skilled labour: which is important in the decision-making process. As it is the worker who decides on the cutting technique according to the characteristics of the timber, thus making the best use of the wood;
- Characteristics of each species.

Generally, sawmills in the Plain of Gioia Tauro during the transformation from logs to lumber have a sawing yield of 90% (olive, locust, chestnut and silver fir). Conversely, if one has processing from both planks and chestnut beams, the sawing yield decreases to just over 56%. Concerning the sawing yield, there are 80.5% and 58.5% for olive and chestnut respectively. The sawing yield for band saws is very variable. It ranges from a yield of around 35.7-45.6% for olive to 72.3-94.8% for silver fir. The sawing yield of chestnut by band saw processing is around 74.5%. In contrast, the multi-blade saw has a sawing yield ranging from 54% for pine species, up to 77% for chestnut. Finally, the moulder sawing yield ranges from 69% to 78% for chestnut and silver fir, respectively. This shows the importance of the characteristics of the individual species, the experience of the operators, and the optimal use of the machines.

An important role for the economy of the rural area of the Plain of Gioia Tauro is played by a number of companies which specialize in processing olive wood (Figure 20): the latter is used for the production of flooring, furniture

and cabinet-making. The wood is used locally or for national, European and extra-European export. Exported products include: logs and semi-finished products, such as sawn boards (Figure 21) and lath.



Figure 20. First processing of olive wood



Figure 21. Various types of laths.

In terms of importance, chestnut processing follows. Other species processed include pine (*Pinus* sp.), silver fir, black locust (*Robinia pseudoacacia* [L.](#)) and walnut (*Juglans regia* [L.](#)). Regarding the type of products, it has emerged that companies are mainly oriented towards the production of boards, laths, followed by pallets, carpentry products, morals and sleepers (Figure 22). There is also a production of beads and beams, generally for use in construction. Most sawmills produce both on commission and for stock.



Figure 22. Sawmill products

## 2. THESIS SCOPE AND ORGANIZATION

The rural area of the Plain of Gioia Tauro represents an important area for the economic foundation of the province of Reggio Calabria. In this area there are numerous but small agro-forestry companies active in the supply of wood assortments and in the first and second transformation of wood itself (sawmills and furniture factories). This reflects the classic wood (and wood products) supply chain comprising: forestry operations, transport of the raw material, processing at sawmills and further distribution to a secondary processing unit or to wholesale and retail facilities.

These agroforestry companies have a low level of mechanisation, but this has been gaining momentum in recent years. In fact, recently, there has been the appearance of new specialised forestry machinery, capable of increasing productivity and safety at work. Furthermore, among the various first processing companies, there are some with technologies and cutting methods that fail to make the most of the characteristics of the various woods: this results in low sawing yields and low productivity. It must be said that the primary processing sector is also adapting to technological development, improving and/or introducing new machinery that can increase productivity and sawing yield, as well as safety at work.

These companies use not only forest essences typical of the area but also the olive tree, a species that characterises the agrarian landscape. In fact, in some areas of the Plain of Gioia Tauro, there are real 'olive groves', which can be used to define and identify the type, majesty and density of these trees. Despite the extensive cultivation of olive trees, especially in southern Italy and the Mediterranean basin, to the author's knowledge, olive wood is still little studied. With regard to the availability of forest resources, the Tyrrhenian slope of Aspromonte varies from chestnut groves; holm oaks and other oak species; conifer reforestations; beech forests, and sometimes mixed formations with silver fir.

For this reason, it is clear that the various companies operating in the area within the Forest-Wood Chain need support to improve their rather limited work activities, with modest innovations in the wood harvesting and processing process. The objectives, therefore, of this project are to:

- Analyse the productivity of these specialised forestry machines operating in Calabrian forests;
- Broaden knowledge of olive wood;
- To define a series of actions aimed at fostering the development of new and innovative production processes in the various phases of wood harvesting and processing.

To achieve its objectives, the three-year research focused on the analysis of the forest-wood sector in the Plain of Gioia Tauro and the valorisation of wood products. The research was divided into six **specific research objectives** (SRO<sub>s</sub>):

- **SRO<sub>1</sub>**. Given the increasing use of specialised forestry machinery in the Calabrian territory, the objective was to analyse the productivity of two forestry machines used in the area: skidders (**SRO<sub>1.1</sub>**) and harvesters (**SRO<sub>1.2</sub>**). This is aimed at deepening the knowledge of these machines also operating in the forests of southern Italy.
- **SRO<sub>2</sub>**. The olive tree has always characterised the agricultural landscape and common uses of the Mediterranean basin, especially when talking about the Plain of Gioia Tauro. In these SROs, the focus was on the study of the anatomy of olive wood, as it is still a little-studied species, given its great importance in the area. The study focused on the study of the anatomy of olive wood, as it is a species that is still little studied, given the great importance it has on the territory. The study focused on the two olive cultivars that characterise the agricultural landscape of the Gioia Tauro Plain: '*Sinopolese*' and '*Ottobratica*'. Moreover, this study acts as a springboard for the three subsequent SRO<sub>s</sub>.

- **SRO<sub>3</sub>**. During the various prunings, various woody assortments are created, some of which are destined for subsequent processing. In this SRO<sub>3</sub>, knowledge of the two olive cultivars that characterise the Plain of Gioia Tauro area ('*Sinopolese*' and '*Ottobratica*') was deepened. Various physical-mechanical tests were carried out on the trunk and branches of both cultivars.
- **SRO<sub>4</sub>**. Considering that the majority of steam treatments are carried out at high temperatures, this study aimed to evaluate the influence of low-temperature treatment on the mechanical properties of wood. Therefore, the study tested wood samples at a constant temperature of 80°C at different times (12, 18, 36 hours).
- **SRO<sub>5</sub>**. The wood from the various uses that are carried out on the agroforestry land is mainly conveyed to sawmills in the area. The predominant species used is the olive tree. In this SRO<sub>5</sub>, the sawing yields, with three different species, of a medium-sized sawmill were evaluated.

This thesis aims to explore the forest-wood sector in the Gioia Tauro plain centred on olive growing. Specifically, it will explore the local scenery in terms of forestry mechanisation and wood technology. We proceeded to refine our knowledge: of the forest machinery used, of the first wood processing and of the species characterising the area (the olive tree). By assessing any gaps within the various sectors of the supply chain and, where possible, enhancing them. Finally, the possibility of introducing olive wood steaming as an alternative method of seasoning or for other uses was evaluated.

### 3. MATERIALS AND METHODS

#### 3.1. Time Motion Study and productivity evaluation

The first activity, consisting of two scientific articles, relates to the study of the productivity of two highly specialised forestry machines (skidder and harvester). Therefore, this section has been divided into two further sub-sections to describe the data collection of these papers.

##### ***Performance of Skidder***

The tests were carried out in the Aspromonte National Park (RC). The work phases, denoted by the letters A and B, were recorded at two distinct worksites. The worksites are located in the Reggio Calabria province's Santa Cristina d'Aspromonte municipality. Silver fir (*Abies alba* Mill.) constitutes the two worksites, A and B (Table 1) (Figure 23). A cut-to-length system method was used. The extension measured 3.23 and 3.30 hectares for sites A and B, respectively. The machine was continuously observed during skidding operations, a time and motion study was used to observe the different work phases, and the extraction distances were noted for every cycle. The total number of logs transported was counted and each tree's volume was calculated using Smalian's formula (Eq. 1):

$$V = \frac{(S_b + S_s)}{2} h \quad (\text{Eq. 1})$$

Where:  $S_b$  is the area of the small end of the log,  $S_s$  is the area of the large end of the log and  $h$  is the length. Both sites are located at an altitude of 1190 metres above sea level. The study was conducted at a thinning site. The stand density was 525 and 850 trees per hectare for site A and B, respectively. Site characteristics are described in table 1 and showed in the figure 1. Site A has an average slope of 10% while site B 20%.

Features	Unit	Site A	Site B
Silvicultural system		High forest	High forest
Species		Silver fir	Silver fir
Extension	ha	3.23	3.30
Stand density	trees ha <sup>-1</sup>	525	850
Slope	%	10	20
Basal area	m <sup>2</sup>	42	56
Average DBH	cm	32	29
Average Height per tree	m	29.3	26.1
Average volume per tree	m <sup>3</sup>	2.36	1.72

Table 1. Test site characteristics.

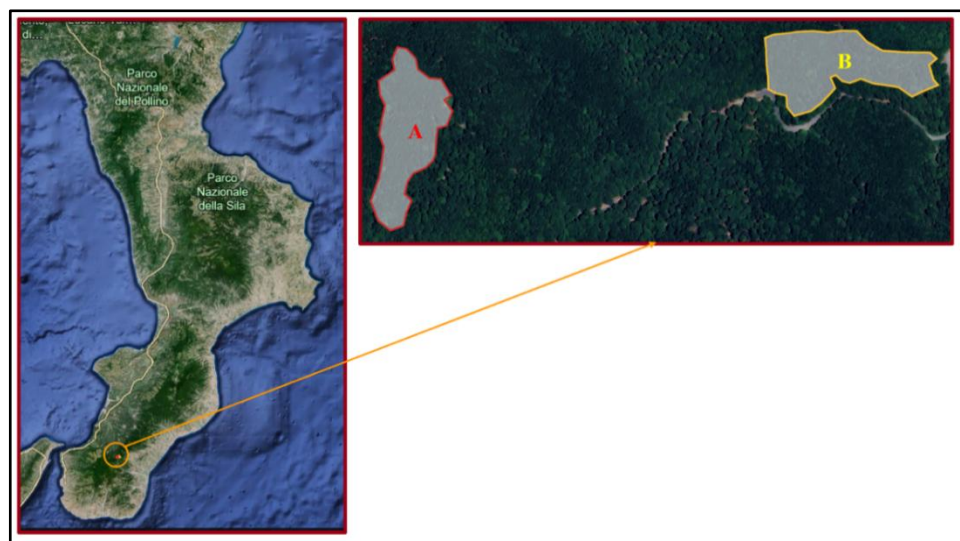


Figure 23. Location of study area

The forestry skidder used was a Equus 175N, equipped with two cable winches, a hydraulic arm and clumbank (Table 2) (Figure 24). The skidding operations were mainly carried out with a hydraulic arm and a clumbank because it was possible to get close to the felled timber. If access to the felled timber was not accessible, winches were used. A Suunto clinometer was used to measure the gradient, and a Magellan TritonTM 2000 handheld Global Positioning System (GPS) was used to measure elevation. A measuring tape was used to measure the extraction distances. The information gathered throughout the winching and skidding phases made it possible to determine the

machine's hourly production.

Parameters	Unit	Value
Manufacture		Equus
Model		175N
Power	kN	129
Weight	tonnes	12.60
Height	mm	2870
Width	mm	2450
Length	mm	7894
Clearance	mm	544
Wheelbase	mm	3208
Clumbank area	m <sup>2</sup>	1.2
Hydraulic arm length	m	8.2
Displacement torque of hydraulic arm	kN	120
Diameter Winches Cable	mm	14
Drums capacity	m	115
Nominal Pulling Force of winch	kN	98

Table 2. Specifications of the skidder



Figure 24. Equus 175 N skidder

The Cut-to-Length (C.T.L.) work system was used at both locations, and there were just two employees on the crew. A skidder operator, who used a skid-

ding clumbank to drag the timber and by the hydraulic arm for the transport of suspended timber to the landing area. The cable was released for hooking when the operator drove the skidder from the roadsite to the felling site. The choker setter secured the loads to the cable, the skidder winched them to the skid tracks, and the skidder removed them to the landing zone.

The times of the different work phases were measured separately using the repetition-timing method to determine the total skidding cycle time (productive time or delay time) [20]. The skidding cycle was divided into several elements:

- Travel unloaded (similar for winches, clumbank, and hydraulic arm): begins when the skidder pulls out of the landing area and ends in the stump area to mark the finish of the run.
- Loading: This phase comprises the following sub-phases:
  - Release and hooking (cable winches): begins as soon as the worker grabs the cable and places the choker on the logs, and it ends when the skidder operator starts to winching.
  - Winching (cable winches): starts when the driver pulls on the winch, and it finishes when the tree reaches the back of the skidder.
  - Grabbing (clumbank): starts when the clumbank opens and the arm starts to load, ends when the clumbank closes.
- Travel loaded (similar for cable winches, clumbank, and hydraulic arm): starts when the machine moves to the landing and finishes when it reaches the landing.
- Unhooking (similar for cable winches, clumbank, and hydraulic arm): starts as soon as the machine reaches the landing and finishes when the load is disconnected.

Productivity was calculated excluding delays (PMH) and as scheduled machine hours (SMH). Operational, technical and personal delay types were measured in skidding. This study measured the impact of several independent variables: skidding distance, number of logs, and load volume on the total cycle

time, considered as a dependent variable.

### ***Performance of Harvester***

This research has collected data in Serre Massif (VV) forest, in Calabria region (Southern Italy) (Table 3). During harvesting operations, the machine was constantly monitored, the various work phases were divided using a time-motion study, and the data of wood logs were recorded and marked with paint on both sides of tree. The forest is mainly composed of silver fir (*Abies alba* Mill.) and it is located at an elevation of 1070 m above sea level (Figure 25). The time motion study was performed in January 2024. The collected data was then organized in tables using Microsoft Excel.



Figure 25. Silver fir forest

<i>Features of study area</i>	<i>Unit</i>	
Silvicultural system	-	High forest
Logging operation	-	Shelterwood cutting
Surface of the area	ha	15
Stand density	trees ha <sup>-1</sup>	550
Average DBH	cm	23.9
Average height per tree	m	20.6
Average volume per tree	m <sup>3</sup>	0.68
Average slope	° (‰)	15.6 (28)

**Table 3.** Test site characteristics

The characteristics of the harvester monitored are shown in Table 4 (Figure 26). The harvester was equipped with the H480 harvesting head. The harvesting system was subdividing in the sequence of searching and cutting, processing, moving and delays time [21].

A time and motion study was carried out to estimate the time consumption and productivity of the harvester. The times of the different work phases were measured separately using the repetition-timing method to determine the total harvesting cycle time (productive time and delay time) [21]. Each work phase was individually timed by a video camera to account for the scheduled machine hours (SMH). Following the field observations, the total work time day was divided into productive time (PMH) and delays time. The delays time included mechanical interruption (general review of the machine; fueling, cutting system adjustments); operational interruption (cleaning the machine with dry leaves and branches, receiving instructions from the manager) and personal interruption (satisfying basic operator needs).

<i>Parameters</i>	<i>Unit</i>	<i>Value</i>
Make	-	John Deere
Model	-	1270D
Power	kW (hp)	160 (215)
Weight	tonnes	17.5
Height	m	3.70
Width	m	2.86
Length	m	7.58

<i>Crane specifications</i>		
Crane model		210 H
Gross lifting moment	kNm	178
Sweling torque	kNm	43.6
Maximum boom reach	m	10
Tilt angle	°	-13 / +25
Sweling angle	°	220
<i>Harvester head specifications</i>		
Model	-	H480
Felling diameter	mm	650
Delimiting knife	n°	4 moving, 2 fixed
Delimiting diameter	mm	480
Max feeding speed	m sec <sup>-1</sup>	5
Weight	kg	1200

Table 4. Harvester specifications



Figure 26. The John Deere 1270D harvester

Particularly, regarding the harvesting cycle, the productive time was subdivided into three elements [22]:

- **Searching and cutting:** it starts when the harvester crane and processor head move in search for a tree to cut, until the separation of the tree from the stump.

- **Processing:** including delimiting, cross-cutting, and stacking of logs at the harvesting site. It starts when the feeding rolls move and ends when the last piece of the tree is dropped from the processing head.
- **Moving:** It starts when the harvester moves from one location to the next and ends when the moving is halted.

The volume ( $V$ , m<sup>3</sup>) was calculated based on Smalian's formula (Eq. 2):

$$V = \frac{(S_0 + S_n)}{2} h \quad (\text{Eq. 2})$$

Note:  $V$  volume (m<sup>3</sup>);  $S_0$  area of log butt (m<sup>2</sup>);  $S_n$  area of log top (m<sup>2</sup>);  $h$  height of tree (m).

The equations for the calculation of the time consumption (Eq. 3) and productivity (PMH) (Eq. 4) are [23]:

$$T_{tot} = t_1 + t_2 + t_3 \quad (\text{Eq. 3})$$

Note:  $T_{tot}$  the productivity time separated from delay time;  $t_1$  time consumption for searching and cutting phase;  $t_2$  time consumption for processing phase;  $t_3$  time consumption for moving phase.

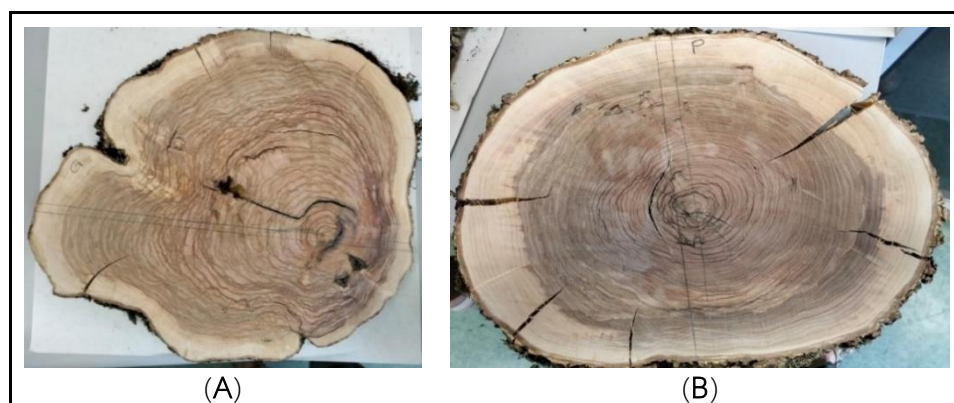
$$P_{PMH} = \frac{3600V}{T_{tot}} \quad (\text{Eq. 4})$$

Note:  $P_{PMH}$  = the harvesting productivity based on a productive machine hour approach.

### 3.2. Wood anatomy study

A wood slice was taken from both trees of the two cultivars (Figure 27). The wood slice obtained from the 'Sinopolese' cultivar had a circumference of 135 cm; the maximum diameter was 46 cm, and the minimum was 37 cm (the average diameter is 40.5 cm), and the thickness was 4.5 cm. The slice had an irregular shape with an obvious eccentricity with the pith displaced laterally.

The growth rings were irregular, like the shape of the wood slice, and tension wood was present on the larger portion of the piece. There were some radial cracks caused by wood shrinkage and two ring shakes (Figure 27A). Both slices were obtained from each stem at 5.50 m height during extraordinary re-form pruning activity. The presence of tension wood in the olive tree is very common because the tree has a very irregular trunk. In the case of the extraordinary pruning activity, the choice of two specimens with similar morphological characteristics was not possible because the selection of the trees to be felled is made upstream and follows a specific authorized felling plan. The '*Ottobratica*' cultivar wood slice shape was more regular than '*Sinopolese*' and it had a circumference of 94 cm, a maximum diameter of 32.5 cm, and a minimum diameter of 26 cm (the average diameter was 29.5 cm). The thickness was 4 cm. This slice had a more regular shape, and the pith was located in the middle of the piece. There were ring shakes and some radial cracks (Figure 27B).

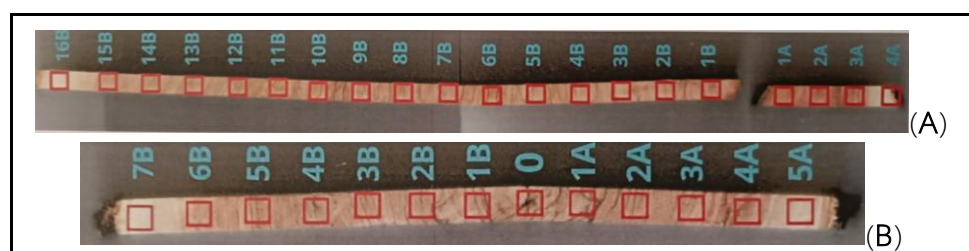


**Figure 27.** Olive wood slices: (A) *Sinopolese* cultivar; (B) *Ottobratica* cultivar.

The slides for the anatomical analysis were obtained from wood samples taken from two strips approximately 1 cm wide cut from the '*Sinopolese*' and '*Ottobratica*' slices (Figure 28). The samples were cut from the pith of the

wood outwards, at a distance of 2 cm from each other, along the diameter shown in pencil in Figure 2. Then, the samples were cut to obtain a cube of 1 cm each side. For the cutting, an automatic fretsaw with a thin blade was used for a precise cut. Due to the different sizes of the two wooden slices, 20 and 13 cubes were obtained from '*Sinopolese*' and '*Ottobratica*', respectively.

After boiling to soften the wood [24], the cubes were cut with a Leica RM2245 semi-automatic rotary microtome (Leica Biosystems, Milan, Italy) to obtain 12–14  $\mu\text{m}$  thick slices. For the anatomical analysis, three sections were cut for each sample: radial, tangential, and cross-section. In the end, 20 slides for '*Sinopolese*' and 13 slides for '*Ottobratica*' cultivars were prepared and 99 sections were analysed to identify the olive wood's anatomical characteristics. From the analysis of the slides, some characteristics not described in the literature were identified. Therefore, to further the analysis, additional analyses were conducted; 4 cubes were selected for each cultivar, with 2 of sapwood and 2 of heartwood. Radial and tangential sections were cut to obtain 16 sections, 8 sections for each cultivar. To prepare permanent slides, a photo-hardening gel, Eukit UV R Low Viscosity gel (ORSAtec, Viterbo, Italy), was used and the slides were put in an oven with a UV lamp for 15–20 min.



**Figure 28.** Olive wood cultivar samples: *Sinopolese* (A) and *Ottobratica* (B). Small red squares indicate where the samples were cut with the respective codes (sample 0 is the pith).

The characterisation of the not-yet-classified substances observed in the pa-

renchyma cells was possible thanks to a specific stain applied to the newly prepared slides. Assuming the presence of starch, it was decided to use Lugol's solution based on iodine (Marco Viti, 7% iodide solution and 5% potassium iodide solution in deionised water and ethanol). If starch is present, the colouring solution reacts and the starch takes on a shade tending towards purple or dark blue. Some drops of staining solution were applied to each of the 16 sections, and after 1 min the sections were washed, first with deionised water and then with a 50% solution of deionised water and ethyl alcohol. Finally, the sections were dehydrated with ethyl alcohol [25]. At the end of this procedure, the permanent slide was mounted. The slides made for the anatomical characteristics study were observed with a Leica DMC 4500 microscope (Leica Biosystems, Milano, Italy), and pictures of the main anatomical characteristics were taken. Stained slides were digitalised with the Axioscan 7 scanner (Zeiss, Milano, Italy), and images were obtained with a specific application, ZEN ZEISS 3.9 (Zeiss, Milano, Italy).

### **3.3. Study of the mechanical properties of wood**

The woody material was gathered from a local orchard of olive trees after fruit harvesting operations in the municipality of Oppido Mamertina, in the "Plain of Gioia Tauro" (South Italy). Regarding temperatures and the climatic regime of the area, in Oppido Mamertina, the summers are short, with clear sky, and characterized by hot, muggy and dry weather, the winters, instead, are long, cold, wet, windy, and partly cloudy sky. During the year, the temperature generally ranges from 7 °C to 28 °C and is rarely below 4 °C or above 30 °C. Basic information about the trees and the growing site are reported in Table 5.

Cultivar	Unit	Sinopolese	Ottobratica		
Latitude	°	38°16'48"	38°16'52"		
Longitude	°	15°59'06"	15°58'58"		
Altitude	m. a.s.l.	340	340		
Age	years	70	70		
Mean height	m	15.5	17.6		
Tree part	Unit	Stem	Branches	Stem	Branches
Mean log diameter	cm	67 (± 13)	38 (± 9)	70 (± 15)	41 (± 9)
Max log diameter	cm	92	52	93	55
Min log diameter	cm	42	24	47	27
Wood density	Kg/m <sup>3</sup> 12% MC	1023 (± 39)	1070 (± 60)	994 (± 44)	1020 (± 49)
Max wood density	Kg/m <sup>3</sup> 12% MC	981	985	922	936
Max wood density	Kg/m <sup>3</sup> 12% MC	1102	1176	1075	113

**Table 5.** Wood tested collection site, timber harvested, and wood characteristics information

The two cultivars were distinguished by botanical morphological characteristics (size and shape of the drupes, difference in leaf colour, size and shape of the leaves, ripening times of the fruit). Both cultivars presented majestic habits, with large branches reaching more than 50 cm in diameter, From the pruning of the olive tree, for each cultivar ('*Sinopolese*' and '*Ottobratica*'), 3 trees were selected to obtain logs from branches and stems for the experimental specimens' production (Figure 29 A). For the choice of parts, the stem was considered to become branch when, above each branch intersection, it changed in diameter and direction of growth. During pruning operation branches were cut from the stem, excluding the branches with a diameter lower than 20 cm. The logs carefully selected and separated by cultivar and tree parts, were sawn into disks with transversal cuts and boards through tangential cuts (Figure 29 C). Among them, the defect-free were selected to prepare the specimens (Figure 29 D) for the experimental material. The specimens were obtained from portions of wood far from the areas where tension wood was present.



**Figure 29.** 'Sinopolese' olive trees (A), branches logs (B), branches sawn wood (C) and branches wood specimens for laboratory tests (D)

The sawn wood collected in the field was transported to the laboratory of Wood Technology and Forest Mechanization of the AGRARIA Department of Reggio Calabria for the production of specimens, conditioning and, subsequently, for carrying out the tests. A total of 400 specimens were obtained for each cultivar, of which 20 specimens were prepared from branches and 20 specimens from stems for carrying out the eleven kinds of tests described in the next section. The dimension of each specimen shown in Table 6. Once the specimens were prepared, they were conditioned in a climatic chamber (*Memmert GmbH, Germany*) at  $20 \pm 2$  °C and 65% ( $\pm 5\%$ ) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12% (Figure 30). Air-dried density of each sample was determined in accordance with the ISO standard 13061-2:2014 [26], and moisture content was determined following

the oven dry method [27, 28]. In the laboratory, ten prismatic samples with dimensions of 30R×30T×40L mm were obtained from each of the trunks and branches of each cultivar to be used to measure the density at 12% (EMC), in accordance with the ISO 13061-2 standard [26].

Properties	Code	Standard	Specimens' dimensions (R × T × L) (mm)
Surface roughness	R <sub>a</sub>	UNI EN ISO 21920-3	100 × 100 × 170 [29]
Dynamic modulus of elasticity (impact wave)	MOEd _MSt	-	30 × 20 × 300
Dynamic modulus of elasticity (vibrational analysis)	MOEd _PLG	-	30 × 50 × 300
Static modulus of elasticity	MOEs	EN 408	20 × 20 × 500 [30]
Bending strength	MOR	EN 408	20 × 20 × 500 [30]
Abrasion resistance	WL	UNI EN 15185	120 × 120 × 20 [31]
Static hardness	SH	ISO 4712	60 × 60 × 100 [32]
Footprints	F	UNI 4712	60 × 60 × 100 [32]
Compression strength	C	ISO 13061-17	20 × 20 × 30 [33]
Screw withdrawal resistance parallel to grain	SW _Par	EN 1382	60 × 60 × 100 [34]
Screw withdrawal resistance perpendicular to grain	SW _Per	EN 1382	60 × 60 × 200 [34]

Table 6. Tests conducted, and specimens used in the study

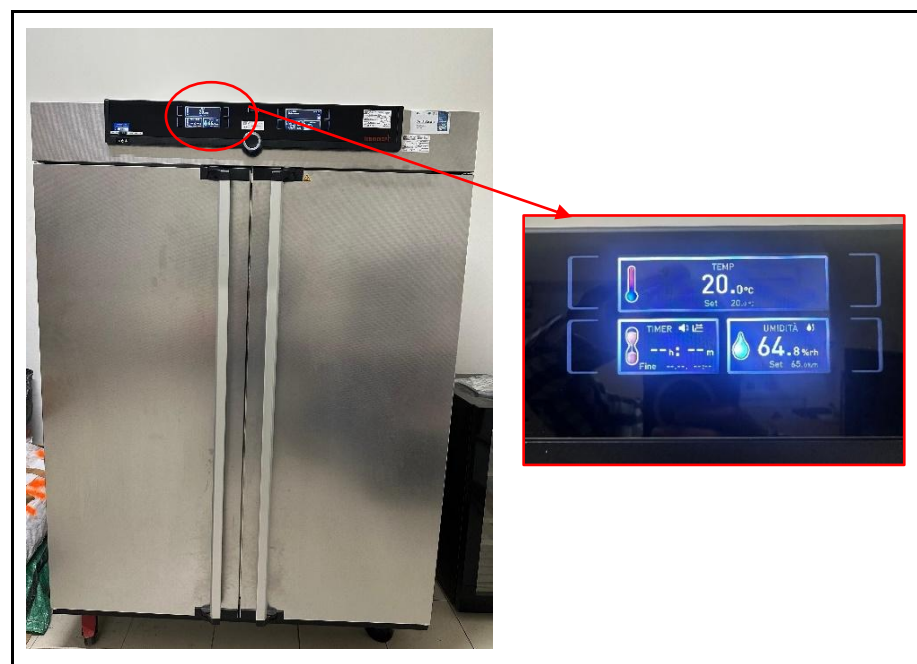


Figure 30. climatic chamber (Memmert GmbH, Germany)

The laboratory tests consisted of non-destructive tests and destructive tests for the characterization of the '*Sinopolese*' and '*Ottobratica*' cultivars olive wood. Non-destructive techniques were applied for the estimation of dynamic modulus of elasticity (MOEd), and for the surface roughness profile measurements. Destructive tests concerned static modulus of elasticity, bending strength, abrasion resistance, static hardness, footprints, compression strength, and screw withdrawal resistance.

For the surface roughness profile measurements, the specimens were sanded sequentially with 100 and 200 grit sandpaper on the tangential surfaces, according to the UNI EN ISO 21920-3:2022 [35]. The roughness profile was recorded with a Mitutoyo Surftest SJ-301 (*Mitutoyo Corporation, Japan*) surface roughness measuring system. Measurements were made with the profile method using a skid type diamond stylus with 5  $\mu\text{m}$  tip radius and a 90-tip angle. The measuring speed was 0.5 mm/min with a cut-off of 8 mm on six plots of 10  $\times$  10 mm distributed randomly on the surface of each specimen for a total of 240 measurements for each olive tree cultivar (120 measurements per each part of tree of each cultivar analysed) (Figure 31). The  $R_a$  parameter ( $\mu\text{m}$ ), the arithmetical mean of the absolute values of the profile deviations from the mean line of the roughness profile, was recorded and used to evaluate the surface roughness of the specimens. The average value of  $R_a$  was obtained by averaging six records on different positions on each sample.



**Figure 31.** Roughness profile was recorded with a Mitutoyo SurfTest SJ-301

The estimation of dynamic modulus of elasticity (MOEd) was determined with two different non-destructive tools, both based on acoustic wood property: the Microsecond Timer (*Fakopp Enterprise, Agfalva, Hungary*) used to conduct the impact wave test (MOEd\_MST), and the Portable Lumber Grader (*Fakopp Enterprise, Agfalva, Hungary*) for the vibrational analysis (MOEd\_PLG).

Both tests were replicated several times deriving the average data from at least three recordings for each sample measurement with each tool.

For the impact wave test, the specimens were tested by Microsecond Timer (*Fakopp Enterprise, Agfalva, Hungary*) device to measure the Time of Flight of an acoustic wave generated mechanically by tapping the start sensor with a hammer which travels through the wood tissue reaching the opposite sensor (Figure 32). The dynamic modulus of elasticity was calculated using Eq. 5:

$$MOEd_{MST} = \rho \cdot v^2 \quad (Eq.5)$$

where  $MOEd_{MST}$  = dynamic modulus of elasticity ( $10^{-6}$  N/mm<sup>2</sup>);  $\rho$  = density (kg/m<sup>3</sup>);  $v$  = wave transmission velocity (m/s<sup>1</sup>).



Figure 32. Specimens were tested by Microsecond Timer

Portable Lumber Grader (*Fakopp Enterprise, Agfalva, Hungary*) tool was used to determine the natural longitudinal vibration frequency of the tested lumber. Specimen vibration has been generated with a hammer on the transversal face of the specimen and the signal is captured by a microphone placed at the opposite transversal face (Figure 33). The acoustic signal is analysed by a computer with the Fourier vibration analyser (*Fakopp Enterprise, Agfalva, Hungary*) to detect the natural frequency of each specimen. This equipment includes a balance to determine the weight of the specimen. Using the specimen's mass ( $m$ , in kg), width ( $w$ , in m), length ( $l$ , in mm), height ( $h$ , in mm), and the longitudinal vibration  $\times$  frequency ( $f$ , in Hz), MOEd\_PLG (in  $10^6$  N/mm<sup>2</sup>) is calculated with the following Eq. 6:

$$MOEd_{PLG} = \frac{m}{lwh} (2fl)^2 \quad (Eq. 6)$$



Figure 33. Specimens were tested by Portable lumber grader

Static modulus of elasticity (MOEs) and bending strength or modulus of rupture (MOR) were determined perpendicular to grain. For these tests, the specimens were tested adopting the four-point bending test, performed using a 300 kN universal testing machine (*METRO COM, Italy – 10402030 model*), applying to the load a speed of 3.6 mm/s. The distance between the two points of the load was 120 mm, while that between the supports is 380 mm, in accordance with European Standard 408:2010 + A1 [30] (Figure 34). Data were recorded by the dedicated *METRO COM* software.

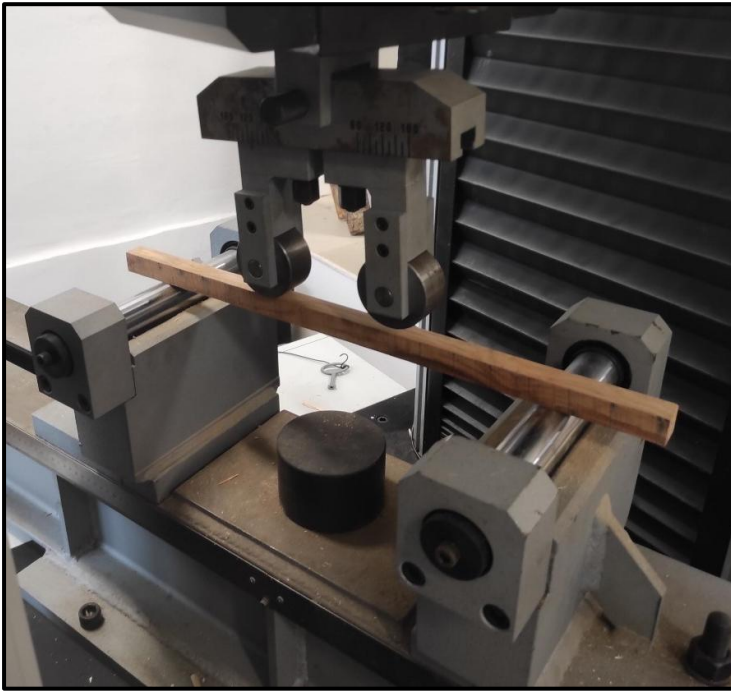


Figure 34. Specimens were tested by universal testing machine

The abrasion resistance measurements were conducted according to the UNI EN 15185:2011 [31]. The specimens were abraded using a Taber Rotary Abraser 5135 (*Taber Industries, USA*) applying loads of 1000 g, with 500 cycles at the controlled speed of 60 revolutions per minute (RPM). S-42 sandpaper strips (*Taber Industries, USA*) were used as the abrasive. Sandpaper was changed after each 250 test cycles to guarantee the same abrasive performance. The specimens were weighed before the abrasion test, after 250 cycles, and after 500 cycles [50] (Figure 35). The weight loss in percentage was determined by Eq. 3:

$$WL = \frac{(W_1 - W_E)}{W_1} \cdot 100 \quad (3)$$

where  $WL$  = weight loss (%);  $W_1$  = weight of test specimen before abrasion (g);  $W_E$  = weight of test specimen after abrasion (g).

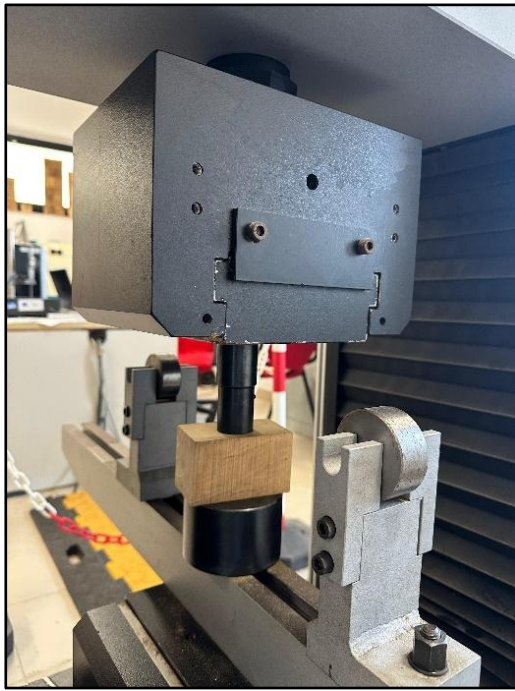


Figure 35. Specimens were tested by Taber Rotary Abraser 5135

The static hardness tests were carried out tangentially on wood specimens and the measurements were performed by applying a force necessary to embed an 11.28-mm-diameter steel ball indenter halfway into a sample according to the ISO standard EN 13061-12:2017 [36] using the same universal testing machine used for bending strength tests (Figure 36). The surface hardness test measures the resistance of a sample of wood to denting and wear and it was calculated using the following Eq. 7:

$$SH = K \cdot F \quad (Eq. 7)$$

where SH = surface hardness at moisture content W (kN); K = coefficient equal to  $4/3$  in the case of penetration of the plunger to a depth of 2.82 mm; F = maximum load during the penetration of the plunger into the test sample to the specified depth (kN).



**Figure 36.** Static hardness tests were carried out tangentially on wood specimens

For the footprints measurements the specimens were tested on 5 points of replication for each sample according to UNI 4712:2011 [32] and using the same universal testing machine used for bending strength tests (Figure 37A). The peak load of 1575 N was applied with a cylindrical indenter (10 mm diameter) steel force punch during the test, corresponding to a unit stress of  $2000 \text{ N/mm}^2$ . For each sample, the deformation was measured at 5 points at three different moments: during the test at the peak load, immediately after the test, and two days after the test (48 hours after), by using a digital comparator ( $1 \mu$  sensitivity). The results were compared to the measurements of the original size of specimens obtained in the same five points (figure 37B).

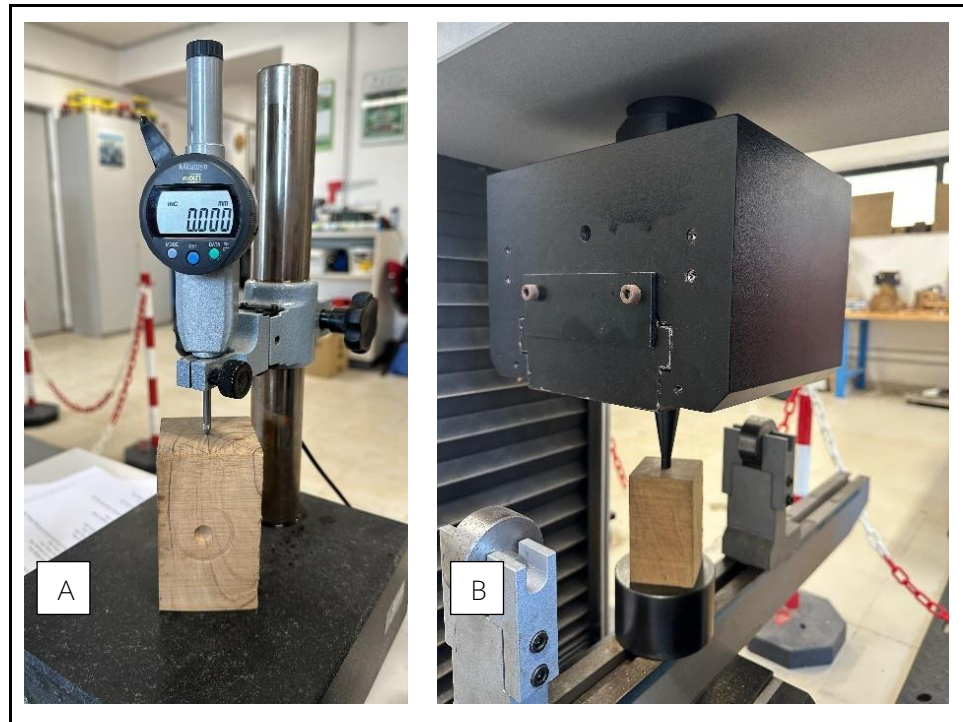
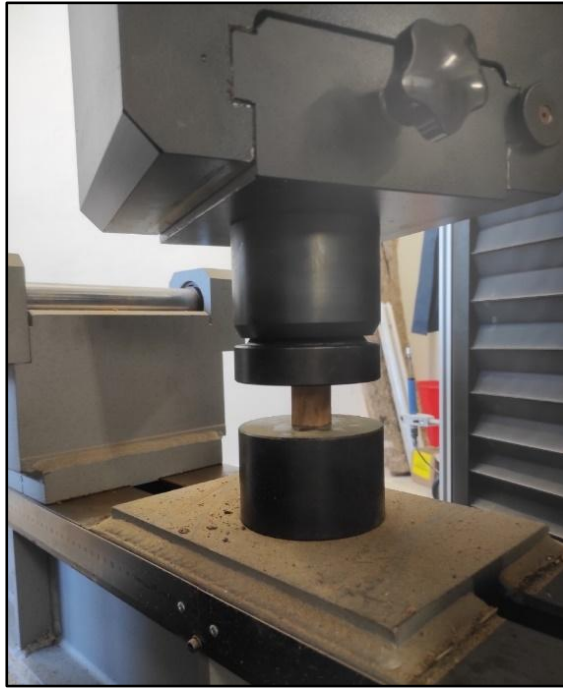


Figure 37. (A) Measurement of 5 points; (B) Footprint test

About the compression strength tests parallel to the grain, the olive wood specimens were tested by the same METRO COM universal testing machine applying a load at a constant loading-head movement settled (in this case at a speed of 5 mm/s) to reach the maximum load within 300 seconds from the start of the test, in accordance with the standard in force for compression tests (ISO 13061-17:2022) [33, 37] (Figure 38). The compressive strength was measured using (Eq. 8)

$$C = \frac{F_{\max}}{A} \quad (\text{Eq. 8})$$

where  $C$  = compressive strength parallel to the grain ( $\text{N}/\text{mm}^2$ );  $F_{\max}$  = maximum load (N);  $A$  = cross-sectional area ( $\text{mm}^2$ ).



**Figure 38.** Specimens were tested by universal testing machine

Screw withdrawal resistance was measured parallel to the wood grain (SW<sub>par</sub>), and perpendicular to them (SW<sub>per</sub>), and was assessed according to EN 1382:2016 [34] (Figure 39 and Figure 40). The tests were conducted with the commercial Screw Withdrawal Force Meter device (*Fakopp Enterprise Bt., Sopron, Hungary*). The screw applied without predrilling was a standard SPAX (PZD) type head screw 45 mm long, with size of diameter 3 mm.



Figure 39. Specimens were tested by Screw Withdrawal Force Meter device



Figure 40. Specimens were tested by Screw Withdrawal Force Meter device

The withdrawal parameter of the screw  $SW$  (N/mm<sup>2</sup>) was calculated according to the following expression (Eq. 9),

$$SW = \frac{F_{\max}}{d \cdot l_p} \quad (\text{Eq. 9})$$

where  $F_{\max}$  is the maximum withdrawal load (N),  $d$  is the diameter of the screw (mm), and  $l_p$  is the depth of the penetration of the screw into the wood (mm).

### 3.4. Steaming treatment tests

The sawn boards were divided into three groups and each group was subjected to steam under saturated conditions and a maximum pressure of approximately 80°C and 140 kPa for 12 hours, 18 hours and 36 hours, respectively.

Dynamic modulus of elasticity (MOEd) and colour measurement were conducted on the sawn-boards before and after steaming. After steaming, from the boards were obtained specimens for: dimensional stability, bending strength, compression strength, Janka hardness, and surface abrasion tests.

Once the specimens were prepared, they were conditioned in a climatic chamber (Memmert 750 Eco, GmbH, Germany) at  $20 \pm 2^\circ\text{C}$  and 65% ( $\pm 5\%$ ) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12%. Air-dried density of each sample was determined in accordance with the ISO standard 13061-2:2014 [40], and moisture content was determined following the oven dry method [41, 42]. The tests were carried out in the laboratory of Wood Technology and Forest Mechanization of the Agraria Department of Reggio Calabria. The distribution of specimens is shown in table 7.

	CM	DS	MOEd	BS	CS	JH	AR
Seasoning	8	40	12	14	35	20	10
12 h cycle	8	40	12	14	35	20	10
18 h cycle	8	40	12	14	35	20	10
36 h cycle	8	40	12	14	35	20	10
	<b>32</b>	<b>160</b>	<b>48</b>	<b>56</b>	<b>140</b>	<b>80</b>	<b>40</b>

CM = Colour measurements; DS = dimensional stability; MOEd = dynamic modulus of rupture; BS = Bending strength; CS = Compressive strength; JH = Janka hardness; AR = Abrasion resistance

**Table 7.** Distribution of specimens

Color measurements of all boards were recorded on the surface of the wood samples before and after steaming treatment with a SAMA tools colorimeter (Figure 41). The sensor head had a diameter of 4 mm. Measurements were made using a D65 illuminant and a standard observer of 8 degrees. The reflectance percentage was converted to the CIELAB color system where  $L$  describes the brightness,  $a$  and  $b$  describe the chromaticity coordinates on the green-red and blue-yellow axis, respectively. Tests were performed on both sapwood and heartwood. A measuring tape was placed diagonally across the board. The first measurement was taken on the sapwood, at approximately 10 cm. The second measurement was taken on the heartwood, at about half length. From the laboratory values, the difference in brightness ( $\Delta L$ ) and chromaticity coordinates ( $\Delta a$  and  $\Delta b$ ) and the total color difference ( $\Delta E$ ) were calculated using the following formulas (Eq. 10; Eq. 11; Eq. 12; Eq. 13):

$$\Delta L = l_2 - l_1 \quad (\text{Eq. 10})$$

$$\Delta a = a_2 - a_1 \quad (\text{Eq. 11})$$

$$\Delta b = b_2 - b_1 \quad (\text{Eq. 12})$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (\text{Eq. 13})$$

Where:  $l_1$ ,  $a_1$  and  $b_1$  = measurements before treatment;  $l_2$ ,  $a_2$  and  $b_2$  = measurements after treatment.

Each sawn board measured 90 cm in length, 25 cm in width and 3.3 cm in thickness.



Figure 41. Color measurements with a SAMA tools colorimeter

The dimensional stability test was carried out until the equilibrium moisture contents of the wood were reached. For this test, a 28-day (4-week) protocol was established, in which the specimens were placed in a climatic chamber at  $20 \pm 2^\circ\text{C}$  and 65% ( $\pm 5\%$ ) relative humidity (RH) (Figure 42). This protocol included volume and weight measurements taken weekly until the equilibrium moisture content was stabilized. The wood moisture content was measured using a hygrometer at the beginning of the test. Measurements were taken in the three anatomical directions (radial, tangential and transverse) using a digital comparator (Mitutoyo ID-C ABSOLUTE Digimatic) to determine volume (Figure 43). An analytical balance (Nimbus NBL 223e) was used to determine the weight of the specimen (Figure 44). The average dimensions of the specimens are: 31.01 mm ( $\pm 1.28$ ), 31.53 mm ( $\pm 1.44$ ), 48.65 mm ( $\pm 1.26$ )

for the radial, tangential and transverse directions respectively. The average weight is 44.48 gr ( $\pm 2.82$ ).



Figure 42. Specimens placed in a climatic chamber



Figure 43. Measuring the three anatomical directions

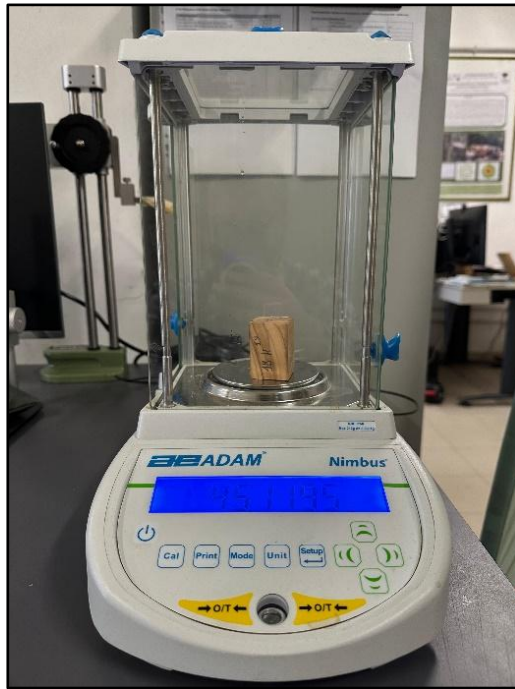


Figure 44. measurement of specimen weights

The dynamic modulus of elasticity (MOEd) was determined perpendicular to the grain. The boards were subjected to a single-path stress wave test using a Fakopp Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary) (Figure 45). This instrument consists of needles connected to accelerometers, used as mediators, that penetrate the bark and reach the sapwood of the tree. A hammer is used to tap the starting sensor to generate a stress wave in the board in the longitudinal direction. The two sensors detect the start and stop signal and the transmission time of the wave is displayed on an LCD screen with a resolution of  $\pm 1 \mu\text{s}$ . The sensors were positioned at 85 cm from each other at an angle of  $45^\circ$ . The test was repeated several times for each pair of sensors to obtain the average value of at least three readings. By measuring the size of the boards, the volume was obtained (Eq. 14). Together with the measurement of the weight of the boards, the density was obtained (Eq. 15). In addition, the moisture content of each sawn board was determined using a digital moisture meter with two electrodes (Schaller, WLW). The measure-

ment was carried out on heartwood and sapwood. The tests were carried out before and after steaming treatment.

$$V = l * w * t \quad (Eq. 13)$$

Where:  $V$  = volume ( $m^3$ );  $l$  = length (m);  $w$  = width (m);  $t$  = thickness (m).

$$D = \frac{w}{v} \quad (Eq. 14)$$

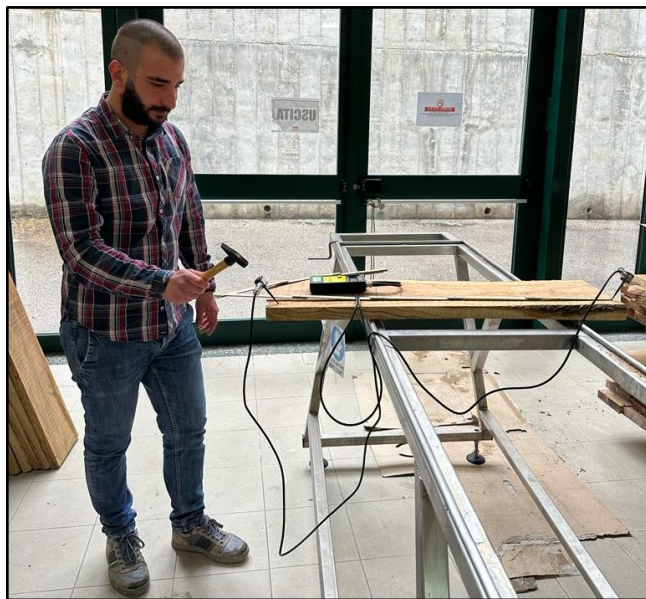
Where:  $D$  = density ( $kg/m^3$ );  $w$  = weight (kg);  $v$  = volume ( $m^3$ ).

With the density and speed of the wave available, it was possible to derive the MOEd (Eq. 15).

$$MOEd = w^2 * D \quad (Eq. 15)$$

Where:  $w$  = wave transmission velocity (m/s);  $D$  = density ( $kg/m^3$ ).

Each sawn board measured 90 cm in length, 25 cm in width and 3.3 cm in thickness.



**Figure 45.** dynamic modulus of elasticity (MOEd) was determined using Fakopp Microsecond Timer

Static modulus of elasticity (MOEs) and bending strength or modulus of rupture (MOR) were determined perpendicular to grain. A four-point bending test was performed using a 300 kN universal testing machine (METRO COM, Italy – 10402030 model), in accordance with European Standard 408:2010 + A1 [30] (Figure 46). Data were recorded by the dedicated METRO COM software. The length of the specimen was 21 times its width. The supports were placed at a distance equal to 18 times the width, and the two load points were placed at a distance from each support equal to 6 times the width (408:2010 + A1) [44]. During the tests, the values of the load and the bend were registered. The specimens had a square cross-section with a side of 3.3 cm. The length, parallel to the grain, was 69.3 cm. The distance between the two loading points was 19.8 cm, while the distance between the two supports was 59.4 cm. The feed rate of the crosshead was 5.9 mm/min.



Figure 46. Test for determination of MOEs and MOR by four-point test.

In the same laboratory, a compressive strength test was performed in accordance with International Standard 13061-17:2022 [33] (Figure 47). The specimens had a square cross-section with a side length of 3.3 cm. The length, parallel to the grain, was 5 cm. The maximum load is reached in no less than 1 minute and no more than 5 minutes after the start of loading (13061-17:2022) [47], a feed speed of 6 mm/min has been set. During the tests, the values of the load and the bend were registered. The compressive strength was measured using (Eq. 16):

$$C = \frac{F_{max}}{A} \quad (Eq. 16)$$

where  $C$  = compressive strength parallel to the grain ( $N\ mm^{-2}$ );  $F_{max}$  = maximum load (N);  $A$  = cross-sectional area ( $mm^2$ ).

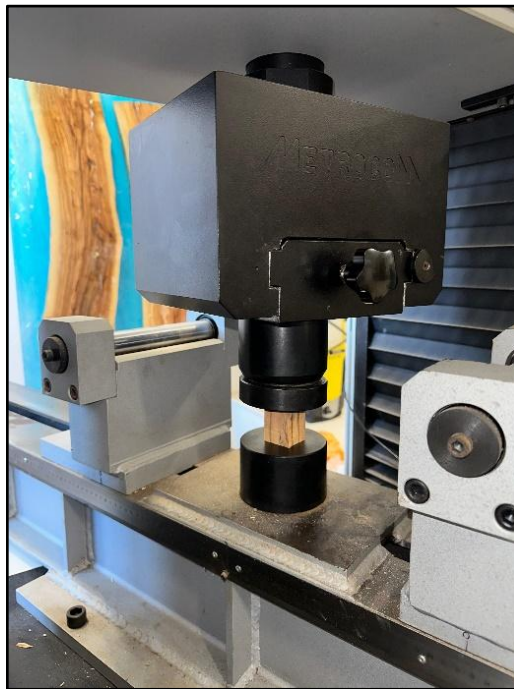


Figure 47. Compression test parallel to the fibre

The Janka hardness was performed in accordance to International Standard

13061-12:2017 [36] (Figure 48). For this method, a hemispherical ball with a radius of 5.64 mm was forced into the sample to a depth of 5.64 mm or 2.82, and the maximum force was recorded during the test. A penetration depth of 2.82 mm was used for the test. The Janka hardness was calculated using (Eq. 17):

$$H_W = K * F \quad (17)$$

Where  $H_W$  = surface hardness at moisture content  $W$  (kN);  $K$  = coefficient equal to  $4/3$  in the case of penetration of the plunger to a depth of 2.82 mm;  $F$  = maximum load during the penetration of the plunger into the test sample to the specified depth (kN).

A feed speed of 6 mm/min was set. The test specimens have a square cross-section of 50 mm × 50 mm and a thickness of 3.3 mm. The test was carried out on the tangential section of the test specimen.

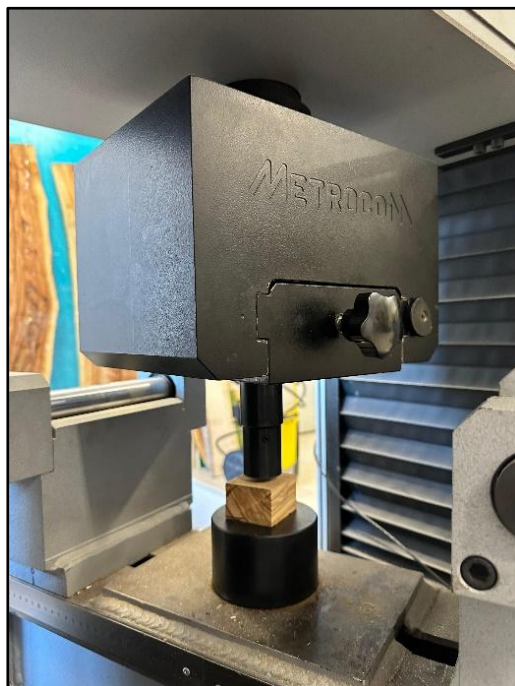


Figure 48. Janka hardness test

Abrasion resistance was determined according to the Taber test (3135 Abraser v2.001), using the sandpaper method, in accordance with UNI EN 15185:2011 [31]. A 240 grit sandpaper and a load of 10 ( $\pm 0.1$ ) N (En 1534) was used for each of the two grinding wheels. The specimens were square (10 cm side) with rounded corners and a thickness of 2.5 cm. Each wood sample was weighed before ( $W_1$ ) subjecting it to the abrasion test using the ADAM Nimbus analytical balance (Figure 49). The samples were fixed to the Taber Abraser and the abrasion test was conducted by setting the wheel rotating at 72 cycles per minute (Figure 50). After 500 revolutions, the weight loss ( $W_2$ ) due to abrasion was recorded. The weight loss ( $W_L$ ) due to abrasion was calculated as a percentage for each sample according to (Eq. 18):

$$W_L = \frac{W_2 - W_1}{W_1} 100 \quad (\text{Eq. 18})$$

where  $W_L$  = weight loss (%);  $W_1$  = weight of test specimen before abrasion (g);  $W_2$  = weight of test specimen after abrasion (g).



Figure 49. Weighing of the specimen before the test.



Figure 50. Abrasion test by Abrasimeter taber

### 3.5. Sawing yields evaluation

The study was conducted on logs of three different hardwood species: olive tree (*Olea europaea* L.), black locust (*Robinia pseudoacacia* L.), and chestnut (*Castanea sativa* Mill.), from forest and agricultural sites located in Calabrian region (South Italy).

In order to avoid possible variations due to the use of different milling machines, as well as the operator's skill and experience, the tests were conducted in only one sawmill [38] which can be considered a representative medium-sized sawmill in Southern Italy as the average processed volume of a general sawmill is estimated to be  $5,000 \text{ m}^3\text{y}^{-1}$  [39, 40]. This industrial sawmill is located in the municipality of Molochio ( $38^\circ 19' 5.423'' \text{ N } -16^\circ 1' 26.526'' \text{ E}$ , Reggio Calabria, Italy) and produces mainly flooring strips and laths.

The study focused on the first step of the sawmill process where the vertical log band saw (SNT 1300 model, Bongioanni company, 75 kW) (Figure 51) with 1.38 mm blade thickness converted logs into boards. Furthermore, to elimi-

nate the possibility of yield variance in the sawing process, the sawing pattern was predefined, and all logs were sawn into boards using the live sawing method, adapted in thickness to the log dimension and the sawmill production objective. Live sawing is a fast method of breaking down the log that involves longitudinal cuts parallel to the axis of the log, parallel to each other [41, 42, 43, 44]. The technical characteristics of the vertical log band saw are described in table 8.



Figure 51. Hydraulic vertical log band saw

Parameters	Unit	Value
Make		Bongiovanni
Model		SNT 1300
Main motor power	kW	55 ÷ 75
Flywheel diameter	mm	1,300
Flywheel band	mm	165 ÷ 190
Blade dimension	mm	180 ÷ 206 x 1,38
Max blade length	mm	9.250
Blade speed	m/s	32 ÷ 42
Weight	kg	4,500
Height	mm	3,100
Width	mm	1,100

Length	mm	2,100
Effective cutting height	mm	1,000
<b><i>Hydraulic log carriage with variable axis</i></b>		
Wagon drive unit model		GEA
Electric positioner model		Alfa 98
Engine power of the lubrication unit	kW	0,09
Engine power chain	kW	11 ÷ 15
Brushless motor power (each)	kW	4
Maximum working pressure	bar	130
Rail gauge	mm	1,200
Blade clamp opening	mm	30 ÷ 1,000
Maximum gripping height	mm	900
Height	mm	2100
Width (slide body + chain)	mm	2.500
Length	mm	6.300
Weight	kg	9.150
Morse maximum traverse speed	m/s	0,5

**Tabel 8.** Characteristics of the Hydraulic vertical log band saw

Considered the availability of logs in the sawmill during the study, for each species a minimum of 30 sample logs were selected: chestnut 30 logs, olive tree 120 logs, black locust 60 logs. In the specific case of olive logs, the sample logs were obtained from the largest branches derived from the extraordinary pruning activities [45], and from the stem logs excluding the logs which presented holes inside. The logs were measured in length and outside bark diameter and then sorted in four main diameter classes: A (20 - 30 cm), B (30.1 - 40 cm), C (40.1 - 50 cm), D (50.1 - 90 cm). In the case of the conspicuous number of olive logs, they were even divided into nine diameter subclasses: A1 (20 - 25 cm), A2 (25.1 - 30 cm), B1 (30.1 - 35 cm), B2 (35.1 - 40 cm), C1 (40.1 - 45 cm), C2 (45.1 - 50 cm), D1 (50.1 - 60 cm), D2 (60.1 - 70 cm), D3 (70.1 - 90 cm). Similar work has been done for the black locust. The logs were measured in length and outside bark diameter and then sorted in two main diameter classes: A (20 - 30 cm) and B (30.1 - 40 cm). Finally, the chestnut tree, falls into a single diameter class: A (20 - 30 cm). At the end of the sawing phase into boards, the moisture content of each sawn was determined using a digital moisture meter with two electrodes (Schaller, WLW), and wood density was determined in laboratory (in accordance with the ISO 13061-1) [27]. Dia-

meter, length, volume, moisture content, and weight measurements were carried out on the logs selected for this study and the data are summarized in Table 3, classifying olive, black locust, and chestnut logs into different main diameter classes considering the average diameter of each log. In the case of the conspicuous number of olive logs, they were even divided into nine diameter subclasses (Table 9).

Species	Diameter class code	Subclass code	Diameter subclass	Number logs	Length (m)	Volume (m <sup>3</sup> )	Moisture content (%)	Weight (kg)
			(cm)					
Olive	A (20–30 cm)	A1	20–25	14	2.50	0.07 (±0.02)	30	85 (±20)
		A2	25.1–30	16	2.50	0.12 (±0.03)	30	135 (±35)
		B1	30.1–35	12	2.50	0.16 (±0.04)	40	186 (±48)
	B (30.1–40 cm)	B2	35.1–40	19	2.50	0.24 (±0.06)	40	274 (±64)
		C1	4.1–45	16	2.50	0.30 (±0.09)	40	340 (±106)
		C2	45.1–50	13	2.50	0.37 (±0.10)	40	420 (±116)
	D (40.1–50 cm)	D1	50.1–60	19	2.50	0.48 (±0.14)	40	554 (±163)
		D2	60.1–70	5	2.50	0.54 (±0.08)	40	616 (±96)
		D3	70.1–90	6	2.50	0.80 (±0.29)	40	919 (±335)
Black locust	A (20–30 cm)	-	-	30	2.50	0.13 (±0.23)	35	104 (±42)
		B	-	30	2.50	0.23 (±0.04)	40	184 (±59)
		A (30.1–40 cm)	-	30	2.50	0.14 (±0.03)	40	93 (±22)
Chestnut	(20–30 cm)	-	-	30	2.50	0.14 (±0.03)	40	93 (±22)

**Table 9.** Sawn logs characteristics and their distribution in diametral classes (wood logs)

Usually, the sawing yield is calculated as the relationship between the volume of products and the volume of log [46, 47, 48]. Taking into account the possibility of having logs characterized by irregular shapes that do not favour a precise volume measure, and to guarantee a single objective measurement that is not affected by operators [49], in this study the determination of the yield of sawed wood was based on the weight of logs and products, following the relationship (Eq. 19):

$$\text{Sawing yield} = \frac{W_p}{W_l} * 100 \quad (\text{Eq. 19})$$

where: Sawing yield = Percent yield of sawn log (%);  $W_p$  = Weight of products (kg);  $W_l$  = Weight of log (kg).

Operatively, the logs were first weighted using a digital floor weighing scale (Model SPF, Range 6,000 kg x 2 kg). Then each log was individually processed into boards during the primary sawmill process. The sawn boards were grouped by log and each one was weighed using a portable digital floor weighing scale (Model Radwag, Range 60 kg x 0.02 kg). For olive species, the average boards thick was 33 mm (between 15 to 85 mm) (Figure 52) obtaining the greatest number of board (almost 310 boards) 22 mm thick. Black locust average boards thick was 27 mm (between 17 to 32 mm) (Figure 53) and chestnut boards thick was always 27 mm (Figure 54). The length of boards was set up 2.50 m and since the boards were not edged, width oversize was not calculated.



Figure 52. Olive boards



Figure 53. Black locust board



Figure 54. Chestnut boards

The European standard EN 844 (2019) [50] was employed to define the terminology adopted in this study about roundwood and sawn. Four wood defects were monitored on logs: taper, ovality, sweep, and fluting. Table 10 shows the criteria for measuring log defects analyzed. Taper was measured by dividing the difference between the large-end diameter ( $D_1$ ) and the small-end diameter ( $D_2$ ), by the distance separating them ( $L$ ). Tapering ( $T$ ) was expressed in centimeters per linear meter. Sweep was measured identifying the maximum deviation of the centre line of the log from a straight line between the two ends divided by the log length ( $L$ ). Fluting ( $F$ ), defined as the longitudinal depression on the log, was calculated as percentage of the length of the groove deeper ( $d$ ) divided by the log diameter regarded ( $D$ ). Fluting is expressed as a percentage. For the measurement of ovality ( $O$ ), the difference ( $D_e$ ) between the maximum diameter ( $D_1$ ) and the minimum diameter ( $D_2$ ) was preliminarily calculated. Ovality ( $O$ ) is determined by the ratio of the obtained value ( $D_e$ ) to the largest trunk diameter ( $D_1$ ). Ovality is expressed as a percentage.

Defects	Equipment	Parameters	Unit	Formulas
Taper	Measurement tape; Caliper	Length ( $L$ )	cm/m	$T = \frac{(D_1 - D_2)}{L}$
		Thick end diameter ( $D_1$ ) Thin end diameter ( $D_2$ )		
Fluting	Measurement tape; Caliper	Diameter ( $D$ )	%	$F = \frac{d}{D_1} 100$
		Depth ( $d$ )		
Sweep	Measurement tape; Caliper	Length ( $L$ ) arrow deflection ( $a$ )	cm/m	$S = \frac{s}{L}$
Ovality	Caliper	Thick end diameter ( $D_1$ )	%	$D_e = D_1 - D_2$ $O = \frac{D_e}{D_1} 100$
		Thin end diameter ( $D_2$ )		

**Table 10.** Parameters evaluated for sawn yield

## 4. RESULTS ORGANIZATION

In order to guarantee a logical flow of topics linked to the forest wood supply chain, the thesis is developed from six scientific papers coming from my PhD research, split into five main activities.

### First activity

Various harvesting methods can be used depending on the specific conditions of the agroforestry site and the degrees of mechanization. The appropriate levels of mechanization depend on several factors. Although significant innovations in forestry use have become available in recent times (skidders, forwarders, harvesters, etc.) [1], in most forest territories (private and public) in Italy and Calabria (especially in the Plain of Gioia Tauro) harvesting is still carried out using traditional methods, i.e. manual felling by motor (chainsaw) [2] and low mechanised methods. These are mainly based on farmer tractors, sometimes equipped with specific forestry accessories (winches, hydraulic cranes, log grapples, etc.). This level of mechanisation in forest resource extraction is due to the characteristics of forest sites, the characteristics of forest properties and the small size of many forest companies. The level of mechanisation in harvesting is low: the most common harvesting method can be described as at an early stage of mechanization [3].

The first activity, consisting of two scientific articles, refers to the study of the productivity of two specialised forestry machines. The importance of this activity was to evaluate the management of forestry operations, at various sites, through the use of advanced utilisation systems.

### Second activity

In the Plain of Gioia Tauro (province of Reggio Calabria), olive cultivation ex-

tends over more than 20,000 hectares. In this area, there are two olive cultivars ('*Sinopolese*' and '*Ottobratica*') that represent 90% of the total cultivars. Both cultivars are characterised by a remarkable growth, perhaps unique in the world, with trees reaching and often exceeding 25 m in height: a true 'olive forest' [4]. Even though olive trees significantly shape the landscape and characterise the agro-ecosystems of the Plain of Gioia Tauro. Despite the extensive cultivation of olive trees, especially in southern Italy and the Mediterranean basin, olive wood is still little studied. Regarding the anatomy of the olive tree, the literature mainly presents archaeobotanical studies related to climatic factors and adaptation [5, 6, 7]. Besides the little-studied anatomy of olive wood, its physical and mechanical characteristics have also been little studied [8, 9], or the information is difficult to access because the studies are not presented in English [10].

In the second activity, consisting of a scientific article, we compared the wood anatomical properties of the two main cultivars present in the Plain of Gioia Tauro, in order to see if there is an anatomical difference between the two cultivars.

### *Third activity*

Wood is the natural renewable resource and it plays a key role in the social and economic development of rural contexts. Nowadays, wood is considered a technologically complex material [32] and has become even more valued and used for furniture, textiles, biofuels, bioplastics, chemicals and other high-value materials [33]. For this reason, there is currently strong interest in wood, and demand for this material is expected to grow significantly worldwide [35]. Specifically, market demand for orchard wood is growing not only for energy use purposes, but also for fine woodworking, tool handles, mosaics, veneers, flooring and marquetry. However, knowledge about the quality of olive wood is not extensive enough. Despite the abundance of raw materi-

als from pruning, the mechanical properties of olive wood have not been fully researched by the scientific community, often due to the small size of the stem of branches and from which woody specimens for testing are obtained.

In the third activity a scientific paper was produced which considered the valuable role of olive wood in the Plain of Gioia Tauro in order to determine and compare the physical and mechanical properties of the branches and stems of two olive cultivars ('*Sinopolese*' and '*Ottobratica*') to provide information on *Olea europaea* (L.): being olive cultivars indigenous to the area.

#### **Fourth activity**

Wood has been used as a raw material for centuries for interior and exterior applications. Steam treatment of wood is one of the most environmentally friendly wood preservation techniques; it is also an effective method for modifying the physical and mechanical properties of wood. The temperature and duration of the steaming treatment are highly variable. Most steaming methods are applied at temperatures between 120 and 220°C for times ranging from a few minutes to several hours. Currently, four main methods of steaming treatment are used in Europe. In addition, these treatments have in common that the wood is subjected to temperatures close to or above 200°C for several hours in a low-oxygen atmosphere [35]. The various fields of application of steamed wood include exterior cladding, window and door frames, wood panels, garden furniture, sauna furniture, floors and terraces, etc [36].

The fourth activity consists of a scientific article in which all studies have tested the effects of steaming at high temperatures (>120°C). Recent research formed by a scientific article aims to evaluate the influence of low-temperature treatment on the mechanical properties of wood. Therefore, the study tested wood samples at a constant temperature of 80°C at different times

(12, 18, 36 hours).

### **Fifth activity**

In Europe, there is a huge demand for logs for further use. Sawmills play a crucial role in producing sawn timber efficiently to maintain their total market share. For this reason, modern sawmills tend to prioritise the speed and volume of log production rather than the volume and value yield, i.e. the ratio of the total volume of logs to the volume of boards produced. It must be said that most sawmill managers have a reasonably good knowledge of the lengths, diameters and taper of the logs processed in their sawmill and this experience enables them to achieve good processing performance. However, log characteristics vary widely within species, harvest site and even within the tree itself. However, in small and medium-sized sawmills, the processed timber has random lengths and widths and contains scattered random defects of various types [16]. A large number of factors influence the volume of timber obtained from a given log through the sawing process [17]. These factors are sometimes recognised as defects present in all wood species. For this reason, the quality of logs entering the production line is important because it controls the quality and yield of timber that can be obtained [18, 19, 20, 21]. The importance of optimising the sawing yield is justified in order to reduce waste in the sawmill. Therefore, it is necessary to collect technical information on the yield as well as on the generation of wood waste in order to maximise the volume of timber produced. For these reasons, this activity includes a scientific article in which the distribution of defects on logs of different species and diameter classes was analysed. Finally, highlighting the impact of defects on the conversion efficiency (cutting yield) obtained when cutting three different species of wood in a medium-sized sawmill and predicting the cutting yield from defective logs of different diameter classes.

## **4.1. Time Motion Study and productivity evaluation**

### **Article 1**

#### **Performance of wheel cable-grapple skidder EQUUS 175N in conifers stand.**

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## Performance of wheel cable-grapple skidder EQUUS 175N in conifers stand.

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### Keywords

Productivity; forest operations; skidding; time-motion study; mechanization.

### Abstract

The mechanization of timber harvesting depends on several factors such as the type of forest, wood species, management methods, terrain and climatic conditions. In several countries, felling trees and motor-manual timber processing are still very common. For example, in Italy, especially in the South, the most used timber extraction method involves the use of farm tractors equipped with forestry equipment, such as winches. Less widespread, however, is the extraction of timber using tractors with a trailer or bin, cable cranes, forwarders, chutes and animals. The use of forestry skidders is still largely unknown. To meet the world's population's growing need for wood and wood-derived products, forestry mechanization is undergoing a boost, leading several forestry companies to improve and innovate the equipment of their forestry machinery or to adopt more efficient other logging systems.

This modernization has led to the appearance of new forestry machines, such as skidders or forwarders, capable of increasing productivity and safety at work.

This study focused on the potential benefits of introducing a more mechanized and purpose-built extraction system, particularly an Equus 175 N skidder. The objective of the study is to analyse working times and productivity during the skidding operation in Mediterranean forests. The study was conducted in the Aspromonte National Park (Calabria Region – South Italy). Two sites with different orographic conditions were monitored and a thinning operation was conducted at both sites. Numerous cycles were monitored for each site and logs were extracted using the Cut-To-Length (CTL) system. The load was moved with the Equus 175N skidder and for each skidding cycle, the times and number of logs were recorded. The results demonstrated that the productivity is very high compared to traditional extraction methods and the resulting extraction costs are very competitive.

# Performance of wheel cable-grapple skidder EQUUS 175N in conifers stand

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**Abstract.** The mechanization of timber harvesting depends on several factors such as the type of forest, wood species, management methods, terrain and climatic conditions. In several countries, felling trees and motor-manual timber processing are still very common. The most common method for extracting timber in Italy, particularly in the South, is using farm tractors equipped with forestry equipment. The use of forestry skidders is still largely unknown. To meet the world's population's growing need for wood and wood-derived products, forestry mechanization is undergoing a boost, leading several forestry companies to improve and innovate the equipment of their forestry machinery or to adopt more efficient other logging systems. This modernization has led to the appearance of new forestry machines capable of increasing productivity and safety at work. This investigation focused on the potential benefits of introducing a more mechanized and purpose-built extraction system, particularly an Equus 175 N skidder. The objective of the study is to analyse working times and productivity during the skidding operation in Mediterranean forests. The study was conducted in the Aspromonte National Park. Two sites with different orographic conditions were monitored and a thinning operation was conducted at both sites. Numerous cycles were monitored for each site and logs were extracted using the Cut-To-Length system. The load was moved with the Equus 175N skidder and for each skidding cycle, the times and number of logs were recorded. The results showed that the productivity is significantly higher than with traditional extraction techniques, and the extraction costs that follow are quite competitive.

**Keywords:** Productivity; forest operations; skidding; time-motion study; mechanization.

## 1 Introduction

Several regions in South Italy have the largest percentage of forest: Calabria is the region with the largest forest area with 650,620 ha of forest territory. These forests account for a wooded area of 43% [1]. Woodlands play an important part in this region's wood harvesting as well as creating landscape variety. Nowadays, woods and their resources serve as a foundation for social, economic, and environmental stability in rural regions, and wood harvesting has long been considered as one of the most strategies for the future [2]. Despite having a substantial forest resource, the harvesting sector within this region is not particularly mechanized. The most common harvesting method are still in line with an early stage of mechanization. The most common method for extracting timber is using farm tractors equipped with forestry tools such as winches and/or grapples. The use of cable cranes, forwarders, chutes, animals,

and tractors with a trailer or bin for the timber extraction are less common [3]. It's still unclear how forestry skidders are used. The most prevalent equipment used in timber cutting activities is the chainsaw. The qualities of the forest sites, the attributes of the forest properties, and the small scale of many forest operations are to blame for this degree of mechanization in the extraction of forest resources [4]. Cut-to-length is the most commonly used working system; and this system includes felling, delimiting and bucking trees into logs of specified lengths at the stump. To meet the growing global demand for wood and its products, forest mechanization is experiencing a surge, prompting various forestry companies to enhance and innovate the equipment of their forestry machines or adopt other more efficient systems. This modernization has led to the emergence of new forestry machines, such as skidders and forwarders, capable of increasing productivity and workplace safety. Knowledge of the productivity of skidder or forwarder, operating under diversified conditions, is essential for an appropriate selection and use of these machines to ensure satisfactory financial results [5 - 7]. One of the ways to achieve this goal is to describe the relations between the productivity of skidding operations and properties of the terrain where skidding operations are performed [8], characteristics of stands under treatments [9], skidding means employed [10], and skidding distance [11, 12]. The skidder is a large forestry machine used on the front line during forest operations, and it can be used in different types of harvesting operations, such as thinning, clear fell, native forest thinning or salvage operation [13]. A skidder can be fitted with different implements, depending on the harvesting conditions, such as different types of grapples, a winch and a cable, a dozer blade, a front-end slash grab. The history of skidder development begins in 1949 in Orleans, Ontario, with the testing of a Walters four-wheel drive truck as a skidder. This was done to increase productivity in this labor-intensive profession and replace the employment of animals in forest operations. Nowadays, due to high labour costs, enhancing efficiency and cutting expenses is still an essential issue [14]. With regard to skidders, cable models are predominant, although grapple skidders have proved to be considerably more efficient [15, 16]. Several studies have evaluated skidders performance in order to find out the influence of different elements on production and cost, or to compare different methods in different countries and different terrain and stand conditions [17]. The several factors that affect the skidding phase, including stand density, slope, volume, number of logs, and skidding distance, were assessed in these investigations [18]. The success of new harvesting techniques in southern Italy has been assessed in numerous of research [19]. However, no previous study has analyzed the productivity of skidders in Calabrian forests, despite the widespread use of skidders over the past few decades in southern Italy. For this reason, the objective of this study, carried out in Calabria Region, has been to analyse performance of Equus 175N skidder during the forest operation in South Italy.

## **2. Materials and Methods**

### **2.1 Study site**

The tests were carried out in the Aspromonte National Park (RC). The work phases, denoted by the letters A and B, were recorded at two distinct worksites. The worksites are located in the Reggio Calabria province's Santa Cristina d'Aspromonte municipality. Silver fir (*Abies alba* Mill.) constitutes the two worksites, A and B. A cut-to-length system method was used. The extension measured 3.23 and 3.30 hectares for sites A

and B, respectively. The machine was continuously observed during skidding operations, a time and motion study was used to observe the different work phases, and the extraction distances were noted for every cycle. The total number of logs transported was counted and each tree's volume was calculated using Smalian's formula:

$$V = \frac{S_b + S_s}{2} h \quad \text{Eq. (1)}$$

Where:  $S_b$  is the area of the small end of the log,  $S_s$  is the area of the large end of the log and  $h$  is the length. Both sites are located at an altitude of 1190 metres above sea level. The study was conducted at a thinning site. The stand density was 525 and 850 trees per hectare for site A and B, respectively. Site characteristics are described in table 1. Site A has an average slope of 10% while site B 20%.

**Table 1.** Test site characteristics.

Features	Unit	Site A	Site B
Silvicultural system		High forest	High forest
Species		Silver fir	Silver fir
Extension	ha	3.23	3.30
Stand density	trees ha <sup>-1</sup>	525	850
Slope	%	10	20
Basal area	m <sup>2</sup>	42	56
Average DBH	cm	32	29
Average Height per tree	m	29.3	26.1
Average volume per tree	m <sup>3</sup>	2.36	1.72

## 2.2 Machine characteristics

The forestry skidder used was a Equus 175N, equipped with two cable winches, a hydraulic arm and clumbank (Table 2). The skidding operations were mainly carried out with a hydraulic arm and a clumbank because it was possible to get close to the felled timber. If access to the felled timber was not accessible, winches were used. A Suunto clinometer was used to measure the gradient, and a Magellan Triton™ 2000 handheld Global Positioning System (GPS) was used to measure elevation. A measuring tape was used to measure the extraction distances. The information gathered throughout the winching and skidding phases made it possible to determine the machine's hourly production.

**Table 2.** Specifications of the skidder

Parameters	Unit	Value
Manufacture		Equus
Model		175N
Power	kN	129
Weight	tonnes	12.60
Height	mm	2870
Width	mm	2450
Length	mm	7894
Clarence	mm	544
Wheelbase	mm	3208
Clumbank area	m <sup>2</sup>	1.2
Hydraulic arm length	m	8.2

Displacement torque of hydraulic arm	kN	120
Diameter Winches Cable	mm	14
Drums capacity	m	115
Nominal Pulling Force of winch	kN	98

### 2.3 Working system

The Cut-to-Length (C.T.L.) work system was used at both locations, and there were just two employees on the crew. A skidder operator, who used a skidding clumbank to drag the timber and by the hydraulic arm for the transport of suspended timber to the landing area. The cable was released for hooking when the operator drove the skidder from the roadsite to the felling site. The chocker setter secured the loads to the cable, the skidder winched them to the skid tracks, and the skidder removed them to the landing zone.

### 2.4 Productivity

The times of the different work phases were measured separately using the repetition-timing method to determine the total skidding cycle time (productive time or delay time) [20]. The skidding cycle was divided into several elements:

- Travel unloaded (similar for winches, clumbank, and hydraulic arm): begins when the skidder pulls out of the landing area and ends in the stump area to mark the finish of the run.
- Loading: This phase comprises the following sub-phases:
  - Release and hooking (cable winches): begins as soon as the worker grabs the cable and places the choker on the logs, and it ends when the skidder operator starts to winching.
  - Winching (cable winches): starts when the driver pulls on the winch, and it finishes when the tree reaches the back of the skidder.
  - Grabbing (clumbank): starts when the clumbank opens and the arm starts to load, ends when the clumbank closes.
- Travel loaded (similar for cable winches, clumbank, and hydraulic arm): starts when the machine moves to the landing and finishes when it reaches the landing.
- Unhooking (similar for cable winches, clumbank, and hydraulic arm): starts as soon as the machine reaches the landing and finishes when the load is disconnected.

Productivity was calculated excluding delays (PMH) and as scheduled machine hours (SMH). Operational, technical and personal delay types were measured in skidding. This study measured the impact of several independent variables: skidding distance, number of logs, and load volume on the total cycle time, considered as a dependent variable.

### 2.5 Data Analysis

Operations examined in this study included observing 29 skidding cycles (15 in site A and 14 in site B), SPSS software version 20.0 IBM Corp., Amonk, NY, USA) was used for the statistical analysis of the data. Sites were considered separately. Four regression models were developed for each site for skidding operations (productivity net, productivity gross, total cycle time net, total cycle time gross). Regression analy-

sis was used to model skidding by explaining the total cycle time variation as a function of operational variables that were considered independent variables in the model (average volume, skidding distance, and number of trees). An additional variable was inserted to differentiate technical configuration of work sites: A = 0 and B = 1.

### 3. Results

At site A, the volume per cycle was 3.81 m<sup>3</sup>, the average skidding distance was 325 m, and the average number of trees taken every cycle was 12. At Site B, the volume per cycle was 3.32 m<sup>3</sup>, the average skidding distance was 183 m, and there were an average of 9 trees every cycle. 17.28 m<sup>3</sup> PMH<sup>-1</sup> was the average skidding productivity at site A. The skidder at location B produced 15.84 m<sup>3</sup> PMH<sup>-1</sup> on average per hour. The average production, including delays, is 15.92 m<sup>3</sup> SMH<sup>-1</sup> at site A and 14.66 m<sup>3</sup> SMH<sup>-1</sup> at site B. The extraction cycle time (including delays) was 14.05 min at Site B and 14.15 min on average at Site A. Table 3 displays the breakdown of the individual elements.

**Table 3.** Descriptive of the mean value at sites A and B.

	Measurement unit	Site A mean	Site B mean
<b>Travel Unloaded</b>	Minutes	1.54 (± 0.3)	2.13 (± 0.2)
<b>Loading</b>	Minutes	5.19 (± 1.2)	4.22 (± 0.2)
<b>Travel Loaded</b>	Minutes	2.34 (± 0.3)	2.59 (± 0.3)
<b>Unhooking</b>	Minutes	3.22 (± 1.0)	3.30 (± 0.3)
<b>Delay</b>	Minutes	1.15 (± 0.1)	1.05 (± 0.0)

With regard to the distribution of time consumption, the highest percentage was recorded during the loading phase: 42% for site A and 35% for site B. In contrast, the lowest percentage was recorded during the empty travel phase, with 13% (site A) and 16% (site B). The release phase has a similar percentage for both sites: 25% (site A) and 27% (site B), respectively. Then, for the loaded travel phase, 19% and 22% were found for site A and site B, respectively. On site A, the factors significantly affecting productivity (net and gross) are skidding distance, skidded volume, and loading time. On site B, the only factor affecting productivity is skidded volume (table 4). Regarding total cycle time (net and gross), in both sites, the factors affecting it are skidding distance and the number of logs per cycle (table 5).

**Table 4.** Cycle time and productivity equations per Site A

Model	Equation	F	P	R <sup>2</sup> <sub>adjusted</sub>
Productivity net	Eq. (2) $P \text{ (m}^3 \text{ h}^{-1}\text{)} = 18.110 - 0.12 \times \text{SD} + 4.772 \times \text{VC} - 1.812 \times \text{TL}$	60.524	0.000	0.967
Productivity gross	Eq. (3) $P \text{ (m}^3 \text{ h}^{-1}\text{)} = 17.615 + 4.651 \times \text{VC} - 1.822 \times \text{TL}$	38.457	0.000	0.955
Total cycle net	Eq. (4) $\text{TC (min)} = 0.014 \times \text{SD} + 0.554 \times \text{NTC}$	31,553	0.000	0.868
Total cycle gross	Eq. (5) $\text{TC (min)} = 0.021 \times \text{SD} + 0.885 \times \text{NLC}$	29.536	0.000	0.859

SD = Skidding Distance; NLC = Number of logs per Cycle; VC = Volume per Cycle; TL = Time Loading.

**Table 5.** Cycle time and productivity equations per Site B

Model	Equation	F	P	R <sup>2</sup> <sub>adjusted</sub>
Productivity net	Eq. (6) $P \text{ (m}^3 \text{ h}^{-1}\text{)} = 10.797 + 5,105 \times \text{VC}$	200.706	0.000	0.991
Productivity gross	Eq. (7) $P \text{ (m}^3 \text{ h}^{-1}\text{)} = 12.518 + 4.483 \times \text{VC}$	163.182	0.000	0.990
Total cycle net	Eq. (8) $\text{TC (min)} = 0.019 \times \text{SD} + 0.715 \times \text{NTC}$	10.496	0,002	0.687
Total cycle gross	Eq. (9) $\text{TC (min)} = 0.015 \times \text{SD} + 0.446 \times \text{NTC}$	10.536	0.002	0.688

SD = Skidding Distance; NLC = Number of Logs per Cycle; VC = Volume per Cycle.

#### 4. Discussion

There are not many studies conducted on the Equus 175N skidder. Only two studies have been conducted, mainly in beech forests in Slovakia [21, 22]. Therefore, it would be appropriate to expand the knowledge of this machine in other environments, especially in the coniferous stands of southern Italy. In detail, Orlovsky studied Equus skidder performance recently. The slope of the two sites is respectively 10% and 20%, in contrast to the studies conducted by Orlovsky (55% and 40%). The skidding distance, 325 m (site A) and 183 m (site B), is shorter than the sites analyzed by Orlovsky (541 m and 530 m). The average unloaded travel speed is 7.36 km h<sup>-1</sup> (site A) and 4.95 km h<sup>-1</sup> (site B), while the average loaded travel speed is 7.22 km h<sup>-1</sup> (site A) and 3.49 km h<sup>-1</sup> (site B). These speeds are higher compared to those recorded by Orlovsky. The average empty travel speed was 4.20 km h<sup>-1</sup> and 4.19 km h<sup>-1</sup>, while the average slippage speed was 3.23 km h<sup>-1</sup> and 3.22 km h<sup>-1</sup>. Regarding time consumption, the highest percentage of time was recorded during the loading phase: 42% for site A and 35% for site B. This is in line with Orlovsky, who found a percentage of 33%. The lowest percentage was recorded during the empty travel phase, with 13% (site A) and 16% (site B), while Orlovsky found a percentage of 11%. During the loaded travel phase, 19% and 22% were recorded for site A and site B respectively, similar to what Orlovsky found (15%). The uncoupling phase shows a similar percentage for both sites: 25% (site A) and 27% (site B), respectively. These values differ from Orlovsky, who found 42%. The longer unloading time is due to the fact that in Orlovsky's study, the skidder arranged the stack neatly. The average number of trees extracted per cycle was 12 and 9 for site A and site B, respectively. The average skidded volume recorded is 3.81 m<sup>3</sup> and 3.32 m<sup>3</sup>. These values are very different from those found by Orlovsky. In both studies, an average number of trees extracted per cycle was 6, with an average skidded volume of 10.96 m<sup>3</sup> and 11.27 m<sup>3</sup>, respectively. The productivity recorded is 17.28 m<sup>3</sup> PMH<sup>-1</sup> and 15.92 m<sup>3</sup> SMH<sup>-1</sup> in site A, while in site B it is 15.84 m<sup>3</sup> PMH<sup>-1</sup> and 14.66 m<sup>3</sup> SMH<sup>-1</sup>. Compared to the data found by Orlovsky in 2020: 7.58 m<sup>3</sup> PMH<sup>-1</sup> and 5.85 m<sup>3</sup> SMH<sup>-1</sup>. The higher productivity we found is due to a lower slope of the sites, higher speed, and shorter skidding distance. According to Nikooy (2013), the volume of each cycle is reduced when the number of logs per load falls, which has a major impact on skidding productivity [23]. Furthermore, another factor that significantly influences productivity is the skidding distance.

#### 5. Conclusion

A study of skidding work and time was performed using an Equus 175N at two coniferous forest sites in southern Italy. Skidder efficiency rises as volume increases and

average extraction distances decrease, and it is highly associated with both load volume and average extraction distance. This unique articulated machine has attracted attention, especially from the forestry industry. The extraction of wood has always been difficult, particularly in hilly areas like southern Italy where the slope limits processing options. Given the high prevalence of forest cover in Southern Italy, the production levels measured in this study are higher than the average output of a normal traditional skidding phase. Therefore, the skidder is also a highly productive machine in Mediterranean forests. At present, basic instrumentation for recording data (such as a measuring tape and chronometer) is widespread. This technology can be improved with the introduction of more sophisticated instrumentation. One of the technologies that could be used are cab-mounted cameras for recording the various operations, as well as the installation of locators for tracking the machine. such technology could broaden the practical implications of the analyses. In addition, having a good planning for harvesting and forwarding trails, in particular planning an optimal road network to reduce the extraction distance and, consequently, limit the time consumption related to the extraction operations, could certainly bring boosting productivity, reducing the impact on terrain, and enhancing operational safety.

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## **4.1. Time Motion Study and productivity evaluation**

### **Article 2**

#### **Productivity and cost of a mid-sized harvester in South Italy: a first case study.**

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## **Productivity and cost of a mid-sized harvester in South Italy: a first case study**

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### **Keywords**

Performance; forest operation; time-motion study; mechanization; processing.

### **Abstract**

In the last decades, the levels of mechanization in Italy have increased, with the introduction of highly specialized machinery, including harvester, forwarder and skidder. In particular, harvester represents a complex machine capable of guaranteeing maximum productivity, optimal performance and safety of operators during wood harvesting. Several studies have been conducted worldwide to determine the characteristics of productivity, economical aspects, and terrain impact of this machine; however, in Italy the studies conducted on performance and cost analysis on harvester are very limited and this lack of information of comparative analyses respect traditional harvesting method has aimed this research. In all Italy, actually there are two mechanization levels – early and medium – in terms of productivity during harvesting operations but the prevailing approach typically involves the use of chainsaws for tree felling, with farm tractors equipped with winches for skidding operations. The introduction and the use of these harvesters is useful for improving: the productivity and performance in forestry operations, the safety of workers, and to achieving greater profitability in the forestry sector. For these reasons, harvesters are widely used in forestry contexts with high levels of mechanization and in recent years, there has been an increase of specialized forestry machines working in Italy. In this contest, the present research aims to develop technical and economical knowledge regarding the use of harvester tested in South Italy to determine the productivity and cost analysis using in harvesting operation. The harvester was tested in Serre Massif (VV) forest and during felling and processing operations, the machine was constantly monitored. A time–motion study was conducted to evaluate the harvester performance. The operational and financial efficiency (time consumption, productivity and cost) obtained in this study showed the high efficiency and level of integration of harvester in Mediterranean forests in order to achieve economic performances during forest operations. The results may be of great practical help in improving logging planning, reducing extraction costs in most timber harvesting operations and consequently for wood supply chain cost competitiveness in small-scale Mediterranean forests.

## Productivity and performance of a mid-sized harvester in South Italy: a first case study

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**Abstract.** In the last decades, the levels of mechanization in Italy have increased, with the introduction of highly specialized machinery, including harvester, forwarder and skidder. In particular, harvester represents a complex machine capable of guaranteeing maximum productivity, optimal performance and safety of operators during wood harvesting. Several studies have been conducted worldwide to determine the characteristics of productivity, economical aspects, and terrain impact of this machine; however, in Italy the studies conducted on the performance of harvester are very limited and this lack of information of comparative analyses with respect to traditional harvesting method has aimed this research. In all Italy, nowadays there are two levels of mechanization – early and medium – in terms of productivity during harvesting operations although the prevailing approach typically involves the use of chainsaws for tree felling, with farm tractors equipped with winches for skidding operations. The introduction and the use of these harvesters is useful for improving: the productivity and performance in forestry operations, the safety of workers, and to achieving greater profitability in the forestry sector. For these reasons, harvesters are widely used in forestry contexts with high levels of mechanization and in recent years, there has been an increase of specialized forestry machines working in Italy. In this contest, the present research aims to develop technical knowledge regarding the use of harvester tested in South Italy to determine the productivity using in harvesting operation. The harvester was tested in Serre Massif (VV) forest and during felling and processing operations, the machine was constantly monitored. A time–motion study was conducted to evaluate the harvester performance. The operational efficiency (time consumption and productivity) obtained in this study showed the high efficiency and level of integration of harvester in Mediterranean forests in order to achieve economic performances during forest operations. The results may be of great practical help in improving logging planning, reducing extraction costs in most timber harvesting operations and consequently for wood supply chain cost competitiveness in small-scale Mediterranean forests.

**Keywords:** Forest operation; time-motion study; mechanization; processing.

## 1 Introduction

Forestry operations are typically associated with a complex combination of natural and material risks that may impact the health and safety of forest workers [1]. Felling, cross-cutting, bunching and skidding operations are the most common operations that result in fatal forestry accidents. The types of collection methods depend both on the natural and production conditions and on the technology used [2,3]. Motor-manual felling is one of the most dangerous operations in the forest and has decreased significantly with the introduction of fully mechanized timber harvesting. In Europe, concerning felling and processing, the chainsaw is still the most common machinery [4,5]. Regarding harvesting operations, cable yarding is the most used extraction method in the northern Alps, because this system is adaptable to all types of terrain as an alternative to harvesters and forwarders [6,7]. In contrast, in the rest of the country, the extraction is based on farm tractors fitted with winches or forwarding boxes [8,9]. Skidders and forwarders have started to be widespread only in recent decades [10,11]. Forest harvesting plays an important role in supplying the economy with a renewable raw material-wood [12]. There are several strategies and options exploitable for timber harvesting. The most technologically advanced is consisting of a harvester and forwarder [13,14]. The performance of harvesting work is determined by various components, which are based on environmental and working conditions, teamwork, operating methods and techniques, machine properties and planning factors [15].

The use of harvesters for felling trees and the production of wood assortments has especially increased throughout Europe in the last 20 years [16]. Typically, the combined use of the harvester-forwarder is applied for harvesting operations in forests, to deliver the wood in the form of logs at the landing, which subsequently will be utilized in the wood processing industry. An important constituent of this system is the harvester, a machine employed in cut-to-length logging operations for felling, delimiting and bucking trees into final assortments; these operational phases are assisted by the highest degree of automation obtainable on the market of forest machines [13,14]. In contrast to chainsaws, which pioneered the mechanized felling of trees and the production of wood assortments, harvesters entail a substantial initial investment, coupled with significantly higher maintenance costs. Conversely, the efficiency of harvesters is challenging to equate with that of chainsaws. Moreover, the ergonomic features of the harvester ensure minimal negative effects on the operator.

This study focused on potential benefits of introducing a more mechanized, harvesting system specifically a harvester John Deere 1270D. The objectives were to calculate the performance of harvester under South Italy conditions, and to develop a model of time consumption and productivity ( $\text{m}^3 \text{h}^{-1}$ ) for wood harvesting.

## 2 Materials and methods

### 2.1 Study site

This research has collected data in Serre Massif (VV) forest, in Calabria region (Southern Italy) (Table 1). During harvesting operations, the machine was constantly monitored, the various work phases were divided using a time-motion study, and the

data of wood logs were recorded and marked with paint on both sides of tree. The forest is mainly composed of silver fir (*Abies alba* Mill.) and it is located at an elevation of 1070 m above sea level (Figure 1). The time motion study was performed in January 2024. The collected data was then organized in tables using Microsoft Excel.



**Figure 1.** Silver fir forest

**Table 1.** Test site characteristics

<i>Features of study area</i>	<i>Unit</i>	
Silvicultural system	-	High forest
Logging operation	-	Shelterwood cutting
Surface of the area	ha	15
Stand density	trees ha <sup>-1</sup>	550
Average DBH	cm	23.9
Average height per tree	m	20.6
Average volume per tree	m <sup>3</sup>	0.68
Average slope	° (%)	15.6 (28)

## 2.2 Description machine and Time motion Study

The characteristics of the harvester monitored are shown in Table 2 (Figure 2). The harvester was equipped with the H480 harvesting head. The harvesting system was subdividing in the sequence of searching and cutting, processing, moving and delays time [7].

A time and motion study was carried out to estimate the time consumption and productivity of the harvester. The times of the different work phases were measured separately using the repetition-timing method to determine the total harvesting cycle time (productive time and delay time) [17]. Each work phase was individually timed by a video camera to account for the scheduled machine hours (SMH). Following the field observations, the total work time day was divided into productive time (PMH) and delays time. The delays time included mechanical interruption (general review of the machine; fueling, cutting system adjustments); operational interruption (cleaning the machine with dry leaves and branches, receiving instructions from the manager) and personal interruption (satisfying basic operator needs).

**Table 2.** Harvester specifications

<i>Parameters</i>	<i>Unit</i>	<i>Value</i>
Make	-	John Deere
Model	-	1270D
Power	kW (hp)	160 (215)
Weight	tonnes	17.5
Height	m	3.70
Width	m	2.86
Length	m	7.58
<i>Crane specifications</i>		
Crane model	-	210H
Gross lifting moment	kNm	178
Sweling torque	kNm	43.6
Maximum boom reach	m	10
Tilt angle	°	-13 / +25
Sweling angle	°	220
<i>Harvester head specifications</i>		
Model	-	H480
Felling diameter	mm	650
Delimiting knife	n°	4 moving, 2 fixed
Delimiting diameter	mm	480
Max feeding speed	m sec <sup>-1</sup>	5
Weight	kg	1200



**Figure 2.** The John Deere 1270D harvester

Particularly, regarding the harvesting cycle, the productive time was subdivided into three elements [7]:

- **Searching and cutting:** it starts when the harvester crane and processor head move in search for a tree to cut, until the separation of the tree from the stump.
- **Processing:** including delimiting, cross-cutting, and stacking of logs at the harvesting site. It starts when the feeding rolls move and ends when the last piece of the tree is dropped from the processing head.
- **Moving:** It starts when the harvester moves from one location to the next and ends when the moving is halted.

The volume ( $V$ , m<sup>3</sup>) was calculated based on Smalian's formula ( $I$ ):

$$V = \frac{(S_0 + S_n)}{2} h \quad (1)$$

Note:  $V$  volume ( $m^3$ );  $S_0$  area of log butt ( $m^2$ );  $S_n$  area of log top ( $m^2$ );  $h$  height of tree ( $m$ ).

The equations for the calculation of the time consumption (2) and productivity (PMH) (3) are [14]:

$$T_{tot} = t_1 + t_2 + t_3 \quad (2)$$

Note:  $T_{tot}$  the productivity time separated from delay time;  $t_1$  time consumption for searching and cutting phase;  $t_2$  time consumption for processing phase;  $t_3$  time consumption for moving phase.

$$P_{PMH} = \frac{3600 V}{T_{tot}} \quad (3)$$

Note:  $P_{PMH}$  = the harvesting productivity based on a productive machine hour approach.

### 2.3 Data analysis

SPSS software version 29.0 (IBM Corp., Amonk, NY, USA) was used for statistical analysis of the data. The null hypothesis was that productivity remained similar across the various sizes of trees. Initially, a 95% significance level was chosen to test the null hypothesis. The prediction of productivity of the machine was performed by statistical modelling, which involved the use of regression analysis. The variables used as predictors were the time consumption for searching and cutting ( $t_1$ ), the time consumption for stem processing ( $t_2$ ), the time consumption for moving ( $t_3$ ), the height of tree ( $h$ ), and the diameter at breast height ( $DBH$ ).

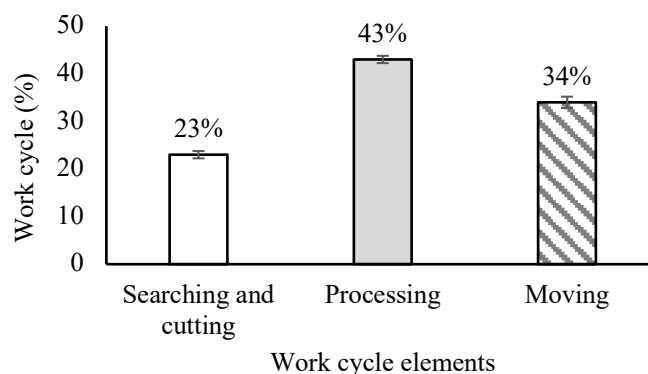
## 3 Results and discussion

The Table 3 shows the descriptive statistics of work elements times for harvesting system, as well as the percentage of time spent on each work phase time (productive time excluded the delay time-PMH), in association to total time. During the time motion study, it was observed that the effective operating time resulted of 72% of the total time and the interruption time (delays) of 28%. For about 66% of cycle time, the harvester carried out the main work elements, specifically cutting and processing of trees (Figure 3). The processing phase was difficult because the trees had heavy branches, the trunks were cut into logs and finally the logs were stacked for later collection. The inexperience of the harvester operator produced an average time of 66.4 sec per work cycle. This data is due also to the silvicultural treatment because the harvester didn't move easily within the forest.

**Table 3.** Descriptive statistics of work phases time

Work phase	Measurement						
	unit	N	Min.	Mean	Max.	SD	%
Searching and cutting	Seconds	50	8.0	15.0	20.0	3.84	23
Processing	Seconds	50	22.0	28.6	34.0	3.81	43

<b>Moving</b>	Seconds	50	15.0	22.8	35.0	5.96	34
<b>Total time</b>	Seconds	50	<b>45.0</b>	<b>66.4</b>	<b>89.0</b>	<b>9.66</b>	<b>100</b>



**Figure 3.** Division of work cycle elements

**Table 4.** Productivity prediction models

Model	Equation	F	P
Productivity (PMH)	Eq. (4) $PMH (m^3h^{-1}) = -0.019 \times P (s) + 0.041 \times H (m) + 2.487 \times DBH (cm)$	7.694	0.00
Productivity (SMH)	Eq. (5) $SMH (m^3h^{-1}) = -0.019 \times P (s) + 0.039 \times H (m) + 2.508 \times DBH (cm)$	6.828	0.00

Note:  $P$  = processing time;  $H$  = height tree;  $DBH$  = diameter at breast height.

The productivity of the harvester was described by the regression equations (Table 4). The harvester productivity (without delays), described by Eq. (4), can increase by reducing the time of the processing phase or by cutting trees with a greater volume. Similarly, this happens for harvester productivity, including delays. (Eq. 5). Thus, the productivity models show that the most significant parameters influencing harvesting productivity under study in the context of shelterwood cutting in the silver fir forest of South Italy are the processing phase and the volume felled per turn.

The mean productivity, considering an average work cycle time of 66.4 sec, an average volume per cycle of 0.68 m<sup>3</sup> and a mean of 54 trees felled per hour, was 36.8 m<sup>3</sup>·PMH<sup>-1</sup> and 26.5 m<sup>3</sup>·SMH<sup>-1</sup>.

The productivity rates obtained by this research are close to those reported by Cabral et al. [18], in Brazil, that have obtained an average productivity for a harvester in a *Pinus taeda* L. stand, under two thinning methods, between 39 and 42 m<sup>3</sup>·PMH<sup>-1</sup>, with a mean of working cycle between 24.7 and 26.7 sec. In Argentina in a *Pinus taeda* L. stand, for the John Deere 1070D harvester, Mac Donagh et al. [19] registered a performance between 12 and 14 m<sup>3</sup>·PMH<sup>-1</sup>, in the first thinning, while for the second thinning, the productivity determined was 30.8 m<sup>3</sup>·PMH<sup>-1</sup>. While in a thinning of Scots pine, Pohjala et al. [7] have determined an average productivity between 23 to

28 m<sup>3</sup>·PMH<sup>-1</sup>. In North Poland, Rosińska et al. [20] have tested 8 different models of harvester, in a silver birch stand. The performance obtained was on a mean of 22 m<sup>3</sup>·PMH<sup>-1</sup> and varied between 5 to 44 m<sup>3</sup>·PMH<sup>-1</sup>, with an average diameter of harvested trees of 23 cm with an average height of 22 m. In Brazil, Stadler et al. [21] have determined the performance of a Ponsse Scorpion King harvester between 36 and 74 m<sup>3</sup>·PMH<sup>-1</sup>, in a stand of *Pinus taeda* L., with a working cycle time of 42.5 sec. In south Italy, the introduction and the use of harvesters is useful for improving the productivity and performance in forestry operations, the safety of workers, and to achieving greater profitability in the forestry sector.

## 4 Conclusion

A time-motion study was conducted to evaluate the performance of a John Deere 1270D harvester in a silver fir high forest in south Italy. The productivity obtained in this research was close to the numerous studies carried out on other harvester machines for cutting and processing the trees for thinning, and considering the forestry cover in south Italy, the data presented are very significant. The observations of this research confirmed that this type of machine can be a good investment, allowing good performance. Furthermore, optimized planning of collection and forwarding routes, based on terrain characteristics and trafficability maps is an essential factor in improving productivity, minimizing the impact on the terrain and enhancing safety.

In conclusion, the investigated harvester is a highly productive machine that needs professional planning and management to improve productivity. Additional studies could evaluate the influence of other factors to compare performance in several forests.

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## 4.2. Olive wood anatomy

### Article 3

#### Qualitative Wood Anatomy Study of Ottobratica and Sinopolese Cultivars of *Olea europaea* L.

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## Article

# Qualitative Wood Anatomy Study of Ottobratica and Sinopolese Cultivars of *Olea europaea* L.

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**Abstract:** Olive wood is used in a niche economic context but is attracting growing interest. In this study, the wood anatomy of *Olea europaea* L. belonging to two cultivars cultivated in the Plain of Gioia Tauro in Calabria (RC) is qualitatively described. Wood samples were obtained along the diameter of wood slices to investigate any anatomical differences between the inner and outer zones of the stem. The microscopic slides were investigated using an optical microscope. The anatomical characteristics observed were compared with existing literature data. The two cultivars show parenchyma rays arranged not only in one to two rows (typical of this species), but also in three rows. Furthermore, in both cultivars, the presence of starch deposits in procumbent parenchyma cells was observed. The Ottobratica cultivar seems to have more starch than the Sinopolese one, but given the high variability of olive wood, further quantitative analysis is needed to determine whether these differences are statistically valid and due to the different cultivars. This work can contribute to a better understanding of the *Olea europaea* L. species and to a better technical valorisation of its wood.

**Keywords:** *Olea europaea* L.; olive wood; wood vessels; starch; sapwood; heartwood



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## 1. Introduction

The cultivation of olive trees for oil production is widespread in the Calabria Region (Southern Italy), where it occupies 70% of the territory. Olive trees in these areas grow vigorously, especially local varieties, and have a significant impact on the economy of the entire region [1,2], with numerous companies involved in both cultivation and product processing. The olive tree (*Olea europaea* L.) is an evergreen tree belonging to the genus “Olea”, family Oleaceae, and is primarily cultivated for food purposes. It is usually a tree of modest size, and rather long-lived. In certain situations, the tree’s growth habits can become shrub-like; for example, when it is found in Mediterranean scrub formations. The species thrives in generally temperate and warm climates, on limestone and rocky soil [3]. To date, the greatest economic relevance of the olive trees comes from the harvesting of olives for oil production, used for food, medicinal, and cosmetic purposes.

In the “Plain of Gioia Tauro”, located in the province of Reggio Calabria (Italy), the cultivation of olive trees spans over 20,000 hectares. Different to other olive-growing areas, two olive cultivars (Sinopolese and Ottobratica) are characterised by a remarkable growth, perhaps unique in the world, with trees reaching and often exceeding 25 m in height: a real “forest of olive trees” [4]. The stem is robust, and its circumference can vary considerably depending on the age and variety of the olive trees. Wood is not the primary product of olive tree cultivation, but it finds a good place in the market. The wood is mainly used in handicraft products, for cabinetmaking, parquet flooring, carving, and turning. Olive wood is hard, with differentiated sapwood and heartwood; the sapwood is lighter than the

heartwood, which has a reddish colour. In general, the colour of olive wood ranges from brown to yellowish-pink, with evident and varied tonal variations, alternating with streaks, which make it particularly appreciated aesthetically. Olive wood is a diffuse-porous wood with numerous vessels, isolated or in groups of 2–5, arranged in radial lines. The rays are uni- to biseriate and the parenchyma is paratracheal. The growth ring boundaries are often indistinct [5,6]. Concerning olive wood anatomy, the literature presents mainly archaeobotanical study related to climate factors and adaptation [3,5,7]. In popular culture, olive wood is typically considered “oily” due to the high presence of oils and extracts [8], and this makes it burn even when still green [9]. Due to these characteristics, and the low cost of pruning residues, olive wood has been the object of several studies concerning its valorisation in biorefinery [10–13]. Given the widespread presence of plantations throughout the Italian peninsula, the use of olive-tree-pruning residues has also been evaluated for biomass energy production [3,14]. In the Gioia Tauro Plain area, olive trees significantly shape the landscape and characterise the region’s agroecosystems. Despite the extensive cultivation of olive trees, especially in southern Italy and in the Mediterranean basin, to the author’s knowledge, olive wood is still little studied.

In addition to the little-studied anatomy of olive wood, its physical and mechanical characteristics have also been under-investigated [15,16], or the information is difficult to access because the studies are not presented in English [17]. A recent study by Mammoliti et al. [18] compared the physical and mechanical properties of branch and stem wood from the two olive cultivars, “Sinopolese” and “Ottobratica”. The authors found some differences between the two cultivars, primarily in mechanical properties such as modulus of elasticity, modulus of rupture, compression strength, footprint, and screw withdrawal resistance. Overall, the “Sinopolese” cultivar exhibited higher values in these properties compared to the “Ottobratica” cultivar. A solid understanding of the theoretical background of the wood structure and its mechanical and physical properties is essential, as these factors are closely linked to wood’s performance and potential applications [19]. For example, fibre length and fibre-wall thickness are also determinants to predict the density and mechanical properties [20]. On the other hand, vessel size is related to the treatment ability, where a large vessel indicates easy treatment compared to small vessels [21,22]. Additionally, the availability and cost of wood as a raw material are key determinants of its overall suitability for use [23,24].

For these reasons, studies on the anatomical property need to be performed on the little-known species to increase scientific knowledge and to explore the suitability of this wood for different uses. In fact, investigations about cell structure and fibre morphology are very important to fill the gap in knowledge and to determine the different areas of application [19]. Based on the differences highlighted by Mammoliti et al. [18] between “Sinopolese” and “Ottobratica” olive wood cultivars, this study aims to present a comparison of wood anatomical properties of the two olive cultivars cultivated in the Gioia Tauro Plain (Calabria Region), in order (i) to see if there is an anatomical difference between the two cultivars and, if there is, (ii) to understand if this plays a role in the differences highlighted in the study by Mammoliti et al. [18].

## 2. Materials and Methods

### 2.1. Study Area

For this study, two olive trees (*Olea europea* L.) of two different cultivars (Sinopolese and Ottobratica) were selected from plants grown in a family-run orchard located in the municipality of Oppido Mamertina, a hamlet of Reggio Calabria (38°16′48″ N, 15°58′55″ E). This orchard is located at 347 m a.s.l. and extends over an area of 0.8 ha, of which 47% is sloped and 53% is flat. The plantation has an 8 × 10 m planting space.

In this plantation, some pathologies such as Peacock eye, leprosy, and olive fly have been found, but Xylella is not present. During the year, the temperature generally ranges from 7 °C to 28 °C and is rarely below 4 °C or above 30 °C. There have been no fires in this orchard, and every two years ammonium sulphate-based fertilisers are applied at 8–10 kg

per tree. Normally, plants are pruned every three/four years, but in 2023, notably extensive pruning and felling work was carried out which gave rise to large-sized wood residues. The two cultivars studied showed different dendrometry measurements (Figure 1):

- Sinopolese cultivar: age: 70 y; 17.0 m height; DBH (diameter breast height): 54 cm.
- Ottobratica cultivar: age: 70 y; 19.0 m height; DBH: 61 cm.



**Figure 1.** Olive trees (*Olea europaea* L.) examined in this study.

## 2.2. Olive Wood Samples

A wood slice was taken from both trees of the two cultivars (Figure 2). The wood slice obtained from the Sinopolese cultivar had a circumference of 135 cm; the maximum diameter was 46 cm, the minimum was 37 cm (the average diameter is 40.5 cm), and the thickness was 4.5 cm. The slice had an irregular shape with an obvious eccentricity with

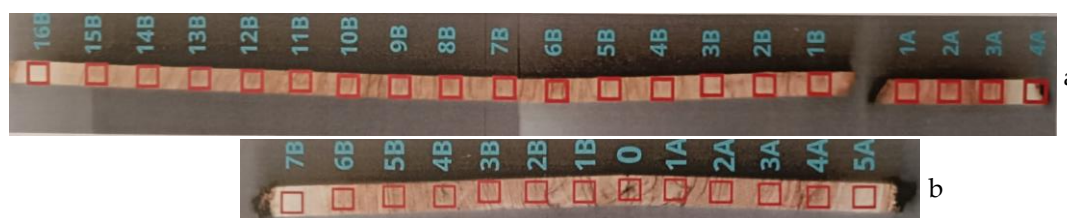
the pith displaced laterally. The growth rings were irregular, like the shape of the wood slice, and tension wood was present on the larger portion of the piece. There were some radial cracks caused by wood shrinkage and two ring shakes (Figure 2A). Both slices were obtained from each stem at 5.50 m height during extraordinary reform pruning activity. The presence of tension wood in the olive tree is very common because the tree has a very irregular trunk (Figure 1). In the case of the extraordinary pruning activity, the choice of two specimens with similar morphological characteristics was not possible because the selection of the trees to be felled is made upstream and follows a specific authorised felling plan. The “Ottobratica” cultivar wood slice shape was more regular than Sinopolese and it had a circumference of 94 cm, a maximum diameter of 32.5 cm, and a minimum diameter of 26 cm (the average diameter was 29.5 cm). The thickness was 4 cm. This slice had a more regular shape, and the pith was located in the middle of the piece. There were ring shakes and some radial cracks (Figure 2B).



**Figure 2.** Olive wood (*Olea europaea* L.) slices: (A) Sinopolese cultivar wood and (B) Ottobratica cultivar wood.

### 2.3. Microscopic Analysis

The slides for the anatomical analysis were obtained from wood samples taken from two strips approximately 1 cm wide cut from the Sinopolese and Ottobratica slices (Figure 3). The samples were cut from the pith of the wood outwards, at a distance of 2 cm from each other, along the diameter shown in pencil in Figure 2. Then, the samples were cut to obtain a cube of 1 cm each side. For the cutting, an automatic fretsaw with a thin blade was used for a precise cut. Due to the different sizes of the two wooden slices, 20 and 13 cubes were obtained from Sinopolese and Ottobratica, respectively.



**Figure 3.** Olive wood cultivar samples: Sinopolese (a) and Ottobratica (b). Small red squares indicate where the samples were cut with the respective codes (sample 0 is the pith).

After boiling to soften the wood [25], the cubes were cut with a Leica RM2245 semi-automatic rotary microtome (Leica Biosystems, Milan, Italy) to obtain 12–14  $\mu\text{m}$  thick slices.

For the anatomical analysis, three sections were cut for each sample: radial, tangential, and cross-section. In the end, 20 slides for Sinopolese and 13 slides for Ottobratica cultivars were prepared and 99 sections were analysed to identify the olive wood's anatomical characteristics. From the analysis of the slides, some characteristics not described in the literature were identified. Therefore, to further the analysis, additional analyses were conducted; 4 cubes were selected for each cultivar, with 2 of sapwood and 2 of heartwood. Radial and tangential sections were cut to obtain 16 sections, 8 sections for each cultivar. To prepare permanent slides, a photo-hardening gel, Eukit UV R Low Viscosity gel (ORSAtec, Viterbo, Italy), was used and the slides were put in an oven with a UV lamp for 15–20 min.

#### 2.4. Staining and Mounting of Slides

The characterisation of the not-yet-classified substances observed in the parenchyma cells was possible thanks to a specific stain applied to the newly prepared slides. Assuming the presence of starch, it was decided to use Lugol's solution based on iodine (Marco Viti, 7% iodide solution and 5% potassium iodide solution in deionised water and ethanol). If starch is present, the colouring solution reacts and the starch takes on a shade tending towards purple or dark blue. Some drops of staining solution were applied to each of the 16 sections, and after 1 min the sections were washed, first with deionised water and then with a 50% solution of deionised water and ethyl alcohol. Finally, the sections were dehydrated with ethyl alcohol [15]. At the end of this procedure, the permanent slide was mounted. The slides made for the anatomical characteristics study were observed with a Leica DMC 4500 microscope (Leica Biosystems, Milano, Italy), and pictures of the main anatomical characteristics were taken. Stained slides were digitalised with the Axioscan 7 scanner (Zeiss, Milano, Italy), and images were obtained with a specific application, ZEN ZEISS 3.9 (Zeiss, Milano, Italy).

### 3. Results and Discussion

#### 3.1. Microscopic Features

The anatomical characteristics were coded using the “IAWA list of microscopic features for hardwood identification” [26] and are reported in Table 1.

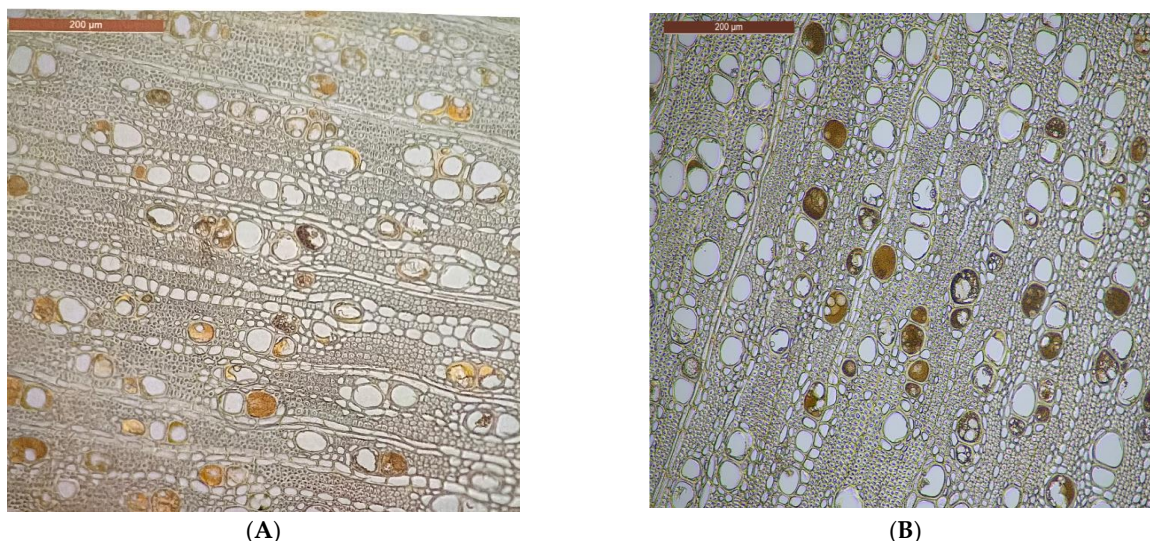
**Table 1.** IAWA features of Ottobratica and Sinopolese cultivars of olive wood (*Olea europaea* L.) (source: [26]).

IAWA Feature	General Description
5. Wood diffuse-porous	Wood in which the vessels have more or less the same diameter throughout the growth ring
8. Vessels in dendritic patterns	Vessels arranged in a branching pattern, forming distinct tracts, separated by areas devoid of vessels
10. Vessels in radial multiples of 4 or more common	Radial files of 4 or more adjacent vessels of common occurrence
11. Vessel clusters common	Groups of 3 or more vessels having both radial and tangential contacts, and of common occurrence
13. Simple perforation plates	A perforation plate with a single circular or elliptical opening
22. Inter-vessel pits alternate	Pits between vessel elements (inter-vessel pits) arranged in diagonal rows (alternate)
36. Helical thickenings in vessel elements present	Ridges on the inner face of the vessel element wall in a roughly helical pattern
38. Helical thickenings only in vessel element tails	Ridges on the inner face of the vessel element wall in a roughly helical pattern only in vessel element tails

Table 1. Cont.

IAWA Feature	General Description
56. Tyloses common	Outgrowths from an adjacent ray or axial parenchyma cell through a pit in a vessel wall, partially or completely blocking the vessel lumen, and of common occurrence (except in outer sapwood)
58. Gums and other deposits in heartwood vessels	Includes a wide variety of chemical compounds, which are variously coloured (white, yellow, red, brown, black)
66. Non-septate fibres present	Fibres without septa
70. Fibres very thick-walled	Fibre lumina almost completely closed
78. Axial parenchyma scanty paratracheal	Axial parenchyma associated with the vessels or vascular tracheids, and types of paratracheal parenchyma are scanty paratracheal, vasicentric, aliform, confluent, and unilateral paratracheal
79. Axial parenchyma vasicentric	Parenchyma cells forming a complete circular to oval sheath around a solitary vessel or vessel multiple
97. Ray width 1 to 3 cells	Ray width in cell numbers as per feature descriptor
107. Body ray cells procumbent with mostly 2–4 rows of upright and/or square marginal cells	Procumbent ray cell = a ray parenchyma cell with its longest dimension radial as seen in radial section; square ray cell = a ray parenchyma cell approximately square as seen in radial section
109. Rays with procumbent, square, and upright cells mixed throughout the ray	Procumbent ray cell (see above description); square ray cell (see above description); upright ray cell = a ray parenchyma cell with its longest dimension axial as seen in radial section

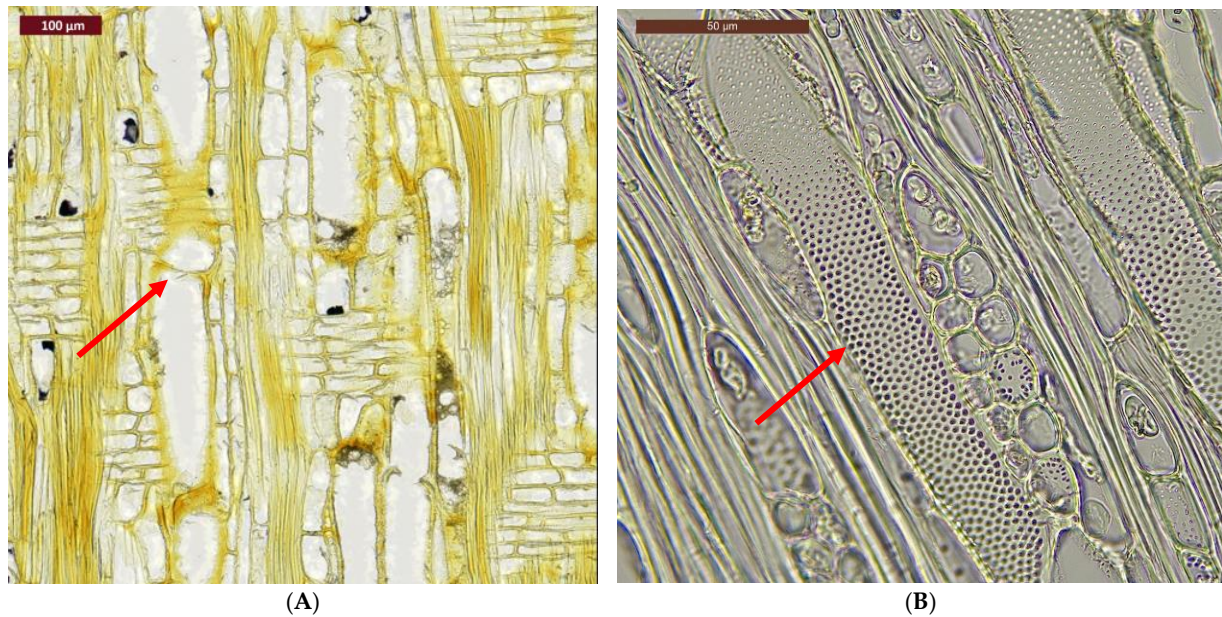
In the analysed microscopic images of both Sinopolese and Ottobratica, the growth rings were indistinct or absent [27]. Furthermore, the microscopic images confirm that there were no variations in the diameter of the vessels between earlywood and latewood, which is a typical anatomical trait of diffuse-porous wood (IAWA feature 5 [26]) such as olive wood (Figure 4). In this type of wood, growth rings should be marked by a radial dimension of fibres; in the latewood, the fibres could be radially flattened with or without thick walls, while in the earlywood, the lumen is larger [6].



**Figure 4.** Olive heartwood cross-section: (A) Sinopolese cultivar: sample 1B; (B) Ottobratica cultivar: sample 2A. Diffuse-porous wood (IAWA feature 5). Vessels in radial/diagonal pattern (IAWA feature 7). Vessels partly solitary, partly in radial multiples of 2–4, or in very small clusters (IAWA features 10, 11). Parenchyma scanty paratracheal/vasicentric (IAWA features 78,79). Presence of common tylosis (IAWA features 56), gums, and other deposits (IAWA feature 58) [26].

The vessels are distributed in a radial pattern, and they are partly solitary and partly in radial multiples of 2–4, or in very small clusters (IAWA features 8, 10, 11 [26]; Figure 4). In cross-section, it is also possible to note axial scanty paratracheal vasicentric parenchyma (IAWA feature 78, 79 [26]), and parenchyma cells are associated with the vessels forming complete circular or oval sheath around solitary or multiple vessels (Figure 4).

In the radial section, the vessels show simple perforation plates (IAWA feature 13 [26]), while in the tangential section, it is possible to see the alternate inter-vessel pits arranged in diagonal rows (IAWA feature 22 [26]; Figure 5). Together with vessel perforations, there are few and dense helical thickenings only in the vessel element tails (features 36 and 38 [26], Figure 6).

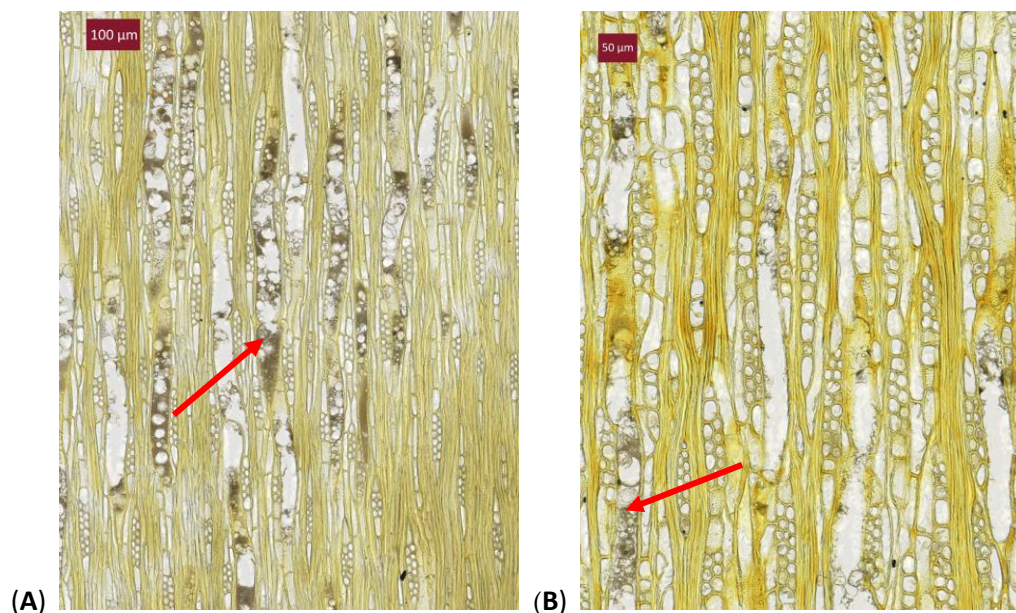


**Figure 5.** Sinopolese olive wood cultivar: (A) 15B sample, sapwood. Radial section, red arrow: simple perforations plate (IAWA feature 13); (B) 12B sample, heartwood. Tangential section, red arrow: alternate inter-vessel pits (IAWA feature 22) [26].



**Figure 6.** Ottobratica olive wood cultivar: 5A sample, sapwood, tangential section. Red circles: helical thickenings only in vessel element tails (IAWA features 36 and 38 [26]).

Olive heartwood is also characterised by the presence of common tylosis (IAWA features 56 [26]) and other coloured deposits (IAWA feature 58 [26]). Tylosis and deposits completely filled some vessels, as is evident in the cross-sections and tangential sections (Figures 4 and 7). It is probable that the deposits in the heartwood are oily substances, and they take on a colour tending towards orange.



**Figure 7.** Olive wood. (A) Ottobratica cultivar, 4B sample. (B) Sinopolese cultivar, 1B sample. Heartwood, tangential section. Presence of common tylosis (red arrows, IAWA features 56), gums and other deposits (IAWA feature 58) [26].

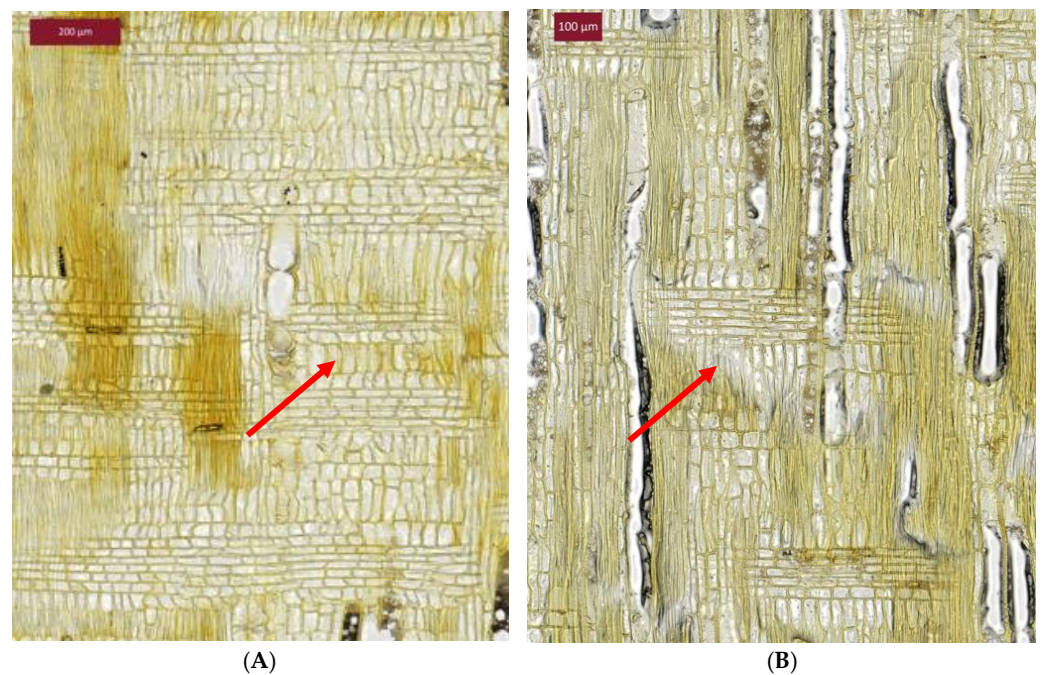
The analysed olive wood fibres are very thick-walled (IAWA feature 70 [26]), and there are no septate fibres (IAWA feature 66 [26]). Tension wood fibres have a thick wall with an unligified gelatinous (G) layer [26], but since this character is present in both cultivars, and the G layer was not observed, the authors cannot conclude that the presence of very thick-walled fibres means that tension wood fibres are detected. This anatomical characteristic certainly influences the high density of the wood of these two cultivars, with  $0.89 \text{ g/cm}^3$  (moisture content: 7.2%) found for the Sinopolese and  $0.92 \text{ g/cm}^3$  (moisture content 5.9%) for the Ottobratica.

Rays are multiseriate with 1 to 3 cells (IAWA feature 97 [26]), and in radial sections, is possible to distinguish procumbent cells with mostly 2 to 4 rows of square marginal cells (IAWA feature 107 [26]). Some rays had procumbent, square, and upright cells mixed throughout the rays (IAWA feature 109 [26]) (Figures 8 and 9).

In the sapwood of each cultivar, the presence of granular material similar to starch was observed.



**Figure 8.** Sinopolese olive wood cultivar: (A) 1B sample, heartwood; (B) 15B sample, sapwood. Tangential section. Yellow boxes: ray width with one to three cells (IAWA feature 97 [26]).



**Figure 9.** Olive wood, heartwood radial sections. (A) Sinopolese, 1B sample; (B) Ottobratica, 4B sample. Red arrow: body ray cells procumbent with mostly two to four upright rows (IAWA feature 107). Red arrow: rays with procumbent, square, and upright cells mixed throughout the ray (IAWA feature 109) [26].

### 3.2. Starch

In order to verify the nature of the granules observed in the sapwood of the two cultivars, Lugol's solution, specific for starch, was used to colour the deposits present in the parenchymal cells of the sapwood of both cultivars, confirming the initial hypothesis that they were composed of starch. Microscopic observations of both Sinopolese and Ottobratica stained slides show evident differences between sapwood and heartwood, visible in both the radial and tangential sections. The presence of starch deposits is notice-

able in the sapwood which, following staining, took on a very dark blue–purple colour (Figures 10 and 11). The deposits are localised in the ray parenchyma cells. In particular, they seem to be present in greater quantities in the procumbent cells of the *Ottobratica* cultivar. In the sapwood area of the *Sinopolese* cultivar, a smaller quantity of starch is noted compared to the *Ottobratica* cultivar, and it is mainly deposited in the straight parenchyma cells (Figure 11). As expected, in both *Ottobratica* and *Sinopolese* cultivars, no starch was found in the heartwood (Figure 9A,B). The presence of starch deposits in ray cells in the sapwood, demonstrated by histochemical staining, has not been found in other literature descriptions on olive wood anatomy.



**Figure 10.** Starch (black spots) in *Ottobratica* olive wood cultivar, 5A sample, sapwood. (A) Radial section, (B) tangential section.



**Figure 11.** Starch (black spots) in *Sinopolese* olive wood cultivar, 15B sample, sapwood (radial section).

The two cultivars show the same anatomical characteristics; any differences could be evident with measurements and statistical analysis, which were not performed in this

study, as it was only qualitative. In the Sinopolese cultivar, despite what was expected, no tension fibres were detected in anatomical slides. Tension cell wood anatomy varies depending on hardwood species, and different anatomical characteristics could be seen [28]. In this qualitative anatomical study, the magnifications used did not allow, for example, for a verification of the presence or absence of the cell wall's gelatinous layer, typical of tension cell wall wood. Furthermore, the presence of tension wood, unlike the compression wood of gymnosperms, is not easily visible macroscopically, especially in wood with an inhomogeneous appearance, such as olive wood. In fact, in the Ottobratica slice, the only indication of the presence of tension wood is given by the eccentric pith.

It is possible to note that in each cultivar, the main difference is between sapwood and heartwood due to the coloured deposits, tylosis, and granular elements (starch). The first two are mostly present in heartwood, while the last is present in sapwood. The anatomical characteristics observed in both cultivars are consistent with those described in the literature [6,29]. In particular, cluster structures inside the heartwood vessels similar to tyloses were observed, which Baas [6] attributes to the presence of chemical deposits for which further investigations would have been necessary in the future. Indeed, the particular configuration of parenchyma-vessel pits, small and bordered, would not be suitable for tylose formation [6]. The literature is very poor regarding studies on olive wood anatomical features. It is therefore difficult to compare the detailed results found in this study with other, similar research. Indeed, when the results of the produced research were analysed, only general information about the anatomy of olive wood was found because the purpose of the studies was different. For example, Santos-Rufo et al. [30] undertook a quantitative analysis of the olive wood anatomy of two cultivars to investigate whether anatomical differences could be related to the differential resistance response to the fungus *Verticillium dahlia*. Terral and colleagues [5,7] studied the anatomical differences between wild and cultivated olive wood in relation to climatic changes [5], using wood and charcoals. The results of qualitative analysis of both wood types were in accordance with the findings of this study, with the only difference concerning the rays. The authors describe them as uni-biseriate, without specifying the type of cells they were composed of, while in this study, one to three cell rays were observed and the type of ray cells described. Differences could be genetic or could be a response to growth conditions [31]. A recent study by Alhaithloul et al. [31] analysed the genotyping and morphological differences between eight olive cultivars growing in Saudi Arabia, but the authors took into account stem anatomy and not cell anatomy.

Concerning the presence of starch in the parenchyma cells of both cultivars, it is well known by plant physiologists [32], but, to the authors' knowledge, its presence has not been highlighted by wood technologists. The presence of starch may play a role in supporting the growth and ripening of fruits [33], and could play a crucial part in the olive trees' survival strategy, helping the tree to recover in the semiarid Mediterranean climate [34]. From a technological point of view, radial cracks can occur in parenchymal rays [35]. How might the presence of starch affect the occurrence of radial fractures? From an initial and only qualitative observation, it emerged that the Ottobratica cultivar seems to have greater starch deposits than the Sinopolese, but a more in-depth analysis is necessary through a quantitative analysis conducted on more specimens to demonstrate this hypothesis.

A recent study [18] compared the physical and mechanical properties of stem wood of "Sinopolese" and "Ottobratica" trees, and in general, the "Sinopolese" cultivar showed higher values. The authors justified these results by the differences obtained in wood density between the cultivars or by some intrinsic characteristics [19]. For these reasons, knowledge about olive wood's anatomical characteristics is desirable to favour its use in multiple sectors.

#### 4. Conclusions

This study reported a detailed and in-depth qualitative anatomical characterisation of two cultivars (Ottobratica and Sinopolese) of olive wood. Based on the results obtained, the

wood of both cultivars exhibited a complex anatomical structure, often irregular, but in line with what is described in the scientific literature on olive wood. Only a small difference was found, and it concerns the parenchymal rays. In this study, some of them were composed of one to three rows, visible in tangential sections, instead of one to two as reported in other studies. In both cultivars, the presence of starch in parenchyma cells has been found, and from the comparison of the two cultivars, the Ottobratica cultivar seems to have a greater amount of granular and other deposits. Furthermore, tylose-like structures seem to be more numerous in the Ottobratica than the Sinopolese cultivar. Despite what has been observed, these differences could be attributed to the variability of wood and therefore may not be sufficient to distinguish the two cultivars. The findings of this qualitative analysis of the anatomy of olive wood need to be verified through a quantitative analysis and, if it is not sufficient, it must be further investigated with a genetic study. Because of the lack of studies addressing the anatomical investigation of centuries-old olive trees, this study, and those that will follow it, will contribute to the understanding of *Olea europaea* L. and the valorisation and use of its wood.

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**Data Availability Statement:** The data are available upon request to Michela Zanetti (michela.zanetti@unipd.it).

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### **4.3. Study of the mechanical properties of wood**

#### **Article 4**

#### **Mechanical properties of branch and stem wood for two Mediterranean cultivars of olive tree**

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NOTE

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# Mechanical properties of branch and stem wood for two Mediterranean cultivars of olive tree

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## Abstract

There is currently a strong interest in wood and the demand for this material is expected to grow significantly worldwide. Consequently, market demand for wood from fruit orchards is growing as an additional source of supply. For these reasons, several studies were conducted to evaluate the properties of wood derived by orchard pruning or dismantling. Despite the abundance of raw materials from pruning, the mechanical properties of olive wood have not been studied completely by the scientific community, so the woody material obtained is usually considered waste or firewood. In fact, there is still a lack of knowledge about olive wood characteristics and considering the valuable role of olive species in the Mediterranean area, the current study aimed to determine and compare the physical and mechanical properties of branches and stem wood of two olive tree cultivars, "Sinopolese" and "Ottobratica", to provide information on this wood species. These two olive cultivars are commonly cultivated in the Calabria region (Southern Italy) for the extraction of oil from drupes, but large masses of wood are derived from their pruning. For the choice of parts, the stem was considered to become a branch when, above each branch intersection, it changed in diameter and direction of growth. The branches with a diameter lower than 20 cm were excluded. The tests conducted for this purpose were: Roughness profile; Impact wave; Vibrational analysis; Static modulus of elasticity; Bending strength; Abrasion resistance; Static hardness; Footprints; Compression strength; Screw withdrawal resistance parallel to grain; Screw withdrawal resistance perpendicular to grain. A MANOVA analysis was conducted between the Cultivar-Tree part and the physical and mechanical properties. The results showed some differences between the two cultivars principally related to mechanical properties such as moduli of elasticity and rupture, footprint, compression strength, and screw withdrawal resistances, where in general, the "Sinopolese" cultivar showed higher values than the "Ottobratica". Between the tree parts (stem and branches) within the same cultivars, branches demonstrated higher results in the majority of the tests, but highlighting statistical differences only in terms of static modulus of elasticity, bending strength, static hardness and screw withdrawal resistances depending on the cultivar. This result suggests that the branch wood, with its characteristics, could be valorized in the commercial utilization representing a valid opportunity for the local rural economy, even considering the conspicuous amount of wood obtained from olive pruning activity. Expanding knowledge about olive wood in terms of physical and mechanical characteristics could increase its use in multiple sectors and ensure a more aware use of the application of the wood resources by supporting the decision on its best end use.

**Keywords** MOE, Footprints, Static hardness, Screw withdrawal, Acoustic tests

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## Introduction

Wood is the renewable natural material par excellence and as a renewable resource plays a fundamental role in social and economic development in rural contexts. Nowadays, wood is considered a technologically complex material [1] and has become even more highly valued and used for fine and intelligent furniture, textiles, biofuels, bioplastics, high-value chemicals and materials [2]. For this reason, there is currently a strong interest in wood, and the demand for this material is expected to grow significantly worldwide [3]. Consequently, market demand for wood from fruit orchard is growing as an additional source of supply, not only for energy use but for fine woodwork, tool handles, mosaics, veneers, flooring, and marquetry, too. McKendry [4] quantified large quantities of fruit tree wood obtained from the pruning operations carried out in Mediterranean fruit plantations as a source of energy and also for other industrial uses [5]. In addition, Kiaei et al. [6] suggested that fruit trees can help solve the problem of the lack of raw materials for the wood industry. In fact, only in the EU, a total of 11,301,345 hectares are dedicated to the cultivation of fruit trees and regarding the distribution of the fruit growing area in the EU member countries, Spain stands out with 43% of the total surface, followed by Italy with 21%, Greece with 10%, France with 8%, and Portugal with 6% [7]. Therefore, evaluating the total area of fruit tree cultivation in Europe, the enormous quantity of wood produced during annual pruning or from replacement or rejuvenation interventions is evident. For these reasons, in the last decades, several studies were conducted to evaluate the properties of wood derived by orchard pruning or dismantling. For example, Berti et al. [8] studied *Citrus × sinensis* (L.) wood to determine specific properties in South Italy while Sahin et al. [9] determined some wood properties of *Citrus × limon* (L.) wood grown in Mezitli-Mersin, Turkey. The results found that the wood from *Citrus* trees is fine-grained, and is characterized by a high density, average dimensional stability, and high surface hardness. Therefore, the results of the tests suggest the possibility of using citrus wood as a renewable raw material for the production of high quality products. Danihelová et al. [10] tested physical-acoustical characteristics of different fruit wood species (i.e., *Cerasus avium* (L. Moench), *Prunus cerasus* (L.), *Pyrus communis* (L.), *Juglans regia* (L), etc.), typically used in making musical instruments. In Greece, Passialis and Grigoriou [11] studied the technical properties of branch wood obtained by pruning of *Malus domestica*, *Pyrus communis* (L.), and *Prunus armeniaca* (L.) fruit-tree plantations.

Regarding olive species, in Spain, Requejo et al. [12] evaluated *Olea europaea* (L.) tree pruning for paper production evaluating as an important and very abundant

wood resource in the Mediterranean areas of southwest Europe. Cara et al. [13] tested the production of fuel ethanol from steam-explosion pretreated olive tree pruning. Rencoret et al. [14] studied the structural characteristics of lignin in pruning residues of olive trees while Alshammari et al. [15] characterized natural fibres obtained from olive wood. Serin and Penezoglu [16] studied the morphological and physical properties of olive trees in Aydin and Kahramanmaraş regions in Turkey. Lo Giudice et al. [17] investigated the olive tree's chemical composition considering the potential uses of raw material derived from annual olive tree pruning. In fact, in Italy as in the world, olive tree is the most popular member of the *Oleaceae* family, and it is among the most extensively cultivated fruit crops [18]. Only in the EU, olive orchards cover the largest area, with more than 5 million hectares [7] and for this reason, olive wood represents a largely unexplored raw material considering the estimation of the large quantity of wood residues derived from periodical pruning of mature olive trees. Nevertheless, the knowledge about the wood quality of olive trees is not wide enough. Despite the abundance of raw materials from pruning, the mechanical properties of olive wood have not been studied completely by the scientific community, often due to the small size of the branches stem and from which to obtain the wood specimens for testing activities. In southern Italy (Calabria Region) there is the "Plain of Gioia Tauro", located in the province of Reggio Calabria, where, differently to other olive growing areas, two olive cultivars ("Sinopolese" and "Ottobratica") are characterized by a remarkable growth, perhaps unique in the world, with trees reaching and often exceeding 25 m in height: a real "forest of olive trees". From a structural anatomical point of view, olive trees have:

- The stem which constitutes the skeletal structure of the tree. It is the main part that rises from the ground and supports all the other parts (branches and crown). The stem is robust and woody, and its circumference can vary considerably depending on the age and variety of the olive tree.
- The branches, inserted on the stem, which vary in number, height and diameter depending on how the tree is agronomically managed, forming the tree crown. The main branches connect directly to the stem, while the secondary and tertiary branches develop from these. The shoots deriving from the year's vegetation grow on the tertiary branches [19–22].

This cultivation of olive trees is extended over more than 20,000 hectares and contributes considerably to the characterization of the physiognomy of the region's

agroecosystems. In fact, in this area, the typical olive plantation is recognizable by medium to large trees that periodically are subject to pruning operations to permit to allow them to restore a vegetative and productive balance. In particular, every 15–20 years, an extraordinary reform pruning activity is conducted, and each olive tree is reduced not only in branches but also in the stem (partially or completely). Thanks to these operations, medium and large portions of olive wood are processed in several sawmills located in this area aimed to produce flooring, paneling, veneer, and indoor furniture. Therefore, branch wood and stem wood are used for sawmilling operations without distinction based on their different wood properties. To the best of the authors' knowledge, studies on the characteristics of olive wood are not numerous and, even more, they are completely non-existent regarding the comparison between branch and stem wood of the same species. In general, branch wood has been poorly investigated compared to stem wood, and currently, there is a lack of data which could support any potential added value of the branches for any production path [23]. Regarding the physical aspects, some studies reported that the mechanical characteristics of branches' wood are usually lowered compared to those of the stems of *Fagus sylvatica* (L.), *Acer* (spp.), *Pinus sylvestris* (L.). The mechanical tests showed that the MOE<sub>c</sub> and compression strength of maple branch wood were slightly lower than those of stem wood, maple MOR was slightly higher for branch wood, and beech compression strength was similar for branch and stem wood [24]; several authors [6, 25] investigated on wood density and anatomical characteristics of branches in different species (*Terminalia superba* (Engl. & Diels) and *Pterygota macrocarpa* (K. Schum), while Cieszewski et al. [26] evaluated wood quality assessment of stem wood from the tree branch sample of different *Betula* (L.) species. Okai et al. [27] assessed the mechanical strengths properties of branch and stem wood of some tropical hardwood species (*Aningeria robusta* (A. Chev.) Aubrév. & Pellegr, and *Terminalia ivorensis* (A. Chev.). Their results showed that the overall compression and shear strengths parallel to the grain of the branch wood of *A. robusta* and *T. ivorensis* were higher than that of their corresponding stem wood. Dong et al. [28] focused their research on the physical and morphological properties of branch and stem wood of *Crataegus azarolus* (L.): the results of hawthorn wood in southwest Iran, indicated that different altitude levels had a significant effect on physical and fiber biometry of both stem and branch woods. There are significant statistical differences of the studied parameters between stem and branch woods. The highest average values of the physical properties of wood were found in the trunk, as regards the length of the fibers of the woody tissue, and

in the branches as regards the diameter of the fibers and the thickness of the cell wall.

Considering the precious role of olive wood in Southern Italy, as in the Mediterranean areas, the current study aimed to determine and compare the physical and mechanical properties of branches and stem wood of two olive tree cultivars ("Sinopolese" and "Ottobratica") to provide information on *Olea europaea* (L.), since they are autochthonous olive cultivars from Southwestern Calabria, commonly cultivated in the Calabria Region for oil extraction and whose pruning activity involves the removal of large masses of wood. In detail, specific objectives have been: (i) to determine the physical properties; (ii) to test the mechanical properties of small clear wood specimens; and (iii) to compare the results between the two cultivars and between branches and stem wood in the same cultivars.

## Materials and methods

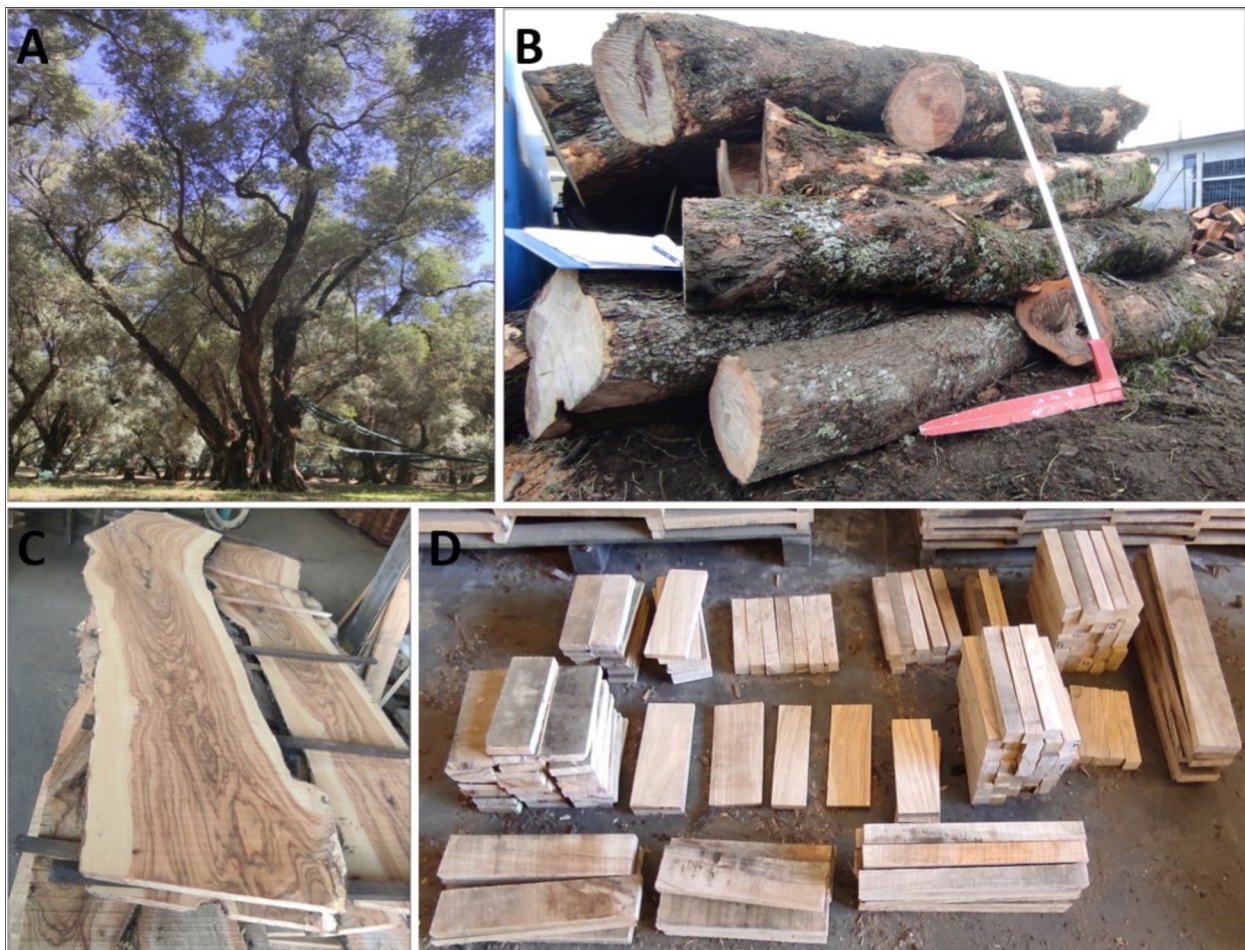
### Materials and samplings

The woody material was gathered from a local orchard of olive trees after fruit harvesting operations in the municipality of Oppido Mamertina, in the "Plain of Gioia Tauro" (South Italy). Regarding temperatures and the climatic regime of the area, in Oppido Mamertina, the summers are short, with clear sky, and characterized by hot, muggy and dry weather, the winters, instead, are long, cold, wet, windy, and partly cloudy sky. During the year, the temperature generally ranges from 7 to 28 °C and is rarely below 4 °C or above 30 °C. Basic information about the trees and the growing site are reported in Table 1.

The two cultivars were distinguished by botanical morphological characteristics (size and shape of the drupes, difference in leaf colour, size and shape of the leaves, ripening times of the fruit). Both cultivars presented majestic habits, with large branches reaching more than 50 cm in diameter, From the pruning of the olive tree, for each cultivar ("Sinopolese" and "Ottobratica"), 3 trees were selected to obtain logs from branches and stems for the experimental specimens' production (Fig. 1A). For the choice of parts, the stem was considered to become branch when, above each branch intersection, it changed in diameter and direction of growth. During pruning operation branches were cut from the stem, excluding the branches with a diameter lower than 20 cm. The logs carefully selected and separated by cultivar and tree parts, were sawn into disks with transversal cuts and boards through tangential cuts (Fig. 1C). Among them, the defect-free were selected to prepare the specimens (Fig. 1D) for the experimental material. The specimens were obtained from portions of wood far from the areas where tension wood was present. The sawn wood collected in the field was transported to the laboratory

**Table 1** Wood tested collection site, timber harvested, and wood characteristics information

Cultivar	Sinopolese		Ottobratica	
Latitude (°)	38°16'48"		38°16'52"	
Longitude (°)	15°59'06"		15°58'58"	
Altitude (m a.s.l.)	340		340	
Age	70		70	
Mean height (m)	15.5		17.6	
Tree part	Stem	Branches	Stem	Branches
Mean log diameter (cm)	67 (±13)	38 (±9)	70 (±15)	41 (±9)
Max. log diameter (cm)	92	52	93	55
Min. log diameter (cm)	42	24	47	27
Wood density (kg/m <sup>3</sup> , 12% MC)	1023 (±39)	1070 (±60)	994 (±44)	1020 (±49)
Max. wood density (kg/m <sup>3</sup> , 12% MC)	981	985	922	936
Min. wood density (kg/m <sup>3</sup> , 12% MC)	1102	1176	1075	1113

**Fig. 1** "Sinopolese" olive trees (A), branches logs (B), branches sawn wood (C) and branches wood specimens for laboratory tests (D)

of Wood Technology and Forest Mechanization of the AGRARIA Department of Reggio Calabria for the production of specimens, conditioning and, subsequently, for carrying out the tests. A total of 400 specimens were obtained for each cultivar, of which 20 specimens were prepared from branches and 20 specimens from stems for carrying out the eleven kinds of tests described in the next section. The dimension of each specimen shown in Table 2. Once the specimens were prepared, they were conditioned in a climatic chamber (*Memmert GmbH, Germany*) at  $20 \pm 2$  °C and 65% ( $\pm 5\%$ ) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12%. Air-dried density of each sample was determined in accordance with the ISO standard 13061-2 [29], and moisture content was determined following the oven dry method [30, 31]. In the laboratory, ten prismatic samples with dimensions of 30R×30T×40L mm were obtained from each of the trunks and branches of each cultivar to be used to measure the density at 12% (EMC), in accordance with the ISO 13061-2 standard [29].

## Methods

The laboratory tests consisted of non-destructive tests and destructive tests for the characterization of the “Sinopolese” and “Ottobratica” cultivars olive wood. Non-destructive techniques were applied for the estimation of dynamic modulus of elasticity (MOEd), and for the surface roughness profile measurements. Destructive tests concerned static modulus of elasticity, bending strength, abrasion resistance, static hardness, footprints, compression strength, and screw withdrawal resistance.

## Surface roughness

For the surface roughness profile measurements, the specimens were sanded sequentially with 100 and 200

grit sandpaper on the tangential surfaces, according to the UNI EN ISO 21920-3 [32]. The roughness profile was recorded with a Mitutoyo SurfTest SJ-301 (Mitutoyo Corporation, Japan) surface roughness measuring system. Measurements were made with the profile method using a skid type diamond stylus with 5  $\mu\text{m}$  tip radius and a 90-tip angle. The measuring speed was 0.5 mm/min with a cut-off of 8 mm on six plots of 10×10 mm distributed randomly on the surface of each specimen for a total of 240 measurements for each olive tree cultivar (120 measurements per each part of tree of each cultivar analysed). The  $R_a$  parameter ( $\mu\text{m}$ ), the arithmetical mean of the absolute values of the profile deviations from the mean line of the roughness profile, was recorded and used to evaluate the surface roughness of the specimens. The average value of  $R_a$  was obtained by averaging six records on different positions on each sample.

## Dynamic modulus of elasticity

The estimation of dynamic modulus of elasticity (MOEd) was determined with two different non-destructive tools, both based on acoustic wood property: the Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary) used to conduct the impact wave test (MOEd\_MST), and the Portable Lumber Grader (Fakopp Enterprise, Agfalva, Hungary) for the vibrational analysis (MOEd\_PLG).

Both tests were replicated several times deriving the average data from at least three recordings for each sample measurement with each tool.

For the impact wave test, the specimens were tested by Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary) device to measure the Time of Flight of an acoustic wave generated mechanically by tapping the start sensor with a hammer which travels through the wood tissue

**Table 2** Tests conducted, and specimens used in the study

Properties	Code	Standard	Specimens' dimension (R×T×L) (mm)
Surface roughness	$R_a$	UNI EN ISO 21920-3 [31]	100×100×170
Dynamic modulus of elasticity (impact wave)	MOEd_MST	–	30×20×300
Dynamic modulus of elasticity (vibrational analysis)	MOEd_PLG	–	30×50×300
Static modulus of elasticity	MOEs	EN 408 [32]	20×20×500
Bending strength	MOR	EN 408 [32]	20×20×500
Abrasion resistance	WL	UNI EN 15185 [33]	120×120×20
Static hardness	SH	ISO 13061-12 [36]	60×60×100
Footprints	F	UNI 4712 [37]	60×60×100
Compression strength	C	ISO 13061-17 [38]	20×20×30
Screw withdrawal resistance parallel to grain	SW_Par	EN 1382 [39]	60×60×100
Screw withdrawal resistance perpendicular to grain	SW_Per	EN 1382 [39]	60×60×200

reaching the opposite sensor. The dynamic modulus of elasticity was calculated using Eq. (1):

$$\text{MOEd\_MST} = \rho \cdot v^2 \quad (1)$$

where MOEd\_MST = dynamic modulus of elasticity ( $10^{-6}$  N/mm<sup>2</sup>);  $\rho$  = density (kg/m<sup>3</sup>);  $v$  = wave transmission velocity (m/s<sup>1</sup>).

Portable Lumber Grader (Fakopp Enterprise, Agfalva, Hungary) tool was used to determine the natural longitudinal vibration frequency of the tested lumber. Specimen vibration has been generated with a hammer on the transversal face of the specimen and the signal is captured by a microphone placed at the opposite transversal face. The acoustic signal is analysed by a computer with the Fourier vibration analyser (Fakopp Enterprise, Agfalva, Hungary) to detect the natural frequency of each specimen. This equipment includes a balance to determine the weight of the specimen [31]. Using the specimen's mass ( $m$ , in kg), width ( $w$ , in m), length ( $l$ , in mm), height ( $h$ , in mm), and the longitudinal vibration  $\times$  frequency ( $f$ , in Hz), MOEd\_PLG (in  $10^{-6}$  N/mm<sup>2</sup>) is calculated with the following Eq. (2):

$$\text{MOEd\_PLG} = \frac{m}{lwh} (2fl)^2 \quad (2)$$

#### Static modulus of elasticity and bending strength tests

Static modulus of elasticity (MOEs) and bending strength or modulus of rupture (MOR) were determined perpendicular to grain. For these tests, the specimens were tested adopting the four-point bending test, performed using a 300 kN universal testing machine (METRO COM, Italy—10402030 model), applying to the load a speed of 3.6 mm/s. The distance between the two points of the load was 120 mm, while that between the supports is 380 mm, in accordance with European Standard 408:2010 + A1 [33] (Table 2). Data were recorded by the dedicated METRO COM software.

#### Abrasion resistance tests

The abrasion resistance measurements were conducted according to the UNI EN 15185 [34]. The specimens were abraded using a Taber Rotary Abraser 5135 (Taber Industries, USA) applying loads of 1000 g, with 500 cycles at the controlled speed of 60 revolutions per minute (RPM). S-42 sandpaper strips (Taber Industries, USA) were used as the abrasive. Sandpaper was changed after each 250 test cycles to guarantee the same abrasive performance. The specimens were weighed before the abrasion test, after 250 cycles, and after 500 cycles [35]. The weight loss in percentage was determined by Eq. (3):

$$\text{WL} = \frac{(W_1 - W_E)}{W_1} \cdot 100 \quad (3)$$

where WL = weight loss (%);  $W_1$  = weight of test specimen before abrasion (g);  $W_E$  = weight of test specimen after abrasion (g).

#### Static hardness tests

The static hardness tests were carried out tangentially on wood specimens and the measurements were performed by applying a force necessary to embed an 11.28-mm-diameter steel ball indenter halfway into a sample according to the ISO standard 13061-12 [36] using the same universal testing machine used for bending strength tests. The surface hardness test measures the resistance of a sample of wood to denting and wear and it was calculated using the following Eq. (4):

$$\text{SH} = K \cdot F \quad (4)$$

where SH = surface hardness at moisture content  $W$  (kN);  $K$  = coefficient equal to 4/3 in the case of penetration of the plunger to a depth of 2.82 mm;  $F$  = maximum load during the penetration of the plunger into the test sample to the specified depth (kN).

#### Footprints tests

For the footprints measurements the specimens were tested on 5 points of replication for each sample according to UNI 4712 [37] and using the same universal testing machine used for bending strength tests. The peak load of 1575 N was applied with a cylindrical indenter (10 mm diameter) steel force punch during the test, corresponding to a unit stress of 2000 N/mm<sup>2</sup>. For each sample, the deformation was measured at 5 points at three different moments: during the test at the peak load, immediately after the test, and two days after the test (48 h after), by using a digital comparator (1  $\mu$  sensitivity). The results were compared to the measurements of the original size of specimens obtained in the same five points.

#### Compression strength tests

About the compression strength tests parallel to the grain, the olive wood specimens were tested by the same METRO COM universal testing machine applying a load at a constant loading-head movement settled (in this case at a speed of 5 mm/s) to reach the maximum load within 300 s from the start of the test, in accordance with the standard in force for compression tests (ISO 13061-17 [36, 38]). The compressive strength was measured using (Eq. 5)

$$C = \frac{F_{\max}}{A} \quad (5)$$

where  $C$  = compressive strength parallel to the grain ( $N/mm^2$ );  $F_{max}$  = maximum load (N);  $A$  = cross-sectional area ( $mm^2$ ).

**Screw withdrawal resistance**

Screw withdrawal resistance was measured parallel to the wood grain (SW\_par), and perpendicular to them (SW\_per), and was assessed according to EN 1382 [39]. The tests were conducted with the commercial Screw Withdrawal Force Meter device (Fakopp Enterprise Bt., Sopron, Hungary). The screw applied without predrilling was a standard SPAX (PZD) type head screw 45 mm long, with size of diameter 3 mm.

The withdrawal parameter of the screw SW ( $N/mm^2$ ) was calculated according to the following expression (Eq. 6),

$$SW = \frac{F_{max}}{d \bullet l_p} \tag{6}$$

where  $F_{max}$  is the maximum withdrawal load (N),  $d$  is the diameter of the screw (mm), and  $l_p$  is the depth of the penetration of the screw into the wood (mm) [35, 39, 40].

**Statistical analysis**

**Data analysis**

Descriptive statistics of the properties of the tree part (branch and stem) wood, distinct for “Sinopolese” and “Ottobratica” cultivars measured during the laboratory tests, were calculated. A multivariate analysis of variance was conducted between the Cultivar—Tree part and the parameters detected; a significance level of 0.05 was applied. The statistical analysis of the data was performed using the SPSS software version 20.0 (IBM Corp., Amonk, NY, USA).

**Results and discussion**

In this study, two different cultivars of olive wood, “Sinopolese” and “Ottobratica”, were investigated about mechanical, physical, and surface properties ( $R_a$ , MOEd\_MST, MOEd\_PLG, MOEs, MOR, WL, SH, F, C, SW\_Par and SW\_Per) distinguishing between two tree parts (branches and stem).

The principal experimental results are summarized in Table 3 which provides the main descriptive statistics of the properties analysed distinct for the two “Sinopolese” and “Ottobratica” cultivars and between branches and stem wood.

**Table 3** Main descriptive statistics of properties tested for olive wood, distinguished for the “Sinopolese” and “Ottobratica” cultivars, and between stem and branches wood

Properties	Units	Sinopolese				Ottobratica			
		Stem		Branches		Stem		Branches	
		Max (min)	Mean (st.dev.)	Max (min)	Mean (st.dev.)	Max (min)	Mean (st.dev.)	Max (min)	Mean (st.dev.)
$R_a$	$\mu m$	7922 (978)	3937 ( $\pm 1494$ )	7748 (1150)	3795 ( $\pm 1508$ )	6462 (1736)	3484 ( $\pm 1105$ )	7128 (1672)	3925 ( $\pm 1444$ )
MOEd_MST	$N/mm^2$	10,587 (2139)	7704 ( $\pm 2614$ )	11,156 (1413)	7053 ( $\pm 3524$ )	10,040 (2431)	8028 ( $\pm 1551$ )	10,230 (2700)	8235 ( $\pm 1632$ )
MOEd_PLG	$N/mm^2$	13,963 (7132)	10,397 ( $\pm 1717$ )	14,072 (6732)	10,604 ( $\pm 1949$ )	10,782 (7971)	9379 ( $\pm 939$ )	10,546 (5714)	9227 ( $\pm 1189$ )
MOEs	$N/mm^2$	11,872 (6257)	8526 ( $\pm 1659$ )	15,571 (6003)	10,476 ( $\pm 2429$ )	10,152 (5111)	7408 ( $\pm 1297$ )	13,737 (4834)	8963 ( $\pm 2339$ )
MOR	$N/mm^2$	104 (29)	71 ( $\pm 21$ )	117 (52)	85 ( $\pm 19$ )	55 (11)	38 ( $\pm 12$ )	90 (15)	48 ( $\pm 19$ )
WL	%	0.51 (0.22)	0.31 ( $\pm 0.06$ )	0.40 (0.27)	0.32 ( $\pm 0.04$ )	0.46 (0.18)	0.36 ( $\pm 0.08$ )	0.41 (0.21)	0.32 ( $\pm 0.07$ )
SH	kN	9.2 (5.2)	7.0 ( $\pm 1.1$ )	11.0 (6.8)	9.1 ( $\pm 1.1$ )	7.6 (4.4)	5.9 ( $\pm 0.9$ )	7.3 (5.0)	6.3 ( $\pm 0.7$ )
F	mm	- 0.01 (- 0.09)	- 0.04 ( $\pm 0.02$ )	- 0.01 (- 0.08)	- 0.03 ( $\pm 0.02$ )	- 0.03 (- 0.09)	- 0.06 ( $\pm 0.02$ )	- 0.02 (- 0.11)	- 0.06 ( $\pm 0.03$ )
C	$N/mm^2$	75 (52)	60 ( $\pm 7$ )	75 (43)	61 ( $\pm 7$ )	54 (28)	46 ( $\pm 6$ )	67 (36)	47 ( $\pm 8$ )
SW_Par	$N/mm^2$	52 (27)	39 ( $\pm 6$ )	50 (31)	42 ( $\pm 6$ )	42 (30)	36 ( $\pm 3$ )	49 (30)	39 ( $\pm 4$ )
SW_Per	$N/mm^2$	53 (38)	44 ( $\pm 4$ )	52 (39)	46 ( $\pm 4$ )	42 (32)	40 ( $\pm 3$ )	47 (38)	43 ( $\pm 3$ )

Comparing the two cultivars, regarding the stem tree part, similarities in some properties ( $p > 0.05$ ) were observed for roughness profile ( $R_a$ ), moduli of elasticity (MOEd\_MST, MOEd\_PLG), abrasion resistance (WL), and static hardness (SH), while significant differences were found in static modulus of elasticity (MOEs,  $p < 0.05$ ), bending strength (MOR,  $p < 0.01$ ), footprint (F,  $p < 0.01$ ), compression strength (C,  $p < 0.01$ ), and screw withdrawal resistances (SW\_Par,  $p < 0.05$ , SW\_Per,  $p < 0.01$ ). Branches wood between the two cultivars demonstrated similarities ( $p > 0.05$ ) concerned about roughness profile ( $R_a$ ), moduli of static and dynamic elasticity (MOEs, MOEd\_MST, MOEd\_PLG), abrasion resistance (WL), static hardness (SH), and screw withdrawal resistance in parallel fiber direction (SW\_Par), while significant differences ( $p < 0.01$ ) emerged in MOR, F, C, SW\_Per.

In regard to the “Sinopolese” cultivar, multivariate analysis of variance (Table 4) among the data of properties collected for the two tree parts, there were no significant differences emerged between branches and stems

for most parameters analysed. There were significant differences between branch and stem wood for MOEs ( $p < 0.01$ ) (Fig. 2), MOR ( $p < 0.05$ ) (Fig. 3) and SH ( $p < 0.01$ ) (Fig. 4).

The branches and stem of the “Ottobratica” cultivar highlighted very similar differences to those found for the “Sinopolese” cultivar, with significant differences between branches and stem in the values regarding MOEs, MOR ( $p < 0.05$ ) and SH ( $p < 0.01$ ) but also, for the parameters SW\_Par and SW\_Per ( $p < 0.01$ ) (Figs. 5, 6).

The estimates of the elastic modulus, between the wood of stem and branches, with the two different acoustic methods (Microsecond Timer—MOEd\_MST, and Portable Lumber Grader—MOEd\_PLG) gave slightly different results. The difference could be because the Portable Lumber Grader is a tool designed to grade longitudinal vibration frequency of the tested sawn lumber, while the Microsecond Timer is designed to evaluate wood from standing trees and construction timber measuring the Time of Flight of an acoustic wave travels through the

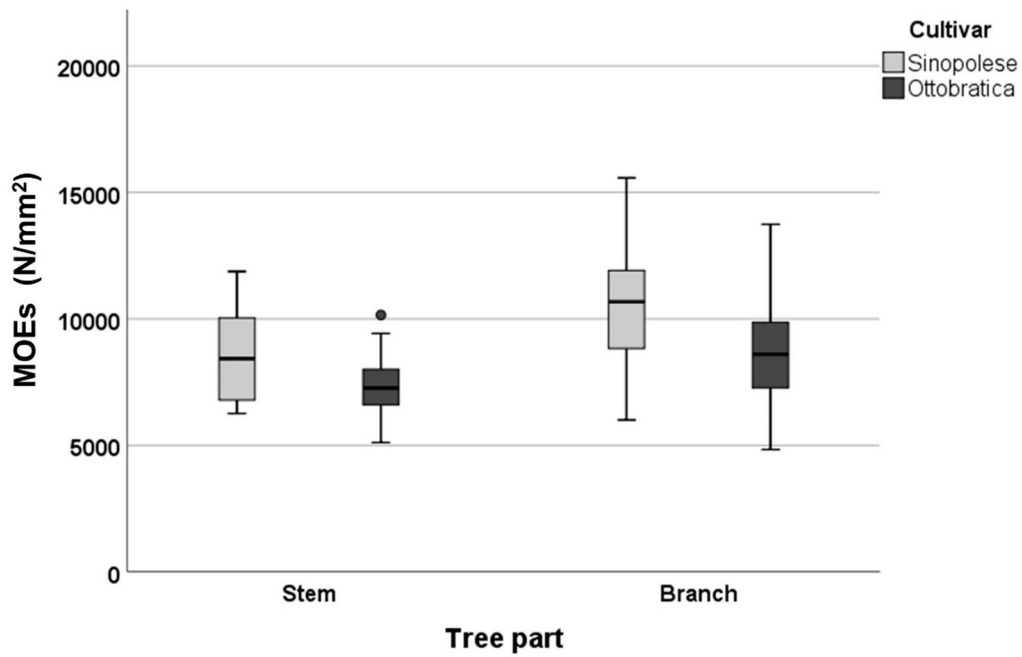
**Table 4** Multivariate ANOVA tests of cultivar-tree part

Cultivar	Dependent variable	Tree part		Mean difference	Std. Error	Sig. <sup>b</sup>	95% Confidence interval for difference <sup>b</sup>	
							Lower bound	Upper bound
Sinopolese	$R_a$	Stem	Branches	141.700	474.654	0.767	- 819.187	1102.587
	MOEd_MST	Stem	Branches	228.200	202.949	0.268	- 182.650	639.050
	MOEd_PLG	Stem	Branches	42.377	88.812	0.636	- 137.414	222.169
	MOEs	Stem	Branches	- 1950.140*	657.800	0.005	- 3281.786	- 618.494
	MOR	Stem	Branches	- 13.595*	6.333	0.038	- 26.415	- 0.775
	WL	Stem	Branches	- 0.011	0.017	0.509	- 0.045	0.023
	SH	Stem	Branches	- 1.574*	0.358	0.000	- 2.299	- 0.849
	F	Stem	Branches	- 0.007	0.006	0.294	- 0.020	0.006
	C	Stem	Branches	- 0.829	2.120	0.698	- 5.121	3.463
	SW_Par	Stem	Branches	- 2.861	1.924	0.145	- 6.755	1.034
	SW_Per	Stem	Branches	- 1.388	1.144	0.232	- 3.704	0.927
Ottobratica	$R_a$	Stem	Branches	- 440.350	406.651	0.286	- 1263.572	382.872
	MOEd_MST	Stem	Branches	0.700	103.995	0.995	- 209.827	211.227
	MOEd_PLG	Stem	Branches	67.072	57.669	0.252	- 49.672	183.817
	MOEs	Stem	Branches	- 1555.282*	598.105	0.013	- 2766.083	- 344.481
	MOR	Stem	Branches	- 10.302*	4.922	0.043	- 20.267	- 0.338
	WL	Stem	Branches	0.040	0.024	0.103	- 0.008	0.089
	SH	Stem	Branches	- 1.049*	0.247	0.000	- 1.549	- 0.549
	F	Stem	Branches	- 0.004	0.008	0.642	- 0.019	0.012
	C	Stem	Branches	- 1.717	2.273	0.455	- 6.320	2.885
	SW_Par	Stem	Branches	- 3.263*	1.166	0.008	- 5.623	- 0.902
	SW_Per	Stem	Branches	- 3.018*	0.801	0.001	- 4.639	- 1.396

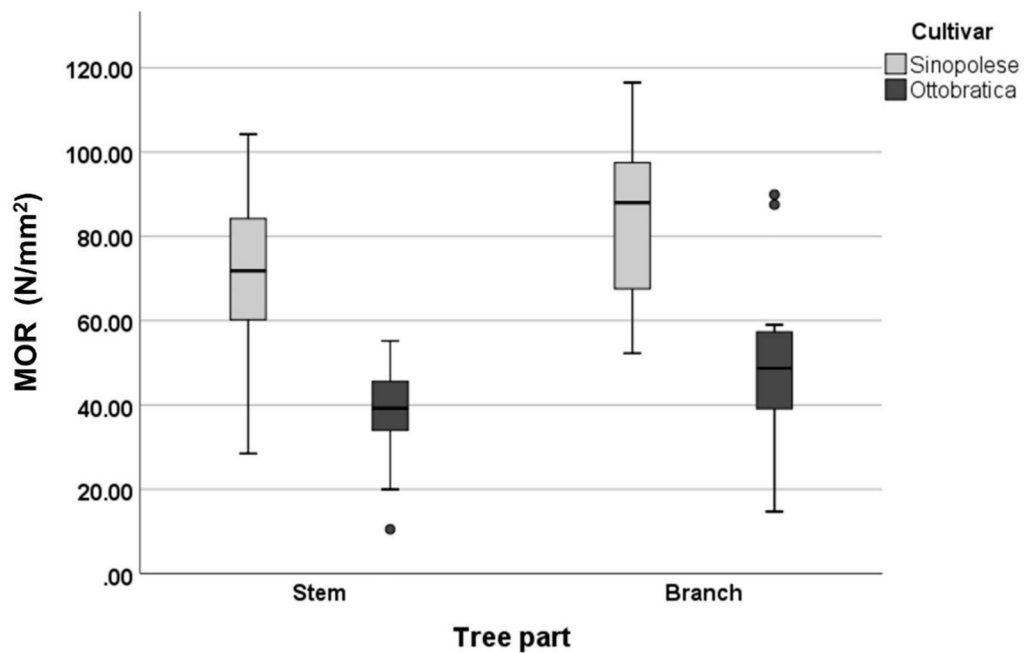
Based on estimated marginal means

\*The mean difference is significant at the 0.05 level

<sup>b</sup> Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)



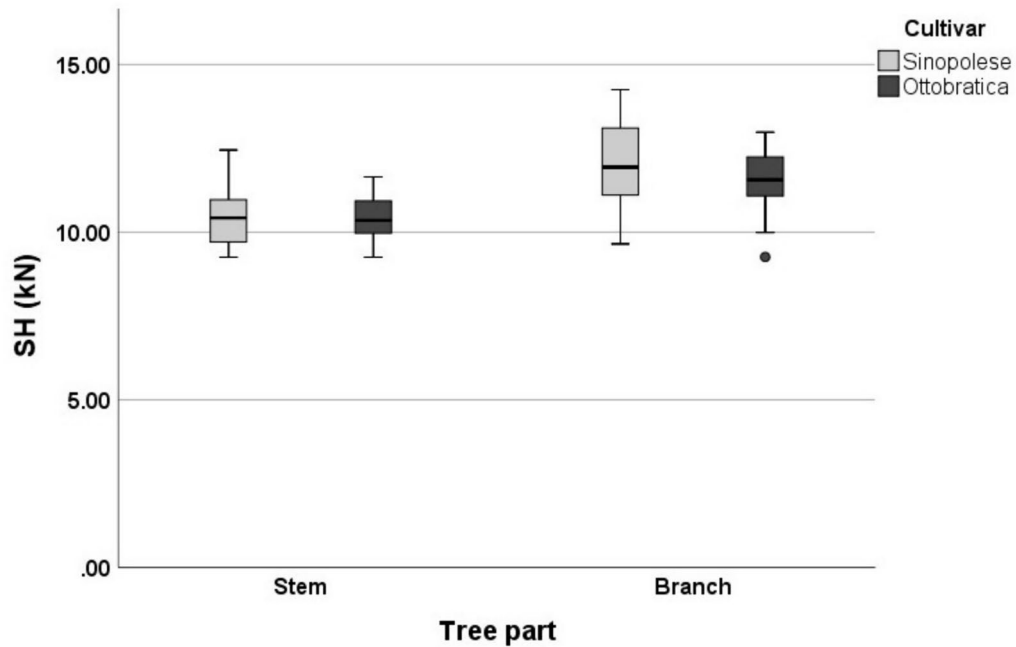
**Fig. 2** Differences between the cultivar olive wood of “Sinopolese” and “Ottobratica”, distinct into stems and branches, about static modulus of elasticity—MOEs



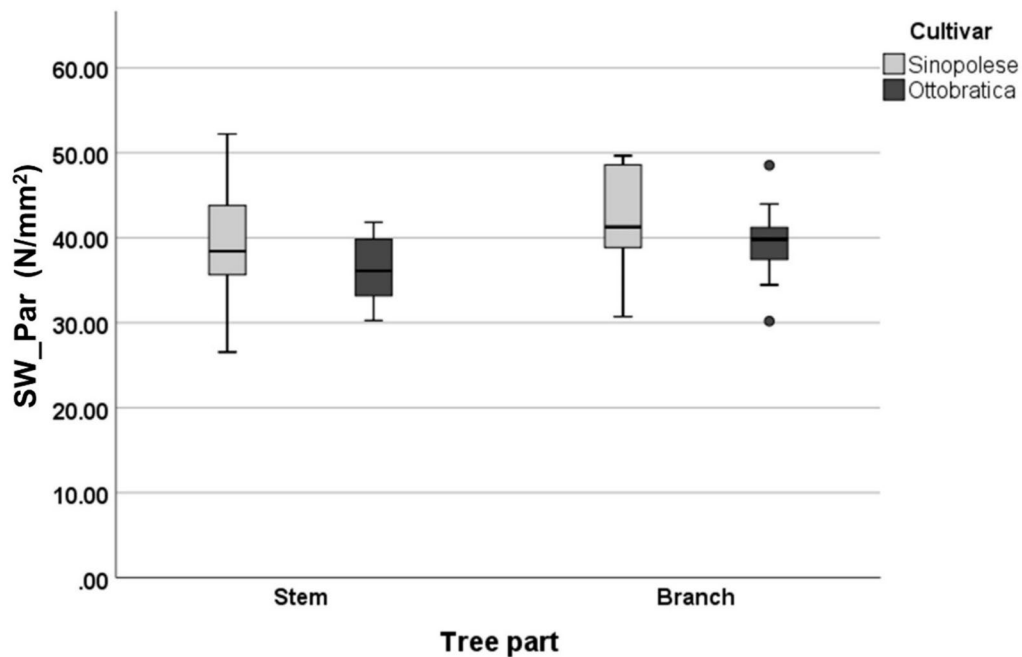
**Fig. 3** Differences between the cultivar olive wood of “Sinopolese” and “Ottobratica”, distinct into stems and branches, about bending strength—MOR

wood tissue, even if several authors use this tool on sawn lumbers [41, 42]. The results of MOEd\_MST showed a slight underestimation of the static MOE, as also found in other studies [43] while, the opposite results, with high

difference compared to the static MOE, were obtained with the Portable Lumber Grader, in accordance with other research [41].



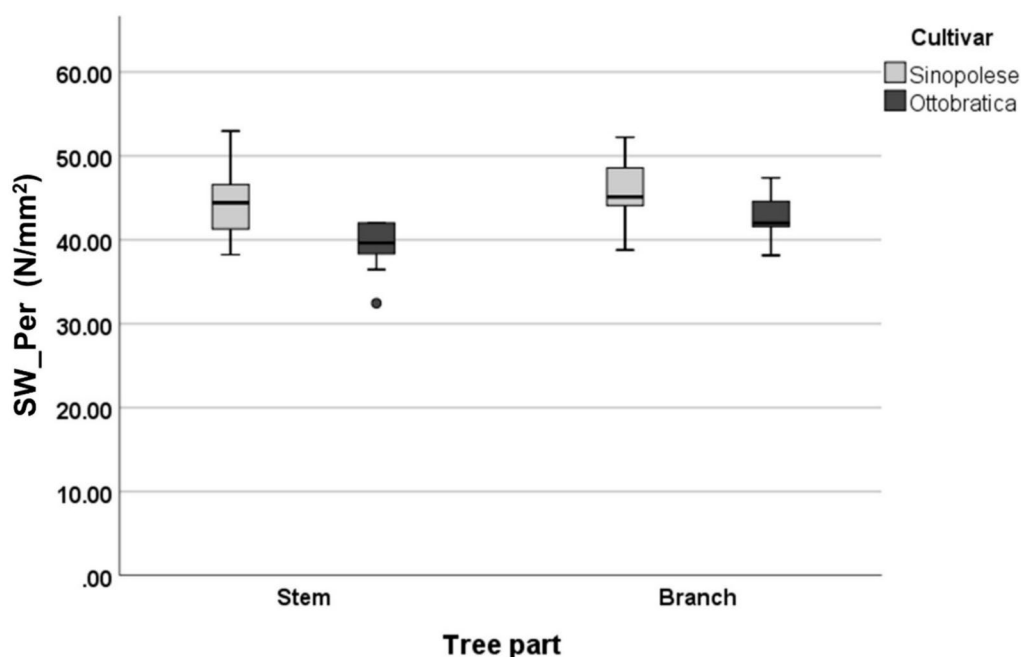
**Fig. 4** Differences between the cultivar olive wood of “Sinopolese” and “Ottobratica”, distinct into stems and branches, about static hardness—SH



**Fig. 5** Differences between the cultivar olive wood of “Sinopolese” and “Ottobratica”, distinct into stems and branches, about screw withdrawal resistance parallel to grain—SW\_Par

Collecting the available information and taking under investigation only the parameters which were determined statistically different between the cultivars or among the tree parts of them, emerged that the values of both the

MOEs and the MOR were lower than those reported in the literature for olive wood [44–46]—MOE 17770 N/mm<sup>2</sup>, MOR 155 N/mm<sup>2</sup>. However, the static elastic modulus found by Düzkalé et al. [47] on *Olea europaea* (L.)



**Fig. 6** Differences between the cultivar olive wood of “Sinopolese” and “Ottobratica”, distinct into stems and branches, about screw withdrawal resistance perpendicular to grain—SW\_Per

in Turkey, is about 50% lower (4444 N/mm<sup>2</sup>) when compared to those obtained from the present study (“Sinopolese” branches 10,476 N/mm<sup>2</sup>—“Sinopolese” stem 8526 N/mm<sup>2</sup>; “Ottobratica” branches 8963 N/mm<sup>2</sup>—“Ottobratica” stem 7408 N/mm<sup>2</sup>). Continuing the comparison with the study by Düzkalé et al. [47], it can be noted that the modulus of rupture (64.82 N/mm<sup>2</sup>) and the compressive strength in the direction parallel to the fibers (C) (53.17 N/mm<sup>2</sup>) obtained for the olive in Turkey, are placed between the average values obtained for the two cultivars tested in this research (“Sinopolese” 78 N/mm<sup>2</sup>—“Ottobratica” 43 N/mm<sup>2</sup>; “Sinopolese” 61 N/mm<sup>2</sup>—“Ottobratica” 47 N/mm<sup>2</sup>, for MOR and compression strength average values between branches and stem, of each cultivar, respectively).

Static hardness (“Sinopolese” branches 9.1 kN—“Sinopolese” stem 7.0 kN—Ottobratica” branches 6.3 kN—Ottobratica” stem 6.0 kN) was found to be consistent with Green et al. [48] who ranged Janka hardness between 1.60 and 10.90 kN for hardwoods, and between 1.50 and 5.33 kN for softwoods since the hardness found with the Janka test is approximately proportional to the density of the wood in general, but above all by the variation in density within an annual ring. Of the two olive tree cultivars analysed, the “Sinopolese” is the one that presented the highest static hardness values, and in both cultivars the hardness was always higher in the branches than in the stems. However, specifically comparing these

values with the SH of the olive tree reported by the Ruffinatto et al. [45] (14.1 kN) they were lower by 35–50% in the case of “Sinopolese”, and by 55–60% in the case of the “Ottobratica” cultivar.

The study of the physical–mechanical properties of olive wood is slightly diffused. No studies were found on the performance of resistance to imprinting and extraction of the screw for olive wood, as well as the evaluation of the hardness of the wood, so the comparison with the results resulting from this research cannot be carried out. However, considering the results obtained from studies carried out on other types of hardwood such as *Quercus cerris* (L.) wood (density 0.834 ± 0.058 g/cm<sup>3</sup>), for indentation resistance, Todaro [49] obtained values of permanent deformation (or residual) equal to – 17.12 μ, values not very discordant from those found in this study. Considering the beech wood to compare the olive compression strength, Kapidani et al. [50] measured 71.96 N/mm<sup>2</sup>, which was, even for this parameter, higher than that of the olive wood (mean of 60.7 and 46.50 N/mm<sup>2</sup> for “Sinopolese” and “Ottobratica” cultivars, respectively). In regard to the screw withdrawal resistance parallel to grain the values were higher than some other hardwood species present in scientific literature [9, 51–53], (*Carpinus Betulus* (L.)—22.78 N/mm<sup>2</sup>, *Fraxinus excelsior* (L.)—16.00 N/mm<sup>2</sup>, *Fagus sylvatica* (L.)—12.60 N/mm<sup>2</sup>), and perpendicular (*Carpinus Betulus* (L.)—25.31 N/mm<sup>2</sup>—*Fagus sylvatica* L.—15.80 N/mm<sup>2</sup>, *Fraxinus excelsior*

(L.)—19.00 N/mm<sup>2</sup>), but lower compared to lemon wood that presents screw withdrawal resistance 44 and 51 N/mm<sup>2</sup> (parallel and perpendicular to grain, respectively) for both cultivars independently of the tree parts tested. Rahmanto et al. [54] focused on the comparison of the properties between branches and stems by analysing anatomically seven different commercial wood species and from their study, it emerged that although there are anatomical differences such as fibre length and vessel diameter between the wood of the two parts of the tree, the fiber derivative resulted in the same quality class for stem and branch, concluding that the main stem and branch have similar wood properties. So, the study of the properties of the wood could be carried out using the branch effectively, especially since stem wood is sometimes not suitable due to the presence of cavities or decays that defect wood quality, while branches wood, is often less involved in wood deterioration.

This first examination suggests the possibility of using the branches wood to obtain similar products produced with stem wood.

## Conclusion

Nowadays, in the agroforestry contexts, there is a growing interest in the use of wood species from alternative sources, especially fruit-tree woods, for multiple purposes. This study took inspiration from this trend, aiming to expand the notions connected to the wood obtainable from the extraordinary pruning of olive trees. In fact, considering the lack of information on this woody species, the results gathered from this study can enrich the interest in the wood olive. The investigation focused on determining and comparing the physical and mechanical properties of branches and stem wood of two olive tree cultivars (“Sinopolese” and “Ottobratica”) to provide information on this species by considering the differences found in intraspecific terms and in the distribution of the wood in the tree. In this study, differences were found on several properties, between the two cultivars when compared to each other for part of the tree, where in general, the “Sinopolese” cultivar showed higher values than the “Ottobratica”. Between the branches and stem wood within the same cultivar, statistical analysis highlighted significant differences only for some properties (static modulus of elasticity, bending strength, static hardness and screw withdrawal resistances depending on the cultivar) with higher results for wood of branches. These results could be motivated by the differences obtained in wood density between the cultivars or by some intrinsic characteristics of each cultivar not yet recognised, but no studies were found about the characterization of the wood olive cultivars, although very widespread is the topic related to olive oil.

That suggests the possibility of using the branches wood to obtain similar products produced with stem wood. The commercial utilization of wood branches can represent a valid opportunity for the local rural economy when stems are not adequate (defected, decayed, etc.). In conclusion, the knowledge about olive wood on its performances concerning physical and mechanical characteristics can increase its use in multiple sectors and ensure a more aware use of the application of the wood resources.

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## Author contributions

Conceptualization, S.F.P., A.R.P.; methodology, A.M., M.F.C., S.F.P., A.R.P.; validation, A.R.P.; formal analysis, M.F.C., S.F.P., A.R.P.; investigation, A.M., A.R.P.; resources, A.R.P.; data curation, A.M., M.F.C., S.F.P., A.R.P.; writing—original draft preparation, M.F.C., S.F.P., A.R.P.; writing—review and editing, M.F.C., S.F.P., A.R.P.; visualization, M.F.C., A.R.P.; supervision, A.M., A.R.P.; project administration, A.R.P.; funding acquisition, A.R.P. All authors have read and agreed to the published version of the manuscript.

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## Availability of data and materials

Data are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Conflict of interest

No potential conflict of interest was reported by the author(s).

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## **4.4. Steaming treatment tests**

### **Article 5**

#### **Influence of steaming treatment on some technological properties of olive wood**

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# Influence of steaming treatment on some technological properties of olive wood

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**Abstract:** Wood modification is a process that alters the properties of wood through chemical, thermal, or physical treatments. This enhances its performance, durability, and dimensional stability. In addition to wood steaming, which is becoming more popular for wood kinds that are thought to be challenging to treat, hygrothermal treatment is an efficient way to change the physical characteristics of wood. Increased dimensional stability, decreased hygroscopicity, resilience to fungal attacks, and color changes indicate the physical property changes. Heat treatment can increase durability, but it can also have a negative impact on mechanical performance. This study assessed how the steaming procedure affected some of the physical-mechanical characteristics of olive wood. The aim was to analyze the impact of steaming time at a fixed temperature but with varying durations. Olive boards were chosen for this investigation and split into four series: three for the various cycles of steaming and Control (T) for normal seasoning. The vaporization cycles consisted of a constant temperature and a variable duration: 12, 18, 36 h. The results from the abrasion tests showed that the thermal treatment did not affect the resistance. The bending tests revealed that the medium-short cycles (12 and 18 hours) of the thermal treatment increased the bending resistance and the static elastic modulus.

**Keywords:** Wood properties, vaporization, color changes, hemicelluloses, lignin

## Introduction

Wood is a natural material that has been used for centuries in numerous applications: in the industrial category for construction, furniture, packaging [1], for wood-based products [2], buildings, and bridges [3]. It has a high economic weight, and it can be easily processed [2,4], it is low-priced and easy to reach [5]. On the other hand, wood is a natural material that comes from various trees, and its characteristics put different limits on it, such as dimensional instability, resistance to biotic and abiotic factors [6], and its mechanical and physical properties [5]. These limitations can be overcome by applying different modifications to increase its practicability [7].

Wood modification means the use of chemical, biological or physical agents on wood leading to the improvement of its properties during the useful life of the product [8]. Wood modification is a treatment that changes the physical and chemical properties of wood to improve its performance and dimensional stability for exterior and interior use [9,10]. One of the oldest methods of modifying wood properties is thermal modification. These modifications alter solid wood, dispersing the heat equally. This treatment is applied in an oxygen-free environment at temperatures between 120-240°C [11]. To hinder

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oxygen entry, steam, nitrogen gas, vegetable oil, or wood can be placed in a vacuum environment [12]. Heat treatment at high temperatures is one of the modifications that improve wood quality in terms of durability and dimensional stability and reduce hygroscopic behavior [13]. The mechanical and physical properties after heat treatment depend on the wood species, the method used and the type of treatment [14]. The high temperatures modify the mechanical properties of the wood due to the degradation of the hemicellulose (hydrolysis) [15,16]. The hydrolysis reactions are also affected by moisture content, treatment temperature, presence and absence of oxygen and treatment time, which change the mechanical properties [15,16]. Salmén [17] and Kelley et al. [18] affirm that the moisture content of wood affects its mechanical properties in several ways. Stamm [19] observed that moisture removal helps carry away acids formed during hydrolysis. In addition, Kininmonth [20] affirms that the hygroscopic character of wood decreases more rapidly under humid conditions. For Rusche [21], in addition to the effect of moisture, the rate of degradation, loss of weight, and mechanical properties increase with increasing oxygen concentration. As the oxygen concentration increases, the loss of mass increases, and the overall extent of modification and the result of the process is quite variable [22]. Kocaefe [15] demonstrated that longer treatment times and higher temperatures negatively affect degradation and, consequently, mechanical properties. Nowadays several treatments are available that differ in inert atmosphere and temperature curing conditions [23]. There are five main methods of wood heat treatment in Europe [24]: the Dutch PLATO Process, the Retification Process (or NOW, France), the Bois Perdure Process (France), the OHT Process (Germany), and the ThermoWood Process (Finland). These wood treatments are subjected to temperatures close to or above 200°C for several hours in a low-oxygen atmosphere. The principal differences between these methods are the technique conditions (oxygen or nitrogen, water spray, use of oil, water steaming) [25].

Steaming treatment of wood is an effective method for changing the physical and mechanical properties of wood. According to Syrjanen [26], the various fields of application for steamed wood include exterior cladding, window and door frames, wood paneling, garden furniture, sauna furniture, flooring and decking, etc. This treatment modifies the wood structure (cellulose, hemicelluloses, and lignin). Changes in the physical properties are reflected in increased dimensional stability, reduced hygroscopicity, decreased absorbability, resistance against fungal attack, and darkening of the wood's color. Steaming treatment leads to an improvement in the natural durability of wood, and at the same time this process represents one of the most environmentally friendly techniques for preserving wood, as it does not entail the use of chemicals [15, 16]. Steaming times range from a few minutes at high temperatures to a few hours at lower temperatures [27]. Wood can change its properties, behaving as a linear elastic solid, a viscous fluid or a viscoelastic material, depending on the heating time, the temperature and the concentration of other components [24]. Hemicelluloses and lignin are amorphous, while cellulose is crystalline. The glass transition temperature is the temperature at which amorphous polymers change from a glassy to a rubbery state [16]. Hemicelluloses and cellulose degrade significantly if the wood is steamed above the glass transition temperature [16]. Due to the large number of parameters that influence degradation, it is difficult to identify a precise mechanism that explains the changes that occur in mechanical properties during steam treatment. The temperature and duration of steaming treatment are highly variable. Most steaming methods are applied at temperatures between 120°C and 220°C ranging from a few minutes to several hours [28]. Korkut and Hiziroglu [29] performed heat treatments on hazelnut wood (*Corylus colurna* L.) at three different temperatures (120°C, 150°C and 180°C) for different intervals: 2 hours, 6 hours and 10 hours. Percin et al. [30] also treated beech (*Fagus orientalis* Lipsky) samples with three different temperatures (150°C, 175°C and 200°C) for 1, 3 and 5 hours. Priadi and Hiziroglu [31], on the other hand, performed heat treatment on four species: mindi (*Melia azedarach* L.), mahogany (*Swietenia macrophylla* King.), southern red oak (*Quercus falcata* Michx.) and loblolly pine (*Pinus taeda* L.). The samples were

exposed to temperature levels between 130°C and 200°C for 2 and 8 hours. Uribe and Ayala [32] performed the treatment on three wood species: rosy trumpet (*Tabebuia rosea* (Bertol.) DC.), teak (*Tectona grandis* L.f.) and chanul (*Humiriastrum procerum* (Little) Cuatrecasas). In this study, the wood was exposed to different temperature levels (130°C, 150°C, 180°C and 210°C) for periods of 2, 4 and 8 hours. Pelit et al. [33] performed the heat treatment at 185°C and 212°C for 2 hours on three species: Uludağ fir (*Abies bornmuelleriana* Mattf.), linden (*Tilia grandifolia* Ehrh.) and black poplar (*Populus nigra* L.). Finally, Pierinik et al. [16] subjected scots pine (*Pinus sylvestris* L.) to heat treatment at 220°C for a period of 1 to 8 hours. The temperature and exposure time for steaming treatment of wood can be adjusted based on species, sample size, moisture content, and target use.

Several studies have been conducted to investigate the influence of steaming treatment on wood performance [33, 34, 35, 36, 13, 15], and the results confirmed that steaming treatment negatively affects mechanical properties. All conclude that during steaming treatment to high temperature, the wood becomes more brittle.

Pelit et al. [33] observed that the mechanical strength of the samples heat-treated, decreased as the treatment temperature increased. Furthermore, the strength values of the samples heat-treated, except for modulus of rupture (MOR), were higher than those of the control samples. Jämsä and Viitaniemi [34] observed that the modulus of elasticity decreased significantly through heat treatment. Korkut and Hiziroglu [35] found reduction values of 68%, 65% and 59% for Janka hardness in radial, tangential and grain-parallel tensile strength for samples exposed to 180°C for 10 hours. Unsal and Ayrilmis [36] indicate that an increase in temperature and duration of heat treatment is associated with a reduction in density, compressive strength, and surface roughness. Shi et al. [13] observed decreases of up to 49% in the MOR depending on the wood species (spruce, pine, fir, aspen and birch) and the treatment used. Also, the decrease in the modulus of elasticity (MOE) of heat-treated spruce and pine ranged from 4% to 28%. Kocaefe et al. [15] state that the degree of change in the physical-mechanical characteristics of jack pine during heat treatment is highly dependent on the treatment conditions used.

Considering that all previous studies mentioned tested the effects of steaming at high temperatures (range 120-220°C), the present study aims to evaluate the influence of low-temperature treatment on the mechanical properties of wood. Therefore, the study tested wood samples at a constant temperature of 80°C at different times (12, 18, 36 hours).

## 2. Materials and Methods

### 2.1. Wood sampling and Steaming treatment

The wood material was collected from a local olive orchard (*Olea europaea* L.) after fruit harvesting operations in the municipality of Molochio, in the 'Plain of Gioia Tauro' (Southern Italy). During pruning operations, branches with a diameter of less than 20 cm were excluded. The carefully selected logs were transported to a sawmill where 48 boards were chosen for steaming treatment. Each board measured 90cm x 25cm x 3.3 cm (length x width x thickness) and divided into four groups: seasoning, 12-hour cycle, 18-hour cycle, and 36-hour cycle; each group consists of 12 sawn-boards.

### 2.2. Laboratory test

The sawn boards were divided into three groups and each group was subjected to steam under saturated conditions and a maximum pressure of approximately 80°C and 140 kPa for 12 hours, 18 hours and 36 hours, respectively.

Dynamic modulus of elasticity (MOEd) and colour measurement were conducted on the sawn-boards before and after steaming. After steaming, from the boards were obtained specimens for dimensional stability, bending strength, compression strength, Janka hardness, and surface abrasion tests.

Once the specimens were prepared, they were conditioned in a climatic chamber (Mettler 750 Eco, GmbH, Germany) at  $20 \pm 2^\circ\text{C}$  and 65% ( $\pm 5\%$ ) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12%. Air-dried density of each sample was determined in accordance with the ISO standard 13061-2 [37], and moisture content was determined following the oven dry method [30]. The tests were carried out in the laboratory of Wood Technology and Forest Mechanization of the AGRARIA Department of Reggio Calabria. The distribution of tests is shown in Table 1.

**Table 1.** Distribution of specimens

	Colour measurements	Dimensional stability	MOEd	Bending strength	Compressive strength	Janka hardness	Abrasion resistance
Seasoning	8	40	12	14	35	20	10
12 h cycle	8	40	12	14	35	20	10
18 h cycle	8	40	12	14	35	20	10
36 h cycle	8	40	12	14	35	20	10
<b>Total number of specimens</b>	<b>32</b>	<b>160</b>	<b>48</b>	<b>56</b>	<b>140</b>	<b>80</b>	<b>40</b>

### 2.3. Colour measurement

Color measurements of all boards were recorded on the surface of the wood samples before and after steaming treatment using a SAMA tools colorimeter. The sensor head had a diameter of 4 mm. Measurements were made using a D65 illuminant and a standard observer of 8 degrees. The reflectance percentage was converted to the CIELAB color system where L describes the brightness, a and b describe the chromaticity coordinates on the green-red and blue-yellow axis, respectively. Tests were performed on both sapwood and heartwood. A measuring tape was placed diagonally across the board. The first measurement was taken on the sapwood, at approximately 10 cm. The second measurement was taken on the heartwood, at about half length. From the laboratory values, the difference in brightness ( $\Delta L$ ) and chromaticity coordinates ( $\Delta a$  and  $\Delta b$ ) and the total color difference ( $\Delta E$ ) were calculated using the following formulas (Eq. 4; Eq. 5; Eq. 6; Eq. 7):

$$\Delta L = l_2 - l_1 \quad (4)$$

$$\Delta a = a_2 - a_1 \quad (5)$$

$$\Delta b = b_2 - b_1 \quad (6)$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (7)$$

where:  $l_1$ ,  $a_1$  and  $b_1$  = measurements before treatment;  $l_2$ ,  $a_2$  and  $b_2$  = measurements after treatment.

Each sawn board measured 90 cm in length, 25 cm in width and 3.3 cm in thickness.

### 2.4. Determination of dimensional stability

The dimensional stability test was carried out until the equilibrium moisture contents of the wood were reached. For this test, a 28-day (4-week) protocol was established, in which the specimens were placed in a climatic chamber at  $20 \pm 2^\circ\text{C}$  and 65% ( $\pm 5\%$ ) relative humidity (RH). This protocol included volume and weight measurements taken weekly until the equilibrium moisture content was stabilized. The wood moisture content was measured using a hygrometer at the beginning of the test. Measurements were taken in the three anatomical directions (radial, tangential and transversal) using a digital comparator (Mitutoyo ID-C ABSOLUTE Digimatic) to determine volume. An analytical balance (Nimbus NBL 223e) was used to determine the weight of the specimen. The average dimensions of the specimens are: 31.01 mm ( $\pm 1.28$ ), 31.53 mm ( $\pm 1.44$ ), 48.65 mm ( $\pm 1.26$ ) for the radial, tangential and transverse directions respectively. The average weight is 44.48 gr ( $\pm 2.82$ ).

### 2.5. Determination of Dynamic modulus of elasticity (MOEd) with Microsecond Timer

The MOEd was determined perpendicular to the grain. The boards were subjected to a single-path stress wave test using a Fakopp Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary). This instrument consists of needles connected to accelerometers, used as mediators, that penetrate the bark and reach the sapwood of the tree. A hammer is used to tap the starting sensor to generate a stress wave in the board in the longitudinal direction. The two sensors detect the start and stop signal and the transmission time of the wave is displayed on an LCD screen with a resolution of  $\pm 1 \mu\text{s}$ . The sensors were positioned at 85 cm from each other at an angle of  $45^\circ$ . The test was repeated several times for each pair of sensors to obtain the average value of at least three readings. By measuring the size of the boards, the volume was obtained (Eq. 1). Together with the measurement of the weight of the boards, the density was obtained (Eq. 2). In addition, the moisture content of each sawn board was determined using a digital moisture meter with two electrodes (Schaller, WLW). The measurement was carried out on heartwood and sapwood. The tests were carried out before and after the steaming treatment.

$$V = l * w * t \quad (1)$$

where: V = volume ( $\text{m}^3$ ); l = length (m); w = width (m); t = thickness (m).

$$D = \frac{w}{v} \quad (2)$$

where: D = density ( $\text{kg}/\text{m}^3$ ); w = weight (kg); v = volume ( $\text{m}^3$ ).

With the density and speed of the wave available, it was possible to derive the MOEd (Eq. 3).

$$MOEd = w^2 * D \quad (3)$$

where: w = wave transmission velocity (m/s); D = density ( $\text{kg}/\text{m}^3$ ).

Each sawn board measured 90 cm in length, 25 cm in width and 3.3 cm in thickness.

### 2.6. Determination of static modulus of elasticity and modulus of rupture

Static modulus of elasticity (MOEs) and bending strength or MOR were determined perpendicular to the grain. A four-point bending test was performed using a 300 kN universal testing machine (METRO COM, Italy – 10402030 model), in accordance with the European Standard 408:2010 + A1 [38]. Data were recorded by the dedicated METRO COM software. The length of the specimen was 21 times its width. The supports were

placed at a distance equal to 18 times the width, and the two load points were placed at a distance from each support equal to 6 times the width (408:2010 + A1) [38]. During the tests, the load and the bend values were registered. The specimens had a square cross-section with a side of 3.3 cm. The length, parallel to the grain, was 69.3 cm. The distance between the two loading points was 19.8 cm, while the distance between the two supports was 59.4 cm. The feed rate of the crosshead was 5.9 mm/min.

### 2.7. Determination of compression strength and static hardness - Janka

In the same laboratory, a compressive strength test was performed following the International Standard 13061-17:2022 [39]. The specimens had a square cross-section with a side length of 3.3 cm. The length, parallel to the grain, was 5 cm. The maximum load is reached in no less than 1 minute and no more than 5 minutes after the start of loading (13061-17:2022) [39], a feed speed of 6 mm/min has been set. During the tests, the values of the load and the bend were registered. The compressive strength was measured using (Eq. 8):

$$C = \frac{F_{max}}{A} \quad (8)$$

where C = compressive strength parallel to the grain (N mm<sup>-2</sup>); Fmax = maximum load (N); A = cross-sectional area (mm<sup>2</sup>).

The Janka hardness was performed in accordance with the International Standard 13061-12:20 [40]. For this method, a hemispherical ball with a radius of 5.64 mm was forced into the sample to a depth of 5.64 mm or 2.82, and the maximum force was recorded during the test. A penetration depth of 2.82 mm was used for the test. The Janka hardness was calculated using (Eq. 9):

$$H_W = K * F \quad (9)$$

where H<sub>w</sub> = surface hardness at moisture content W (kN); K = coefficient equal to 4/3 in the case of penetration of the plunger to a depth of 2.82 mm; F = maximum load during the penetration of the plunger into the test sample to the specified depth (kN). A feed speed of 6 mm/min was set. The test specimens have a square cross-section of 50 mm × 50 mm and a thickness of 3.3 mm. The test was carried out on the tangential section of the test specimen.

### 2.8. Determination of Abrasion resistance

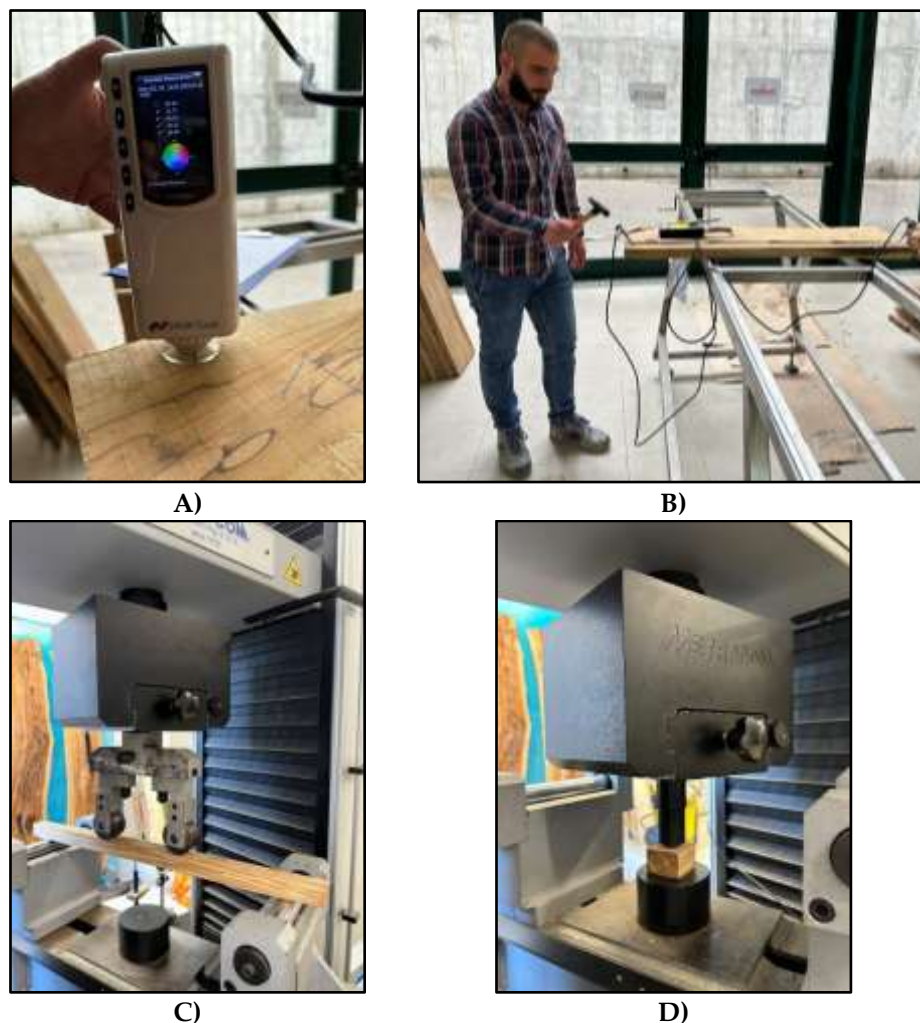
Abrasion resistance was determined according to the Taber test (3135 Abraser v2.001), using the sandpaper method, following UNI EN 15185 [41]. A 240-grit sandpaper and a load of 10 (± 0.1) N (En 1534) was used for each of the two grinding wheels. The specimens were square (10 cm side) with rounded corners and a thickness of 2.5 cm. Each wood sample was weighed before (W<sub>1</sub>) subjecting it to the abrasion test using the ADAM Nimbus analytical balance. The samples were fixed to the Taber Abraser and the abrasion test was conducted by setting the wheel rotating at 72 cycles per minute. After 500 revolutions, the weight loss (W<sub>2</sub>) due to abrasion was recorded. The weight loss (W<sub>L</sub>) due to abrasion was calculated as a percentage for each sample according to (Eq. 10):

$$W_L = \frac{W_2 - W_1}{W_1} 100 \quad (10)$$

where W<sub>L</sub> = weight loss (%); W<sub>1</sub> = weight of test specimen before abrasion (g); W<sub>2</sub> = weight of test specimen after abrasion (g).

The figure 1 shows the different tests conducted.

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**Figure 1.** Tests conducted: A) Color measurements; B) MOEd; C) Bending strength; D) Compressive strength; D) static hardness - Janka

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### 2.9. Data analysis

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The statistical analysis examined which dependent variables were statistically different in relation to the duration of steaming treatment. A multivariate analysis was carried out, thus considering the duration of steaming treatment as the independent variable, and then a post hoc test was performed, applying a 95% confidence interval. SPSS software version 20.0 (IBM Corp., Amonk, NY, USA) was used for the statistical analysis of the data.

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## 3. Results and Discussion

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### 3.1. Colour measurements

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During the visual analysis with the colorimeter, it was found that the sapwood was more affected than the heartwood. The sapwood showed greater browning ( $\Delta L$ ) than the heartwood. The greatest darkening of sapwood occurred in the 36-hour cycle, with a loss of 13.60 units. This was followed by the 12-hour cycle, the 18-hour cycle and untreated wood, with a loss of 11.75, 6.74 and 1.69 units, respectively. Heartwood also suffered more darkening with the 36-hour cycle (-7.88 units). This was followed by the 12-hour cycle (-

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6.15 units), the 18-hour cycle (-5.52 units) and untreated wood (-1.74 units). For both heartwood and sapwood, an increase in  $\Delta a$  is observed in all treatment cycles and for untreated wood. For heartwood, an increase in  $\Delta b$  is observed. In contrast, for sapwood, a loss of  $\Delta b$  is observed in the treatment cycles and an increase for the untreated cycle. Finally, the total color change ( $\Delta E$ ) of heartwood occurs in the 36-hour cycle (9.70 units), followed by the 18-hour cycle (9.29 units) and the 12-hour cycle (8.31 units). The largest total color change ( $\Delta E$ ) of sapwood occurs for the 36-hour cycle (15.75 units) and the 12-hour cycle (13.56 units). This is followed by the 18-hour cycle (9.44 units) and the untreated cycle (3.64 units). Table 2 illustrates how the various color parameters change according to the duration of the steaming treatment.

**Table 2.** Variations between the colour parameters expressed as percentage

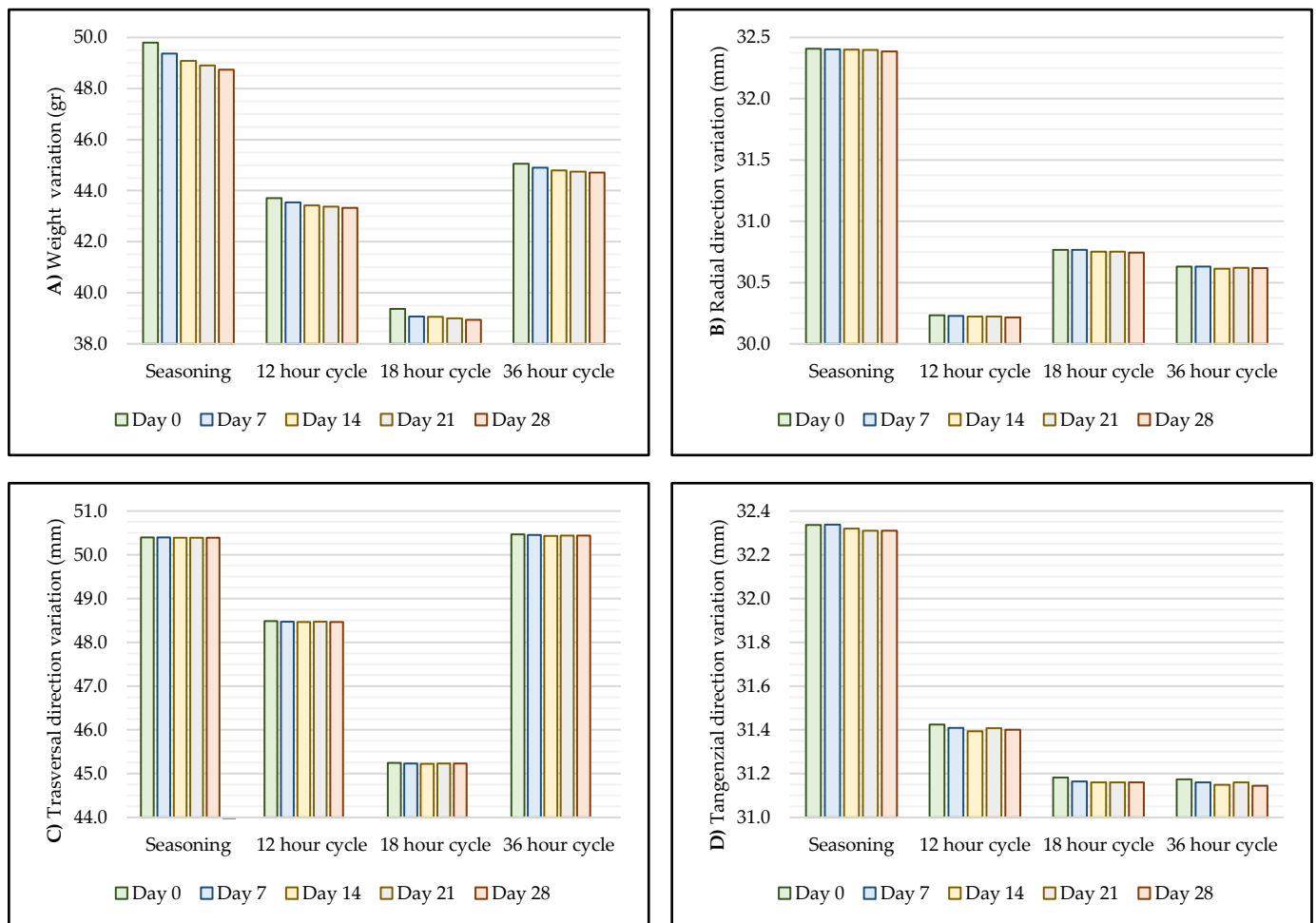
<b>Heartwood</b>				
	$\Delta L$	$\Delta a$	$\Delta b$	$\Delta E$
<b>C</b>	- 1.74 ( $\pm$ 1.96)	2.93 ( $\pm$ 1.65)	1.97 ( $\pm$ 1.27)	4.39 ( $\pm$ 1.96)
<b>12 h</b>	- 6.15 ( $\pm$ 4.87)	1,73 ( $\pm$ 2,18)	-2.55 ( $\pm$ 3.35)	8.31 ( $\pm$ 3.88)
<b>18 h</b>	- 5.52 ( $\pm$ 1.94)	1.68 ( $\pm$ 3.01)	- 6.08 ( $\pm$ 7.89)	9.70 ( $\pm$ 6.28)
<b>36 h</b>	- 7.88 ( $\pm$ 3.50)	2.12 ( $\pm$ 1.96)	- 3.78 ( $\pm$ 2.69)	9.29 ( $\pm$ 4.14)
<b>Sapwood</b>				
	$\Delta L$	$\Delta a$	$\Delta b$	$\Delta E$
<b>C</b>	- 1.69 ( $\pm$ 2.59)	2.15 ( $\pm$ 1.62)	1.26 ( $\pm$ 1.13)	3.64 ( $\pm$ 2.40)
<b>12 h</b>	- 11.75 ( $\pm$ 3.88)	- 2.92 ( $\pm$ 2.76)	- 4.88 ( $\pm$ 2.57)	13.56 ( $\pm$ 3.74)
<b>18 h</b>	- 6.74 ( $\pm$ 6.55)	1.89 ( $\pm$ 4.96)	- 3.81 ( $\pm$ 2.40)	9.44 ( $\pm$ 5.89)
<b>36 h</b>	- 13.60 ( $\pm$ 3.30)	4.36 ( $\pm$ 2.59)	- 5.70 ( $\pm$ 1.97)	15.75 ( $\pm$ 2.92)

$\Delta L$ ,  $\Delta a$  and  $\Delta b$  are the differences of the initial and final values (before and after the steaming treatment) of L, a and b parameters, respectively.  $\Delta E$  is the total color change

Bekhta and Niemz [42] found that the color changes were drastic after steaming treatment at a temperature of 200°C: with each treatment time, the darkening increased. The greatest L reduction was observed for wood samples completely saturated with water: the loss of brightness was about 72.81% after 24 hours of treatment at 200°C, reaching a very low value (21 units) compared to 77.24 units for unsteamed wood. Furthermore, Bekhta and Niemz [42] observed a drastic decrease in brightness during the first 4 hours of treatment. The *a* value increased by approximately 38-53% during the first 2 hours and remained almost the same thereafter. The *b* value decreased significantly by approximately 30-45% after 24 hours of treatment. During the first 2 hours, this value increased compared to unsteamed wood and decreased thereafter. Thus, during the first 4 hours, the wood changed its color to yellow and then to blue. A significant decrease (approx. 22-29%) in the hue angle (h) was observed as the treatment duration increased from 0 to 24 hours. Thus, the color of the wood became redder during the steaming treatment. The total color difference increased from 22-28% after 2 hours of treatment to 43-57% after 24 hours of treatment. Pienik et al. [43] found that extending the duration of steaming treatment of Scots pine leads to an increase in  $\Delta E$  of approximately 20%. In addition, the longer duration leads to a decrease in  $\Delta L$  of about 35 per cent, therefore, the color of the wood becomes darker. With an extension of the steaming treatment duration, an upward trend is observed for  $\Delta E$ . The level of total wood color change is mainly determined by the parameter whose value changes the most, i.e.  $\Delta L$ .

### 3.2. Dimensional stability

From volumetric swelling tests, a slight decrease in all three anatomical directions of the wood was observed, indicating volumetric shrinkage. The untreated wood exhibits a volumetric shrinkage of 0.16%. The 12-hour and 18-hour cycles both show a volumetric shrinkage of 0.17%. Finally, the 36-hour cycle presents a decrease of 0.19%. Therefore, the increase in steaming treatment directly affects dimensional stability. Regarding the radial direction, there is a loss of 0.07% for both untreated wood and the 36-hour cycle. The 12-hour cycle shows a decrease of 0.06%, and the 18-hour cycle, a decrease of 0.04%. The transverse direction shows a decrease of 0.02%, 0.04%, 0.03%, and 0.05% respectively for the untreated cycle, 12-hour cycle, 18-hour cycle, and 36-hour cycle. For the tangential direction, there is a shrinkage of 0.08% for both the untreated cycle and the 12-hour cycle. The 18-hour and 36-hour cycles show losses of 0.07% and 0.10% respectively. Finally, the untreated cycle shows the greatest weight loss (2.13%), while the smallest is with the 36-hour cycle (0.75%). The 12-hour and 18-hour cycles show a loss of 0.86% and 1.08% respectively. Figure 2 shows the effects of steaming treatment on the three anatomical directions and weight.



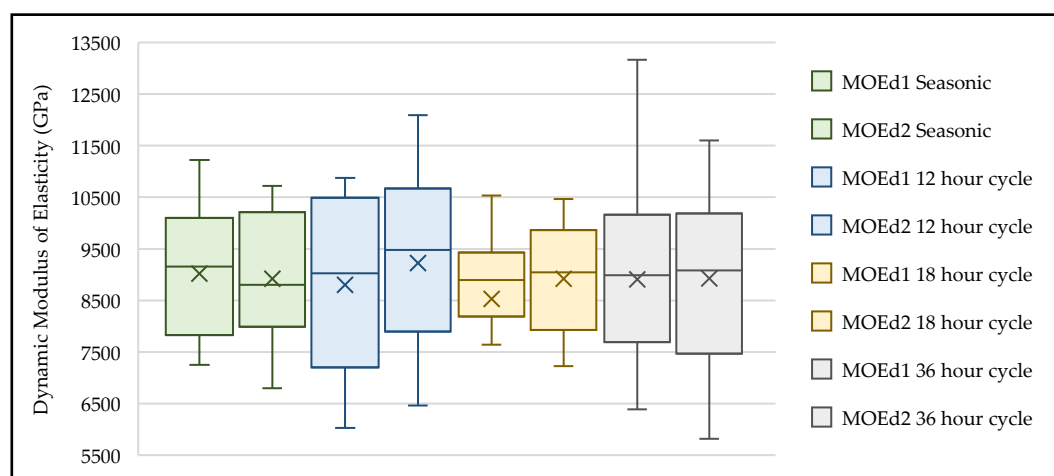
2. Effects of steaming treatment on the dimensional stability: **A)** Weight; **B)** Radial direction; **C)** Transversal direction; **D)** Tangential direction.

Priadi and Hiziroglu [31] found that control samples had higher swelling values compared to those exposed to temperature levels of 130°C and 200°C. For example, control samples of mahogany had an average swelling value of 2.5% as a result of 2 hours of water immersion. When such samples were immersed into the water for 2 hours after thermal treatment at a temperature of 130°C, this value was 2.0%. A similar trend was determined for samples of mindi, oak, and pine. Both mahogany and oak had overall lower swelling

values compared to those of mindi and pine. Pine control samples had an average swelling value of 6.5%, but this value was reduced to 4.4% when exposed to a temperature of 200°C for 8 hours. Mindi, mahogany, and oak samples had reduced swelling characteristics to two-thirds of the control samples when exposed to the above conditions. Volkmer et al. [44] found that the modification process affects swelling properties in the anatomical directions differently. They found no influence in the tangential direction (0.02%). However, they observed differential swelling degrees of treated samples in the radial and tangential directions. Swelling was lower by 17% and 10%, respectively, compared to untreated samples. Tiriyaki et al. [45] noted that the swelling and volumetric shrinkage of beech are greater compared to pine. The swelling and volumetric shrinkage of beech are 15.77% and 14.07%, respectively; while the corresponding values for pine are 9.04% and 8.25%. Regarding the influence of temperature and time of thermal treatment on swelling and volumetric shrinkage, they observed that both swelling and volumetric shrinkage decrease significantly in both tangential and radial directions. The reduction becomes greater with the increase in temperature and duration of the thermal treatment. In terms of volumetric swelling, the highest value was found to be 12.69% for pine samples and 18.97% for beech samples treated at 130°C for 2 hours. With thermal treatment applied at 190°C for 8 hours, the amount of volumetric swelling dropped to 4.37% for pine samples and 10.84% for beech samples. Corresponding volumetric shrinkage values were found to be 12.09% for pine samples and 16.52% for beech samples treated at a temperature of 130°C for 2 hours. Similarly to volumetric swelling, volumetric shrinkage values dropped to 3.84% and 9.73% for pine and beech samples after the thermal treatment applied at a temperature of 190°C for 8 hours, respectively. Overall, the results reported by the above-mentioned studies revealed that thermal treatment considerably reduces swelling and volumetric shrinkage.

### 3.3. Dynamic modulus of elasticity

Starting to evaluate the tests performed with the microsecond timer, we can deduce that the thermal treatment slightly increases the MOEd for the 12-hour, 18-hour, and 36-hour cycles by 4.57%, 4.39%, and 0.23%, respectively. For the control samples, a decrease of 1.08% was observed. Therefore, the thermal treatment has a positive effect. Figure 3 shows how the dynamic modulus of elasticity changes according to the duration of the steaming treatment.



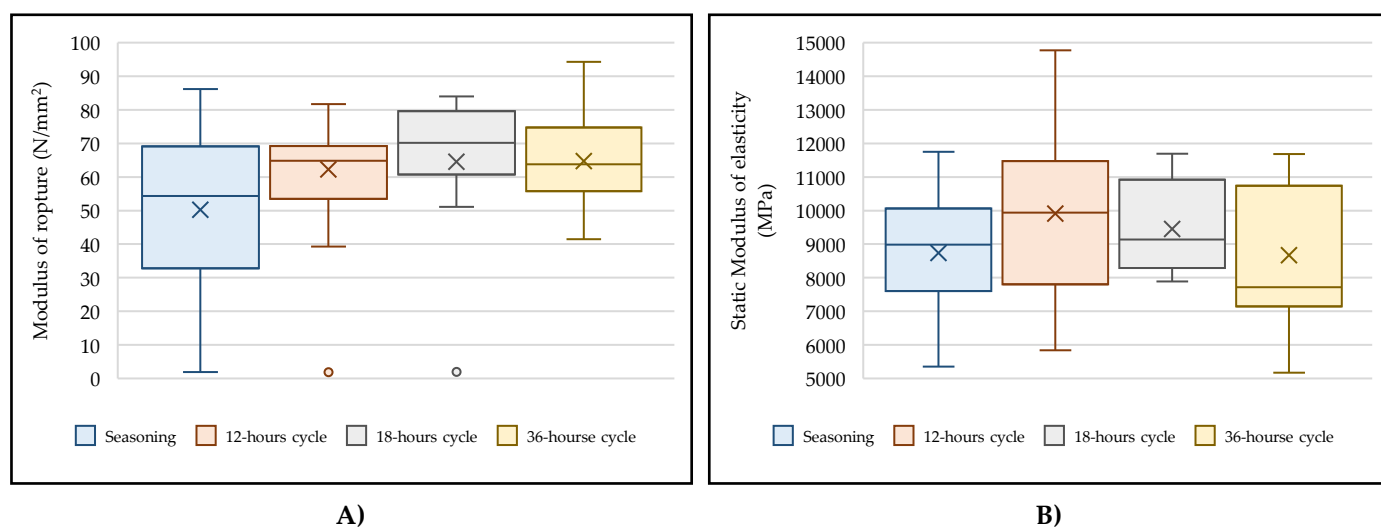
MOEd1 is the MOEd before treatment while MOEd2 is the dynamic MOEd after treatment.

Figure 3. Effects of steaming treatment on the Dynamic modulus of elasticity

Todaro et al. [46] found that the MOEd of black poplar wood samples was significantly higher for wood samples modified at 180°C than for those steamed at 220°C. Compared to the control samples (10.39 GPa), the MOEd increased by 9.71% (11.51 GPa) at 180°C and then decreased by 5.91% (9.78 GPa) at 220°C. Thus, the MOEd appears to increase after milder thermal modification of wood, while it decreases with strong modification temperatures. Cetera et al. [47] revealed that the MOEd of the turkey oak wood samples was 17.48 GPa for heartwood and 16.06 GPa for sapwood. Compared to the control samples, the MOEd decreased by 24.08% (13.27 GPa) for heartwood and 21.75% (12.57 GPa) for sapwood. The results show that even short durations (3 hours) at 160°C affect the mechanical performance of hardwoods.

### 3.4. Static modulus of elasticity and modulus of rupture

Bending tests showed that steaming treatment positively influenced MOR. As the steaming treatment duration increases, the MOR increases as well. The following values were found to be 50.21 N/mm<sup>2</sup> for the untreated samples, 62.24 N/mm<sup>2</sup> for the 12-hour cycle, 64.57 N/mm<sup>2</sup> for the 18-hour cycle, and 64.71 N/mm<sup>2</sup> for the 36-hour cycle. The medium-short cycles positively affect the MOEs, while the longer cycle negatively affects performance. Comparing the steaming treatment cycles with the untreated samples, we find an increase of 11.80% for the 12-hour cycle, an increase of 7.59% for the 18-hour cycle, a decrease of 0.81% for the 36-hour cycle. Figure 4 shows the effects of steaming treatment on the MOR and MOEs.



**Figure 4.** Effects of steaming treatment on the MOR (A) and the MOEs (B)

Boonstra et al. [37] found that a two-phase thermal treatment resulted in a small reduction (3%) in MOR. Scots pine showed an increase (10%) in MOE during bending tests. The thermal treatment of radiata pine at 165°C resulted in a decrease in MOR (9%) and an increase in MOE (13%). An increase in the effective treatment temperature to 185°C during the hydro thermolysis phase led to a further reduction in MOE (38%). There is a significant increase in MOE (26%) in radiata pine samples when the hydro thermolysis treatment temperature was increased to 175°C, followed by a subsequent decrease in MOE (-2%) in radiata pine samples when treated at 175°C and then at 185°C. An increase in the residence time during hydro thermolysis at 165°C (from 30 to 90 minutes) resulted in a further reduction (20%) in MOR. Although there is no difference in MOE between an effective treatment time of 60 and 90 minutes, the variation in test results of radiata pine samples treated for 90 minutes is greater than that of samples treated for 60 minutes, indicating some differences. The MOE seems to increase when the effective treatment duration increases to 90 minutes. Thermal treatment resulted in a decrease in MOR (31%), while MOE increased

after thermal treatment (5%). Kartal et al. [48] found that MOR in Japanese cedar decreases with increasing duration and temperature. At a temperature of 180°C, there is a reduction in MOR of 1.22% at 2 hours and 6.67% at 4 hours. Conversely, at a temperature of 220°C, there is a reduction of 58.28% at 2 hours and 77.60% at 4 hours. Regarding MOE, they found a loss of 2.18% and 12.17% respectively for the 2-hour and 4-hour cycles at 180°C. Gunduz et al. [49] conducted a study on wild pear, determining that the lowest decrease in MOR, 7.5%, compared to control samples, occurs at 160°C for 2 hours. The percentage decreases in MOR at 160°C for 2, 4, and 6 hours were 7.50%, 13.37%, and 21.40%, respectively. Furthermore, it was determined that MOE at 160°C for 2, 4, and 6 hours were 7060.05 N/mm<sup>2</sup>, 6869.26 N/mm<sup>2</sup>, and 6144.14 N/mm<sup>2</sup>, respectively. At 180°C for 2, 4, and 6 hours, the MOE values were determined to be 6645.96 N/mm<sup>2</sup>, 6545.86 N/mm<sup>2</sup>, and 5974.97 N/mm<sup>2</sup>, respectively. The highest decrease in MOR was 26.02% at 180°C for 6 hours compared to control samples. While MOR had a minimal decrease at 160°C for two treatment times, MOE in this treatment period showed a maximum increase. The increasing percentages were determined to be 4.9% at 160°C for 2 hours. The modulus of elasticity values for other treatment times and temperatures decreased. From the results obtained in the thermal treatment of wild pear wood at 160 and 180°C for different treatment times, it was found that the mechanical properties were affected in the range from 2.5% to 27%. Kamperidou [50] conducted tests on Scots pine and found that the values of MOR and MOE decrease with increasing duration of thermal treatment. The average MOR value of samples treated for 4 hours was 0.34% lower than the corresponding value of untreated wood samples, while samples treated for 6 and 8 hours recorded MOR values lower by 14.6% and 25.90%, respectively. The average MOE value of samples treated for 4 hours was 4.4% lower than the corresponding value of untreated samples, while the average MOE value of samples treated for 6 and 8 hours showed decreases of 3.5% and 5.83%, respectively. In general, the reduction in MOE was found to be less than that of MOR. In the study conducted by Gennari et al. [51], thermally treated wood showed a reduction in static bending strength from 61.1 to 37.6 MPa.

### 3.5. Compression strength and static hardness - Janka

Comparing the specimens subjected to treatment with the untreated ones, the medium-short cycle positively influences the compressive strength, in contrast to the longer cycle. Compared to the untreated specimens, the compressive strength increases by 1.02% and 2.54% for the 12-hour and 18-hour cycles, respectively. In contrast, it decreases by 3.05% for the 36-hour cycle. Figure 5 shows the effects of steaming treatment on the breaking load.

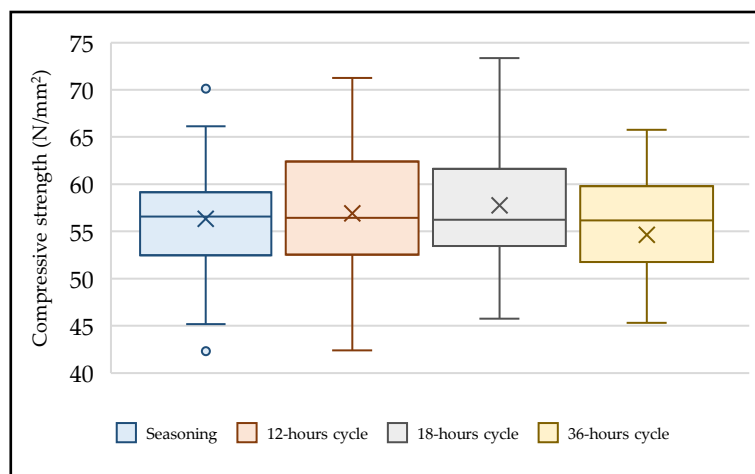


Figure 5. Effects of steaming treatment on the compressive strength

Boonstra et al. [36] found that compression strength parallel to the grain clearly increased after thermal treatment (28%). Romagnoli et al. [22] reported that thermal treatment negatively affected the performance of Douglas fir. Treated specimens showed a reduction in compression strength in both heartwood (7.64%) and sapwood (12.50%). Conversely, for Corsican Pine, an increase of 3.48% was observed. Gunduz et al. [49] conducted a study on the effect of thermal treatment on the compression strength of wild pear wood. They stated that as the treatment time increased from 2 hours to 6 hours at different temperatures, the compression strength decreased during the thermal treatment process. After thermal treatment, the compression strength was 47.25 N/mm<sup>2</sup> for 2 hours, 44.72 N/mm<sup>2</sup> for 4 hours, and 44.04 N/mm<sup>2</sup> for 6 hours at 160°C. At 180°C, the compression strength was 45.34 N/mm<sup>2</sup> for 2 hours, 42.62 N/mm<sup>2</sup> for 4 hours, and 41.48 N/mm<sup>2</sup> for 6 hours, compared to the control samples. The percentages of compression strength losses for 2, 4, and 6 hours were 7.42%, 12.38%, and 13.71% at 160°C, and 11.16%, 16.49%, and 18.73% at 180°C. Kamperidou [50] found that samples of all different treatment durations had slightly higher compression strength values compared to untreated wood samples. The average compression value of samples treated for 4 hours was 13.76% higher than untreated wood, while treatment for 6 and 8 hours resulted in compression strength increases of 6.09% and 4.88%, respectively. Gennari et al. [51] found that compression strength was reduced from 36.6 MPa in untreated wood to 34.2 MPa. Piernik et al. [43] also found a performance loss for Scots Pine. The average value found was 62.5 MPa, while in untreated wood it was 70.2 MPa. Furthermore, the duration of thermal treatment negatively affected the compression strength. Specifically, it decreased from approximately 64 MPa after one hour of treatment to approximately 55.7 MPa after eight hours.

Hardness tests showed that steaming treatment negatively affects the performance. Compared to the untreated specimens, there is a greater loss of resistance in the 18-hour cycle (-13.59%). Following is the 12-hour cycle (-7.40%) and 36-hour cycle (-5.08%). Figure 6 shows the effects of steaming treatment on Janka hardness.

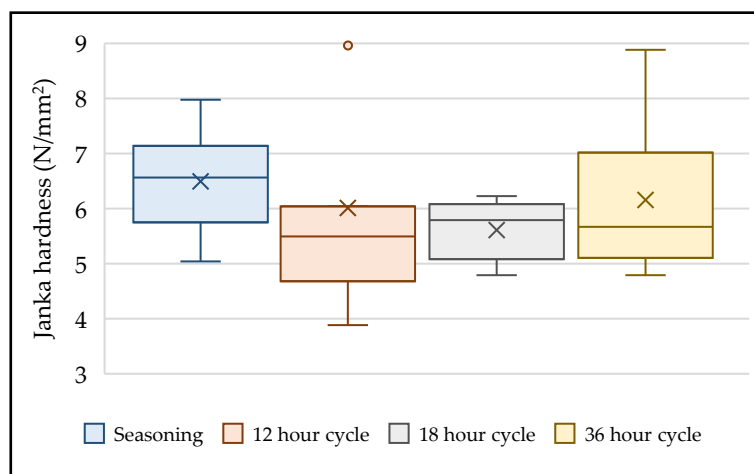


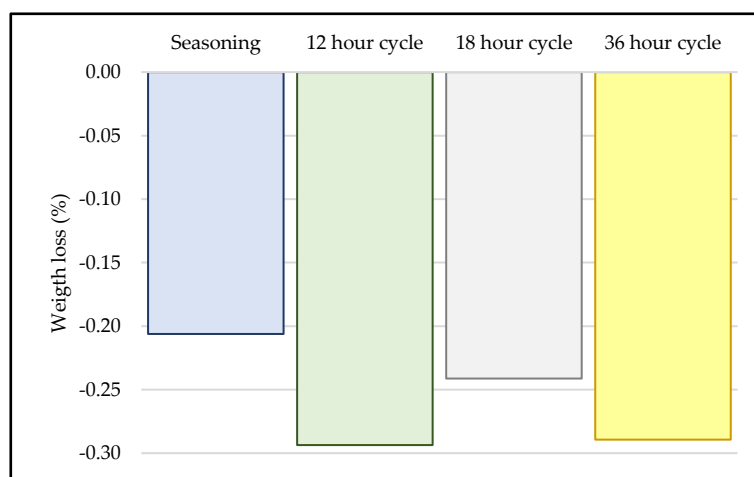
Figure 6. Effects of steaming treatment on the static hardness during the Janka test

Priadi and Hirioglu [31] found that the control samples of oak had the highest average hardness value among the four species studied. Mahogany and mindi followed oak in terms of characteristic hardness of the specimens. In the case of pine, no significant reduction in hardness was found. However, mindi, mahogany, and oak showed a significant reduction in hardness when exposed to a temperature of 200°C for 2 hours. The extent of the reduction was more evident with an increase in exposure time to 8 hours. Although oak had the highest hardness value for the control samples, the reduction in hardness for these samples was also greater compared to any other species considered. Oak

samples had a 42.7% reduction in their hardness values with exposure to 200°C for 8 hours, followed by reductions in mindi and mahogany of about 20.0% and 17.3%, respectively. In Kamperidou's study [50], the hardness values of treated specimens showed a decrease due to thermal treatment. In the first 4 hours of treatment, the hardness values recorded a sharp drop, while with increasing duration, the hardness values showed a slight increase, without reaching the resistance level of the control specimens. The average hardness value in the tangential direction of samples treated for 4 hours was measured to be 25.13% lower than that of untreated wood, while treatment for 6 and 8 hours resulted in lighter decreases of 24.73% and 9.34%, respectively. This trend in hardness values was similar for both the tangential and radial directions of the specimens. Salca and Hiziroglu [52] conducted tests on four different species. When exposed to a temperature of 120°C for 3 hours, the red oak samples recorded an average hardness value 18.7% lower than before thermal treatment. However, the average hardness value of the same species exposed to a temperature of 190°C for 6 hours was 41.7% lower than that recorded before thermal treatment. The extent of hardness reduction in the samples was more evident with an increase in exposure time to 6 hours. In the case of black alder samples, a slow decrease in hardness values was determined with increasing temperature and exposure time. The highest difference recorded for black alder in terms of hardness value compared to untreated samples was about 4.3% at a temperature level of 120°C applied for a time of 6 hours. The temperature of 190°C reduced the hardness values of these samples by 7.9% with an increase in exposure time from 3 hours to 6 hours. Little significant differences were found between the samples of southern pine and yellow poplar before and after thermal treatment in terms of hardness values, which could be related to their low density. Although red oak had the highest hardness values before thermal treatment, the reduction in these samples was also greater compared to other wood species.

### 3.6. Abrasion resistance

Both the treated and untreated cycles show similar abrasion resistance during the experiment. Figure 7 shows the effects of steaming treatment on abrasion.



**Figure 7.** Effects of steaming treatment on abrasion

Jirous-Rajković et al. [53] found the highest weight loss in untreated specimens (2.02%). For the 190°C cycle, there was a weight loss of 1.69% and 1.80% for the 1-hour and 2-hour cycles, respectively. Finally, for the 212°C cycle of 1 hour and 2 hours, they found the same weight loss, equal to 1.82%. Kol et al. [54] demonstrated that after the abrasion test, thermal treatment induced greater weight losses in wood materials, and higher thermal treatment temperatures caused greater weight losses in the samples. It is

stated that the minimum weight losses (0.28%) from abrasion in spruce wood were in the control samples, while the maximum weight losses (0.52%) were in samples treated at a treatment temperature of 212°C. Similarly, for beech wood, the results were similar. The maximum weight losses from abrasion (0.44%) occurred in samples treated at 212°C, and the minimum weight losses from abrasion (0.07%) were in the control samples.

### 3.7. Data analysis

Multivariate analysis showed that the different duration of steaming treatment significantly influenced some dependent variables (Table 3). Tukey's test showed that the color variation of heartwood and sapwood varied, as did the abrasion weight loss (Table 4). The color variation of duramen was found to be significantly between the 36-hour cycle and the witnesses. The change in sapwood color was found to be significantly affected by all durations of steaming treatment compared to the control, and also between 12 and 18 h and between 18 and 36 h, the change in sapwood color was statistically different. The abrasion weight loss was only significantly different between the control wood and the wood that had undergone a 12-hour steaming treatment.

Table 3. Multivariate analysis

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Series	MST_MOEd <sub>2</sub>	251500.130	3	83833.377	0.122	0.946
	ΔE_heartwood	129.999	3	43.333	4.531	0.014
	ΔE_sapwood	554.908	3	184.969	28.655	0.000
	MOEs	16238686.355	3	5412895.452	2.197	0.120
	MOR	84.310	3	28.103	1.917	0.159
	H	4.274	3	1.425	2.617	0.079
	WL	0.029	3	0.010	3.721	0.028

MST\_MOEd<sub>2</sub> = dynamic modulus of elasticity post treatment; ΔE\_heartwood = total color variation of heartwood; ΔE\_sapwood = total color variation of sapwood; MOEs = static modulus of elasticity; MOR = modulus of rupture; WL = weight loss due to abrasion

Table 4. Tukey test

Dependent Variable	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval		
				Lower Bound	Upper Bound	
ΔE_heartwood	12	-4.077	1.785	0.136	-9.074	0.921
	0	-4.875	1.785	0.057	-9.872	0.122
	36	-6.2483*	1.785	0.011	-11.246	-1.251
	0	4.077	1.785	0.136	-0.921	9.074
	12	-0.798	1.785	0.969	-5.796	4.199
	36	-2.172	1.785	0.624	-7.169	2.826
	0	4.875	1.785	0.057	-0.122	9,872
	18	0.798	1.785	0.969	-4.199	5.796
	36	-1.373	1.785	0.867	-6.371	3.624
	0	6.2483*	1.785	0.011	1.251	11.246
	36	2.172	1.785	0.624	-2.826	7.169
	18	1.373	1.785	0.867	-3.624	6.371

<b>ΔE<sub>sapwood</sub></b>	<b>0</b>	<b>12</b>	-10.4517*	1.467	0.000	-14.557	-6.346
		<b>18</b>	-5.3550*	1.467	0.008	-9.461	-1.249
		<b>36</b>	-12.3733*	1.467	0.000	-16.479	-8.268
	<b>12</b>	<b>0</b>	10.4517*	1.467	0.000	6.346	14.557
		<b>18</b>	5.0967*	1.467	0.012	0.991	9.202
		<b>36</b>	-1.9217	1.467	0.567	-6.027	2.184
	<b>18</b>	<b>0</b>	5.3550*	1.467	0.008	1.249	9.461
		<b>12</b>	-5.0967*	1.467	0.012	-9.202	-0.991
		<b>36</b>	-7.0183*	1.467	0.001	-11.124	-2.913
	<b>36</b>	<b>0</b>	12.3733*	1.467	0.000	8.268	16.479
		<b>12</b>	1.9217	1.467	0.567	-2.184	6.027
		<b>18</b>	7.0183*	1.467	0.001	2.913	11.124
<b>WL</b>	<b>0</b>	<b>12</b>	.0875*	0.029	0.033	0.006	0.169
		<b>18</b>	0.0375	0.029	0.584	-0.044	0.119
		<b>36</b>	0.0765	0.029	0.072	-0.005	0.158
	<b>12</b>	<b>0</b>	-.0875*	0.029	0.033	-0.169	-0.006
		<b>18</b>	-0.0501	0.029	0.343	-0.132	0.032
		<b>36</b>	-0.0110	0.029	0.981	-0.093	0.071
	<b>18</b>	<b>0</b>	-0.0375	0.029	0.584	-0.119	0.044
		<b>12</b>	0.0501	0.029	0.343	-0.032	0.132
		<b>36</b>	0.0390	0.029	0.552	-0.043	0.121
	<b>36</b>	<b>0</b>	-0.0765	0.029	0.072	-0.158	0.005
		<b>12</b>	0.0110	0.029	0.981	-0.071	0.093
		<b>18</b>	-0.0390	0.029	0.552	-0.121	0.043

ΔE<sub>heartwood</sub> = total colour variation of heartwood; ΔE<sub>sapwood</sub> = total colour variation of sapwood; WL = weight loss due to abrasion

### 5. Conclusions

This work presents the results of analyses regarding the physical-mechanical properties of olive wood, which was subjected to thermal treatment at a temperature of 80°C for durations of 12, 18, and 36 hours. During the swelling tests, desorption, and consequently shrinkage, were observed. Additionally, there was a weight loss. The experimental results demonstrated that the thermal treatment reduced the amount of volumetric shrinkage of the wood in the three anatomical directions and weight loss. The results from the abrasion tests showed that the thermal treatment did not affect the resistance. The bending tests revealed that the medium-short cycles (12 and 18 hours) of the thermal treatment increased the bending resistance and the static elastic modulus. However, with the increase in the duration of the thermal treatment, there was a decrease in maximum load resistance. An increase in breaking load resistance was observed for the medium-short cycles, with a decrease for the 36-hour cycle. Finally, the thermal treatment negatively affected the hardness resistance. The results of this study have revealed that thermal treatment can add potential value to olive wood, making it more effectively usable in the production of indoor products (flooring, furniture, etc.). Moreover, the results of this study contribute to a better understanding of the potential use of this species, which has been increasingly gaining traction in the market in recent years.

**Author Contributions:** Conceptualisation, A.R.P. and L.T.; methodology, A.R.P. and L.T.; validation, A.R.P. and L.T.; formal analysis, A.M. and L.T.; resources, A.R.P. and L.T.; data curation, A.M., S.P. and A.R.P.; writing—original draft preparation, A.Z., A.M.; A.R.P. and L.T.; writing—review and editing, A.Z., A.M.; A.R.P. and L.T.; project administration, A.R.P.; funding acquisition, A.R.P. All authors have read and agreed to the published version of the manuscript.

**Data Availability Statement:** The data are available upon request to Angelo Mammoliti.

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## 4.5. Sawing yields evaluation

### Article 6

#### Estimating hardwood sawmill conversion efficiency based on log characteristics

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## Estimating hardwood sawmill conversion efficiency based on log characteristics --Manuscript Draft--

<b>Manuscript Number:</b>	
<b>Full Title:</b>	Estimating hardwood sawmill conversion efficiency based on log characteristics
<b>Article Type:</b>	Research Paper
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<b>Abstract:</b>	In the international wood supply chain, quantitative analyses of outputs are essential to precisely evaluate the productivity and economic potential of the industry. In order to benefit wood-base product production and to minimize the environmental impact associated with low yields of sawmills, two parameters are indispensable: the lumber yield and the quality of the logs. The aims of this study were to analyze the wood quality and sawn yield from different hardwood logs collected in South Italy. Over two hundred logs were evaluated for lumber yield, assessing the role of wood defects in the sawmill conversion efficiency. The evaluation of the performance of the sawing process was performed via the determination of yield with respect to taper, ovality, sweep, and fluting defects. The results show that for taper and fluting defects, the distribution among the diameter classes of the logs was found to increase as the diameters increased, while that the sweep and ovality defects tend to be less marked in logs with large diameters. The mean yield values observed for all three species, in fact, were influenced by some defects. Still, the results of this research suggest that, despite the olive, black locust and chestnut species being less commonly studied, they offer competitive yield potential that reinforces their suitability for commercial sawing applications.
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<b>Author Comments:</b>	Dear Publication Office,  Thank you for considering our manuscript. This study addresses an underexplored area of hardwood sawmill efficiency and contributes to the literature by analyzing Mediterranean species, such as olive, black locust, and chestnut, which are increasingly relevant in sustainable wood processing. We believe this work aligns well with the journal's focus on forestry science and wood technology.  Should you require any additional information or documentation, please do not hesitate to contact us.

	Kind regards, Salvatore Francesco Papandrea
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<b>Question</b>	<b>Response</b>

Dear Editor,

We are pleased to submit the manuscript entitled “*Estimating hardwood sawmill conversion efficiency based on log characteristics*” for possible publication in the esteemed *Annals of Forest Science*.

The growing global focus on sustainable production systems and waste reduction has driven our research to prioritize the efficient use of wood resources. As a renewable material, wood plays a pivotal role in fostering social and economic development, particularly in rural contexts. While significant advancements have been made in managing sawmill waste, primarily for energy production, minimizing its generation remains a critical objective for sawmills, especially when processing wood species with limited availability. Our study aligns with these goals, aiming to optimize resource utilization and improve conversion efficiency in sawmills.

We were particularly inspired by the research published in your journal, especially the work of Riesco Muñoz et al. (2013), titled “Variation in log quality and prediction of sawing yield in oak wood (*Quercus robur*).” Their study not only underscored the importance of raw material quality in determining sawing yield but also provided a robust foundation for modeling conversion efficiency based on log characteristics. Similarly, our research expands on this concept by exploring Mediterranean hardwood species, including olive, black locust, and chestnut, which are underrepresented in the literature. By applying comparable methodologies, we demonstrate the critical role of log defects and diameter classes in influencing sawing yields, thus contributing to a broader understanding of hardwood processing in diverse contexts.

The *Annals of Forest Science* has a strong tradition of publishing significant advancements in wood technology. However, in recent years, there has been limited focus on studies addressing sawing yields and the development of predictive models for yield efficiency. Our work seeks to fill this gap, topic has not been extensively studied in the literature. In Southern Italy, mediterranean wood is increasingly being valued for high-end applications such as parquet and interior finishes, which are in high demand in both international markets and the Italian construction sector.

Given the limited research available on the sawing efficiency of the species we analyzed and the close alignment of our study with previously published works in your journal, we believe this



manuscript will be of considerable interest to your international readership. It not only addresses a gap in the literature but also offers practical insights for improving hardwood utilization, aligning with the growing demand for sustainable and efficient resource management.

This work is original, has not been published elsewhere, and is not under consideration for publication in any other journal. We thank you for considering our submission and hope it meets the high standards of Annals of Forest Science. We are confident that this manuscript will contribute meaningfully to the ongoing discussions on sustainable wood resource management and sawmill efficiency.

Thank you for your time and consideration.

Reggio Calabria, 03/12/2024

Best regards

The Authors

# Estimating hardwood sawmill conversion efficiency based on log characteristics

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**Keywords:** lumber yield, defects, sawn timber, wood resources, live sawing

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## Author contributions

Conceptualization: [Maria Francesca Cataldo, Andrea Rosario Proto, Salvatore Francesco Papandrea]; methodology: [Maria Francesca Cataldo, Angelo Mammoliti, Andrea Rosario Proto, Salvatore Francesco Papandrea]; validation: [Andrea Rosario Proto]; formal analysis: [Maria Francesca Cataldo, Andrea Rosario Proto, Salvatore Francesco Papandrea]; investigation: [Angelo Mammoliti, Andrea Rosario Proto]; resources: [Andrea Rosario Proto]; data curation: [Maria Francesca Cataldo, Angelo Mammoliti, Andrea Rosario Proto, Salvatore Francesco Papandrea]; writing—original draft preparation: [Maria Francesca Cataldo, Andrea Rosario Proto, Salvatore Francesco Papandrea]; writing—review and editing: [Maria Francesca Cataldo, Andrea Rosario Proto, Salvatore Francesco Papandrea]; visualization: [Maria Francesca Cataldo, Andrea Rosario Proto]; supervision: [Angelo Mammoliti, Andrea Rosario Proto]; project administration: [Andrea Rosario Proto]; funding acquisition: [Andrea Rosario Proto]. All authors have read and agreed to the published version of the manuscript.

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# Estimating hardwood sawmill conversion efficiency based on log characteristics

## **Key message**

This study assessed sawmill efficiency for olive, black locust, and chestnut logs in Southern Italy. Defects like taper, ovality, sweep, and fluting were analyzed for their impact on lumber yield. Taper was the most significant defect, especially for olive and chestnut logs. Black locust showed stable yields (70%), highlighting its commercial potential. The findings emphasize the importance of selecting high-quality raw materials and optimizing cutting techniques to reduce waste and enhance the economic value of Mediterranean hardwoods.

## **Abstract**

### **Context:**

The international wood supply chain requires precise evaluations of productivity and economic potential. Hardwood sawmills play a critical role in producing sawn timber, yet their efficiency is affected by the quality of raw materials and inherent defects in logs. Optimizing yield can reduce waste and support sustainable forestry practices.

### **Aims:**

This study aimed to evaluate the quality and yield of hardwood sawn timber from olive, black locust, and chestnut logs sourced from Southern Italy. Specifically, it investigated the impact of log defects on sawmill conversion efficiency across different diameter classes.

### **Methods:**

Over 200 logs were analyzed for sawing yield using a vertical band saw. Defects such as taper, ovality, sweep, and fluting were measured and statistically assessed. Yield was calculated as the ratio of sawn product weight to raw log weight.

### **Results:**

Taper significantly reduced yield, particularly in olive and chestnut logs. Black locust and chestnut maintained stable yields (70%), demonstrating strong commercial potential. Olive logs showed competitive yields in larger diameter classes, despite their irregular shapes.

### **Conclusion:**

These findings emphasize the importance of log quality and highlight the need for optimized cutting techniques to enhance efficiency and sustainability in hardwood processing. Mediterranean hardwoods offer viable options for commercial applications

**Keywords:** lumber yield, defects, sawn timber, wood resources, live sawing

## **1. Introduction**

Managed forests and products derived from these play an essential role in mitigating climate change by reducing greenhouse gas emissions and contribute to environment-friendly economic growth (EOS, 2021; Stragliotto et al., 2023), representing a load-bearing pillar in social and economic development in many rural contexts. Sawmills make and market products with a small carbon footprint from raw materials procured from forests that capture and sequester large quantities of carbon, replacing other materials that generate large volumes of greenhouse gases. For this reason, raw materials remain a key area of focus for softwood and hardwood producers alike, and in the last few years, the value of the product “wood” has been increasingly recognized. In Europe, there is enormous demand for logs to be used for sawing, veneer, and other solid wood applications, and recent data from the European Sawmill Organisation (EOS) indicate that sawn consumption in Europe in 2022 reached slightly over 110 million m<sup>3</sup> (90% softwood and 10% hardwood), increasing the value compared to the previous 6 years (FAO, 2022). In particular, sawmills play a crucial function in efficiently producing sawn wood in order to maintain their share of the total market. Hence, modern sawmills tend to prioritize the speed and production volume of sawn logs, instead of the volume and value yield, i.e., the ratio between the total log volume and the volume of produced boards. It is interesting to note that the categorization of European sawmills into small-, medium- and large-scale mills does not imply market differentiation. In fact, both medium and large sawmills and small sawmills process wood products for both domestic needs and export. The only difference is that medium and large mills have adequate capital for investment in higher-end production processes, and can utilize scarce resources efficiently (Faruwa et al., 2017). In this context, several studies have identified a determinant of competitiveness in sawmills as the efficiency of production; the smaller these plants are, the higher this index should be. In order to valorize such a renewable but always precious resource as wood, it is crucial to examine the relationship between the raw material’s quality and the yield of sawed wood production. For this reason, most sawmill managers have a reasonably good knowledge of the lengths, diameters, and tapers of

logs processed in their mills, and this experience permits them to achieve good processing performance. The characteristics of logs vary widely within species, harvest sites, and even the same tree. However, in small and medium sawmills, lumber can be of random lengths and widths and contain randomly dispersed defects of various severities (Buehlmann and Thomas, 2001). Yield is defined as the ratio of the amount of primary product output to the amount of raw material input, expressed as a percentage (Mitchell et al., 2005; Stragliotto et al., 2023). A large number of factors affect the volume of lumber obtained from any given log by the sawing process (Hallock, 1976). These factors are sometimes recognized as defects that are present in all wood species. For this reason, the quality of logs entering the production line is important because it determines the quality and lumber yield that can be obtained (Borz et al., 2021; Musat et al., 2017; Papandrea et al., 2022; Wiedenbeck et al., 2003). Sawmill productivity studies have a long tradition. Freese (1973) defined and compared different log rules to estimate net yield for logs of a given diameter and length. Hallock and Lewis (1976) employed the Best Open Face (BOF) program to compare the potential yields of five different sawing methods and to obtain an increasing percentage of cuts from sawn logs. Steele (1984) identified and discussed in detail seven factors influencing lumber yield; knowing these variables can elucidate the factors affecting a specific mill. Carpenter et al. (1989) determined that holes, knots, wounds, and other growth defects on logs reduce the strength and appearance of any products, reducing the value of the log and its products. Feuillat and Keller (1997) considered as influential factors the overall conditions of the timber stand, the site, the soil type, the tree geometry and form, and the growth rate. Doussot et al. (2002) identified a combination of similar factors that affect the product quality, and Buehlmann and Thomas (2001) proposed the necessity of distinguishing between lumber types of lower quality (boards with many and/or large defects) and higher quality (i.e., boards with few or no defects), starting from sawn log grades. In fact, quality classes can be applied, starting from the raw material, to assess the impacts of individual defects on the quality of produced assortments. Silva et al. (2014) classified hardwood logs into three classes according to general shape, visible defects, and abnormalities to determine lumber yield, and Afrifah and Frimpong-Mensah (2014) used a similar approach to maximize timber product yield from the limited logs currently available in Ghana. Recently, Wang et al. (2018) showed that the location, type, and size of defects in hardwood logs dictate the potential grade and value of the resulting lumber. For this reason, the influence of several defects has been studied and, in many cases, external and internal defects have been assessed for their effects on lumber yield. In fact, internal defects such as cracks, pith eccentricity, knots, etc., are not easy to detect on piled logs, and only external defects (sweep, ovality, etc.) can be quickly evaluated on the log before sawing using a measuring tape and a caliper. For example, Nassur et al. (2013) evaluated the taper coefficient, while Vital (2008) and Luz et al. (2021) calculated the effects of sweep on sawn timber yield. Riesco Muñoz et al. (2013) graded 46 oak trees into four quality grades basing on log dimensions and visible defects to determine the prediction of sawing yield. Ištvančić et al. (2011) researched the lumber yield of European walnut and European wild cherry logs in Croatia by measuring internal defects, and Karaszewski et al. (2013) scrutinized wood defects impacting the quality of beech logs, taking into consideration eleven defects. Recently, Melo et al. (2019) evaluated the sawn yields of four native species from the Amazon Region considering log diameter; Rozas et al. (2023) estimated the yield of *Eucalyptus regnans* logs for lumber production, measuring the length and the width of radial cracks. Stragliotto et al. (2023) assessed log quality derived from Amazonian species, and evaluated the lumber yield for the export of five Brazilian species. The importance of optimizing the sawing yield is justified via the desire to reduce waste in sawmills; in fact, several studies have estimated that total production costs could be reduced by 2% for every additional 1% of input lumber used (i.e., an increase in yield of 1%) (Buehlmann and Thomas, 2001; Kline et al., 1998; Wengert et al., 1994). Therefore, it is necessary to gather technical information regarding the yield, such as that on wood waste generation, to maximize the volume of lumber produced. For these reasons, the aims of the present work have been (i) to analyze the distribution of defects on logs of different species and different diameter classes, (ii) to highlight the impacts of the defects on the conversion efficiency (sawing yield) obtained during the sawing phase of three different wood species in a medium-sized sawmill, and (iii) to predict sawing yield from defective logs of different diameter classes.

## 2. Material and Methods

### 2.1 Study site and Log sampling

This study was conducted on logs of three different hardwood species—olive tree (*Olea europaea* L.), black locust (*Robinia pseudoacacia* L.), and chestnut (*Castanea sativa* Mill.)—from forests and agricultural sites located in the Calabrian region (South Italy).

In order to avoid possible variations due to the use of different milling machines, as well as the operator's skill and experience, the tests were conducted in only one sawmill (Riesco Muñoz et al., 2013), considered a representative medium-sized sawmill in Southern Italy, as the average processed volume of a general sawmill is estimated to be

5,000 m<sup>3</sup>y<sup>-1</sup> (Giametta G., 2008; Proto et al., 2012). This industrial sawmill is located in the municipality of Molochio (38° 19' 5.423" N -16° 1' 26.526" E, Reggio Calabria, Italy) and produces mainly flooring strips and laths.

This study has focused on the first step of the sawmill process, wherein a vertical log band saw (SNT 1300 model, Bongioanni company, 75 kW) with 1.38 mm blade thickness converts logs into boards. Furthermore, to eliminate the possibility of yield variance in the sawing process, the sawing pattern was here predefined, and all logs were sawn into boards using the live sawing method, adapted in terms of thickness to the log dimension and the sawmill production objective. Live sawing is a fast method of breaking down the log that involves longitudinal cuts parallel to the axis of the log, and parallel to each other (Ištvanic et al., 2011; Pinto et al., 2006; Popadić et al., 2014; Stängle et al., 2015; Steele et al., 1993).

Considering the availability of logs in the sawmill during this study, for each species, a minimum of 30 sample logs was selected: 30 chestnut logs, 120 olive tree logs, and 60 black locust logs. In the specific case of olive logs, the samples were obtained from the largest branches derived from extraordinary pruning activities (Mammoliti et al., 2024) and from stem logs (excluding logs that presented with holes inside). The logs were measured in terms of length and outside bark diameter, and then sorted into four main diameter classes: A (20-30 cm), B (30.1-40 cm), C (40.1-50 cm) and D (50.1-90 cm). At the end of the phase of sawing into boards, the moisture content of each sawn sample was determined using a digital moisture meter with two electrodes (Schaller, WLW). Diameter, length, volume, moisture content, and weight measurements were carried out on the logs selected for this study, and these data are summarized in Table 1, classifying olive, black locust, and chestnut logs into different diameter classes considering the average diameter of each log. In the case of the conspicuous number of olive logs, these were further divided into nine diameter subclasses (Table 1).

Table 1. Sawn logs' characteristics and their distribution in diametral classes (wood logs).

Species	Diameter class code	Subclass code	Diameter subclass (cm)	Number logs	Length (m)	Volume (m <sup>3</sup> )	Moisture content (%)	Weight (kg)
Olive	A (20-30 cm)	A1	20 – 25	14	2.50	0.07 (± 0.02)	30	85 (± 20)
		A2	25.1 – 30	16	2.50	0.12 (± 0.03)	30	135 (± 35)
	B (30.1-40 cm)	B1	30.1 – 35	12	2.50	0.16 (± 0.04)	40	186 (± 48)
		B2	35.1 – 40	19	2.50	0.24 (± 0.06)	40	274 (± 64)
	C (40.1-50 cm)	C1	41 – 45	16	2.50	0.30 (± 0.09)	40	340 (± 106)
		C2	45.1 – 50	13	2.50	0.37 (± 0.10)	40	420 (± 116)
	D (50.1-90 cm)	D1	50.1 – 60	19	2.50	0.48 (± 0.14)	40	554 (± 163)
		D2	60.1 – 70	5	2.50	0.54 (± 0.08)	40	616 (± 96)
		D3	70.1 – 90	6	2.50	0.80 (± 0.29)	40	919 (± 335)
Black locust	A (20 - 30 cm)	-	-	30	2.50	0.13 (± 0.23)	35	104 (±42)
	B (30.1-40 cm)	-	-	30	2.50	0.23 (± 0.04)	40	184 (±59)
Chestnut	A (20-30 cm)	-	-	30	2.50	0.14 (± 0.03)	40	93 (± 22)

## 2.2 Data Collection and Statistical Analysis

Usually, the sawing yield is calculated as the relationship between the volume of products and the volume of logs (Ištvanic et al., 2019; Li et al., 2015; Melo et al., 2019). Taking into account the possibility of having logs characterized by irregular shapes that do not favor a precise volume measure, and to guarantee a single objective measurement that is not affected by operators (Guttenberg S., 1960), in this study, the determination of the yield of sawed wood was based on the weights of logs and products, considering the following relationship:

$$\text{Sawing yield} = \frac{W_p}{W_l} * 100$$

Here, the following pertains:

Sawing yield = Percent yield of sawn log (%);

W<sub>p</sub> = Weight of products (kg);

W<sub>l</sub> = Weight of log (kg).

Operatively, the logs were first weighted using a digital floor weighing scale (Model SPF, Range 6,000 kg x 2 kg). Then, each log was individually processed into boards during the primary sawmill process. The sawn boards were grouped by log, and each one was weighed using a portable digital floor weighing scale (Model Radwag, Range 60

kg x 0.02 kg). For olive species, the average board thickness was 33 mm (between 15 to 85 mm), with the greatest number of boards (almost 310 boards) being 22 mm thick. Black locust boards were on average 27 mm (between 17 to 32 mm) thick, and chestnut boards were always 27 mm thick. The lengths of the boards were set as 2.50 m, and since the boards were not edged, width oversize was not calculated. The European standard EN 844 (2019) was employed to define the terminology adopted in this study concerning roundwood and sawn wood. Four wood defects were monitored in the logs: taper, ovality, sweep, and fluting. Table 2 shows the criteria for measuring the log defects analyzed. Taper was measured as the difference between large-end diameter ( $D_1$ ) and small-end diameter ( $D_2$ ), divided by log length. Sweep was measured, identifying the maximum deviation of the center line of the log from a straight line between the two ends, divided by the log length ( $L$ ). Fluting, defined as the longitudinal depression on the log, was calculated as a percentage of the length of the deeper groove ( $d$ ) divided by the log diameter ( $D$ ). Ovality was calculated based on both the lengths of the major ( $D_1$ ) and minor ( $D_2$ ) axes at the end of the log with the largest diameter. The difference, as a percentage, was divided by the thick-end diameter.

Table 2. Parameters evaluated for sawn yield.

Defects	Equipment	Parameters	Unit	Formulas
Taper	Measurement tape, caliper	Length ( $L$ )		
		Thick-end diameter ( $D_1$ )	cm/m	$T = \frac{(D_1 - D_2)}{L}$
		Thin-end diameter ( $D_2$ )		
Fluting	Measurement tape, caliper	Diameter ( $D$ )		$F = \frac{d}{D_1} * 100$
		Depth ( $d$ )	%	
Sweep	Measurement tape, caliper	Length ( $L$ )		$S = \frac{s}{L}$
		Arrow deflection ( $a$ )	cm/m	
Ovality	Caliper	Thick-end diameter ( $D_1$ )		$O = \frac{(D_1 - D_2)}{D_1} * 100$
		Thin-end diameter ( $D_2$ )	%	

The data collected have been statistically analysed; we performed descriptive statistics and linear regression analysis with a stepwise method to investigate if the parameters of taper, fluting, sweep and ovality were significantly responsible for the sawmill yield, applying a significance level of 0.05. In addition, the log volume and mean diameter were included in the statistical analyses to investigate, with a broader view, whether dimensional parameters can also influence sawing yield. Length was not included in the analyses, as it was fixed at 2.5 m. The statistical analysis of the data was performed using the SPSS software version 20.0 (IBM Corp., Armonk, NY, USA).

### 3. Results

The investigated defects were detected in logs with different percentages of presence (Table 3). Regarding olive logs, we found that a taper defect was always present in all classes and subclasses studied, except for the A1-diameter class (20–25 cm), where 29.6% of logs belonging to this subclass were free of taper defects. The fluting defect was observed to increase with the increase in diameter, starting from about 10% of defect presence in the A class to 95% in the D class. An opposite trend was seen for the sweep defect, which tended to decrease with the increase in diameter class. The ovality defect did not appear to be influenced by the diameter. From the investigation of defects on the logs of black locust, we found that all the logs showed a taper defect. Each log of the diameter class A (20-30 cm) exhibited ovality, and none had a fluting defect. Only 20% of the logs had sweep defects. Concerning diameter class B (30.1-40 cm), about 30% presented fluting and/or sweep defects, and almost all logs showed ovality. For the study concerning chestnut sawing yield, unfortunately we only had one diameter class available (diameter class A). Taper and ovality were the defects that were most present on the 30 chestnut logs (about 100%), with 33% of logs showing sweep defects and no logs showing a fluting defect. The distribution of the defects for the olive logs is shown in Table 4; in detail, we can see how many types of defects simultaneously affected the logs, distinguished by diameter classification. A1 was the only diameter subclass free of defects,

representing 7.1% of the logs. The higher concentrations of defects detected at the same time on the same log were identified in the D3 and C1 subclasses, with 80% of logs examined in the D3 subclass having three types of defects, and about 31% of the logs investigated in the C1 subclass having four types of defects. Concerning the simultaneous presence of more than one singular defect in black locust logs, both diameter classes (A and B) showed that no log was without defects or had only one defect; 80% of logs in diameter class A were affected by two defects, and 20% were affected by three defects at the same time, while no log showed four defects. The diameter class B contained 63%, 20% and 17% of logs with two, three and four defects simultaneously. All the chestnut logs were affected by at least one defect (one log), two defects (19 logs) or three defects (10 logs) at the same time (Table 4).

Table 3. Logs affected by defects distinguished by species and diameter classes.

	Logs				Taper defect	Fluting defect	Sweep defect	Ovality defect
	Diameter class code	Subclass code	Diameter (cm)	Tot. logs	Logs (%)	Logs (%)	Logs (%)	Logs (%)
Olive	A (20-30 cm)	A1	20 – 25	14	71.40%	14.30%	50.00%	71.40%
		A2	25.1 – 30	16	100.00%	6.30%	68.80%	93.80%
	B (30.1-40 cm)	B1	30.1 – 35	12	100.00%	25.00%	75.00%	91.70%
		B2	35.1 – 40	19	100.00%	36.80%	57.90%	89.50%
	C (40.1-50 cm)	C1	40.1 – 45	16	100.00%	75.00%	43.80%	68.80%
		C2	45.1 – 50	13	100.00%	84.60%	30.80%	84.60%
	D (50.1-90 cm)	D1	50.1 – 60	19	100.00%	84.20%	31.60%	94.70%
		D2	60.1 – 70	5	100.00%	100.00%	20.00%	80.00%
D3		70.1 – 90	6	100.00%	100.00%	17.00%	83.00%	
Black Locust	A (20 - 30 cm)	-	20 – 30	30	100.00%	0.00%	20.00%	100.00%
	B (30.1-40 cm)	-	30.1 – 40	30	100.00%	30.00%	33.00%	90.00%
Chestnut	A (20-30 cm)	-	20 – 30	30	100.00%	0.00%	33.00%	97.00%

Table 4. Logs affected by different defects simultaneously, distinguished into species and diameter classes.

	Logs				Defect free	1 defect	2 defects	3 defects	4 defects
	Diameter class code	Subclass code	Diameter (cm)	Tot. logs	Logs (%)	Logs (%)	Logs (%)	Logs (%)	Logs (%)
Olive	A (20-30 cm)	A1	20 – 25	14	7.10%	14.30%	42.90%	35.70%	0.00%
		A2	25.1 – 30	16	0.00%	6.30%	18.80%	75.00%	0.00%
	B (30.1-40 cm)	B1	30.1 – 35	12	0.00%	0.00%	33.30%	41.70%	25.00%
		B2	35.1 – 40	19	0.00%	0.00%	31.60%	52.60%	15.80%
	C (40.1-50 cm)	C1	40.1 – 45	16	0.00%	6.30%	31.30%	31.30%	31.30%
		C2	45.1 – 50	13	0.00%	0.00%	15.40%	69.20%	15.40%
	D (50.1-90 cm)	D1	50.1 – 60	19	0.00%	0.00%	5.30%	78.90%	15.80%
		D2	60.1 – 70	5	0.00%	0.00%	20.00%	60.00%	20.00%
D3		70.1 – 90	6	0.00%	0.00%	20.00%	80.00%	20.00%	
Black Locust	A (20 - 30 cm)	-	20 – 30	30	0.00%	0.00%	80.00%	20.00%	0.00%
	B (30.1-40 cm)	-	30.1 – 40	30	0.00%	0.00%	63.30%	20.00%	16.70%

Chestnut	A (20-30 cm)	-	20 – 30	30	0.00%	3.30%	63.30%	33.30%	0.00%
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Table 5. Descriptive statistics of logs by defects and sawing yield.

Species	Diameter class code	Parameter	Minimum	Maximum	Mean	Std. Deviation
Olive	A (20-30 cm)	Taper (cm/m)	0.00	0.06	0.02	0.01
		Fluting (%)	0.00	26.09	1.88	6.29
		Sweep (cm/m)	0.00	12.90	3.44	3.61
		Ovality (%)	0.00	20.97	9.29	6.70
		Sawing yield (%)	50.66	71.64	64.81	5.25
	B (30.1-40 cm)	Taper (cm/m)	0.00	0.06	0.02	0.02
		Fluting (%)	0.00	46.15	7.03	12.27
		Sweep (cm/m)	0.00	11.25	4.14	3.54
		Ovality (%)	0.00	3.85	2.81	0.99
		Sawing yield (%)	60.63	77.30	66.83	3.60
	C (40.1-50 cm)	Taper (cm/m)	0.00	0.11	0.04	0.03
		Fluting (%)	0.00	50.25	15.05	13.20
		Sweep (cm/m)	0.00	7.74	2.11	2.87
		Ovality (%)	0.00	3.13	1.95	1.16
		Sawing yield (%)	55.27	71.17	65.35	4.37
	D (50.1-90 cm)	Taper (cm/m)	0.00	0.19	0.06	0.05
		Fluting (%)	0.00	51.67	20.28	11.28
		Sweep (cm/m)	0.00	14.62	2.08	3.88
		Ovality (%)	0.00	2.94	1.73	0.69
		Sawing yield (%)	50.83	71.50	64.85	5.08
Black Locust	A (20-30 cm)	Taper (cm/m)	0.00	0.02	0.01	0.00
		Fluting (%)	0.00	0.00	0.00	0.00
		Sweep (cm/m)	0.00	4.55	0.63	1.38
		Ovality (%)	2.03	13.46	6.41	2.99
		Sawing yield (%)	65.60	74.40	69.76	2.27
	B (30.1-40 cm)	Taper (cm/m)	0.00	0.04	0.02	0.01
		Fluting (%)	0.00	6.00	0.90	1.77
		Sweep (cm/m)	0.00	5.20	1.29	1.95
		Ovality (%)	0.00	26.47	11.02	8.09
		Sawing yield (%)	65.60	73.60	70.19	2.05
Chestnut	A (20-30 cm)	Taper (cm/m)	0.00	0.04	0.02	0.01
		Fluting (%)	0.00	0.00	0.00	0.00
		Sweep (cm/m)	0.00	1.85	0.38	0.61
		Ovality (%)	3.45	21.43	12.79	4.58
		Sawing yield (%)	57.60	76.00	69.52	4.32

Descriptive statistics of logs for defects and sawing yield, distinguished by species and diameter classes, are reported in Table 5. In studying the presence in the logs of the different defects examined in this research (taper, fluting, sweep, and ovality), two different trends emerged for olive logs. For taper and fluting, the distribution among the diameter classes of the logs was found to increase as the diameters increased, while an opposite trend was observed for the sweep and ovality defects. This information suggests that the sweep and ovality defects tend

to be less marked in logs with large diameters. Logs with smaller diameters instead show more pronounced taper and fluting defects.

In black locust, all defects increased as the diameter increased, affecting the sawing yield and maintaining it at around 70% in both diameter classes. This suggests that black locust may be less sensitive to defect variability, maintaining stable yield across logs with minor structural irregularities. Among the observed defects, taper was the most impactful, although less so than for olive logs.

Compared to the other species, chestnut logs presented ovality as the predominant defect, with the highest average value (12 cm). Despite this, with the same diameter class, ovality did not appear to reduce sawing yield, which was approximately 69.5%, similar to that for black locust.

A statistical analysis of the olive wood data highlighted that the sawmill yield was not significantly affected by the diameter class ( $p$ -value > 0.05), divided into nine subclasses. From the analysis of the data collected during the sawmill surveys aggregated into the four classes of diameter (A—20-30 cm, B—30.1-40 cm, C—40.1-50 cm, and D—50.1-90 cm), the yield of sawn olive logs increases with the increase in the volume and diameter classes of the logs.

From the stepwise regression analysis of data not distinguished into diameter classes (Table 6), in which the sawing yield was assumed as the dependent variable, we found that among the independent variables (taper, fluting, sweep, ovality, volume of log ( $V_{log}$ , m<sup>3</sup>) and mean diameter of log ( $D_{mean}$ )), the dimensional variables, and most notably the average diameter, generally positively affect the yield, while the volume of log significantly decreases the sawing yield. Among the defects, the results of the analysis highlight that the taper, and, to a small extent, the ovality, can reduce the sawing yield significantly, and can slightly reduce the ovality defect.

Table 6. Regression analysis of data distinguished for species but not sorted into diameter classes.

Species		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
Olive	(Constant)	63.680	1.498		42.523	0.000
	D_mean (cm)	0.212	0.050	0.645	4.227	0.000
	V_log (m <sup>3</sup> )	-7.990	2.973	-0.362	-2.687	0.008
	Taper (cm/m)	-119.827	9.277	-0.879	-12.916	0.000
	Fluting (%)	0.011	0.024	0.031	0.455	0.650
	Sweep (cm/m)	-0.007	0.079	-0.006	-0.094	0.925
	Ovality (%)	-0.169	0.068	-0.169	-2.473	0.015
Black Locust	(Constant)	71.866	4.547		15.804	0.000
	D_mean (cm)	-0.067	0.284	-0.160	-0.237	0.813
	V_log (m <sup>3</sup> )	8.789	23.714	0.252	0.371	0.712
	Taper (cm/m)	-105.739	43.863	-0.443	-2.411	0.019
	Fluting (%)	0.109	0.238	0.068	0.459	0.648
	Sweep (cm/m)	0.118	0.236	0.094	0.498	0.621
	Ovality (%)	-0.021	0.072	-0.065	-0.293	0.771
Chestnut	(Constant)	51.044	36.823		1.386	0.178
	D_mean (cm/m)	1.923	2.868	1.069	0.670	0.509
	V_log (m <sup>3</sup> )	-209.400	280.737	-1.188	-0.746	0.463
	Taper (cm/m)	-252.960	56.416	-0.668	-4.484	0.000
	Sweep (cm/m)	-1.893	0.964	-0.265	-1.964	0.061
	Ovality (%)	0.115	0.106	0.122	1.082	0.290

Note:  $D_{mean}$  = mean diameter of log;  $V_{log}$  = volume of log.

More specifically, to identify the variables that manifest significant differences at  $p < 0.05$  in sawing yield, the linear regression analysis conducted by sorting the data into four diameter classes (A, B, C, D) exhibited that the sawing yield of olive log can be predicted with a precision ranging from 53 to 97% for diameter classes A, C and D, while for class B, the predictive model of sawing yield is not applicable ( $p > 0.05$ ) (Table 7).

From the stepwise regression analysis of black locust logs not distinguished into diameter classes, the sawing yield exhibited significant differences in terms of taper defect ( $p < 0.05$ ) (Table 6). Linear regression analyses conducted by sorting the data into two diameter classes (A, B) showed that the sawing yield can be predicted with 45% and 68% precision for diameter classes A and B, respectively (Table 7), when knowing the taper value for diameter class A and the taper and mean diameter values for diameter class B. The predictive model for calculating the yield of sawn chestnut logs through regression analysis is expressed in Equation (7), where, by inserting the value of the taper, it is possible to achieve a model accuracy of 78%.

Figures 1-3 represent the influence of taper defects on the sawing yield for the olive, black locust, and chestnut logs, respectively. Although the taper was found to be a significant statistical factor affecting the sawing yield for all species investigated, as regards the olive logs, it was found to be an excellent parameter for predicting sawing yield in the largest diameter classes (C and D) and a good predictor in the case of chestnut, while for the smallest olive diameter classes (A and B) and for the black locust logs, the  $R^2$  between sawing yield and taper defect was less than 0.5.

Table 7. Linear regression models used to predict the sawing yields of logs.

Species	Diameter class code	Linear Regression Model	Sig.	R <sup>2</sup>	Eq.
Olive	A (20-30 cm)	Sawing yield (%) = 59.616 – 203.243 * T – 0.272 * O	0.005	0.530	(1)
	B (30.1-40 cm)	Sawing yield (%) = 54.014 – 86.998 * T	0.072	0.361	(2)
	C (40.1-50 cm)	Sawing yield (%) = 62.52 + 0.29 * D <sub>mean</sub> – 14.582 * V <sub>log</sub> – 135.716 * T	0.000	0.968	(3)
	D (50.1-90 cm)	Sawing yield (%) = 59.012 + 0.259 * D <sub>mean</sub> – 6.827 * V <sub>log</sub> – 104.44 * T	0.000	0.903	(4)
Black Locust	A (20-30 cm)	Sawing yield (%) = 92.69 – 463.177 * T	0.009	0.453	(5)
	B (20-30 cm)	Sawing yield (%) = 94.551 – 0.729 * D <sub>mean</sub> – 192.706 * T	0.000	0.679	(6)
Chestnut	A (20-30 cm)	Sawing yield (%) = – 252.96 * T	0.000	0.775	(7)

Note: T (cm/m) = Taper defect; O (%) = Ovality defect; D<sub>mean</sub> (cm) = mean diameter of log; V<sub>log</sub> (m<sup>3</sup>) = volume of log.

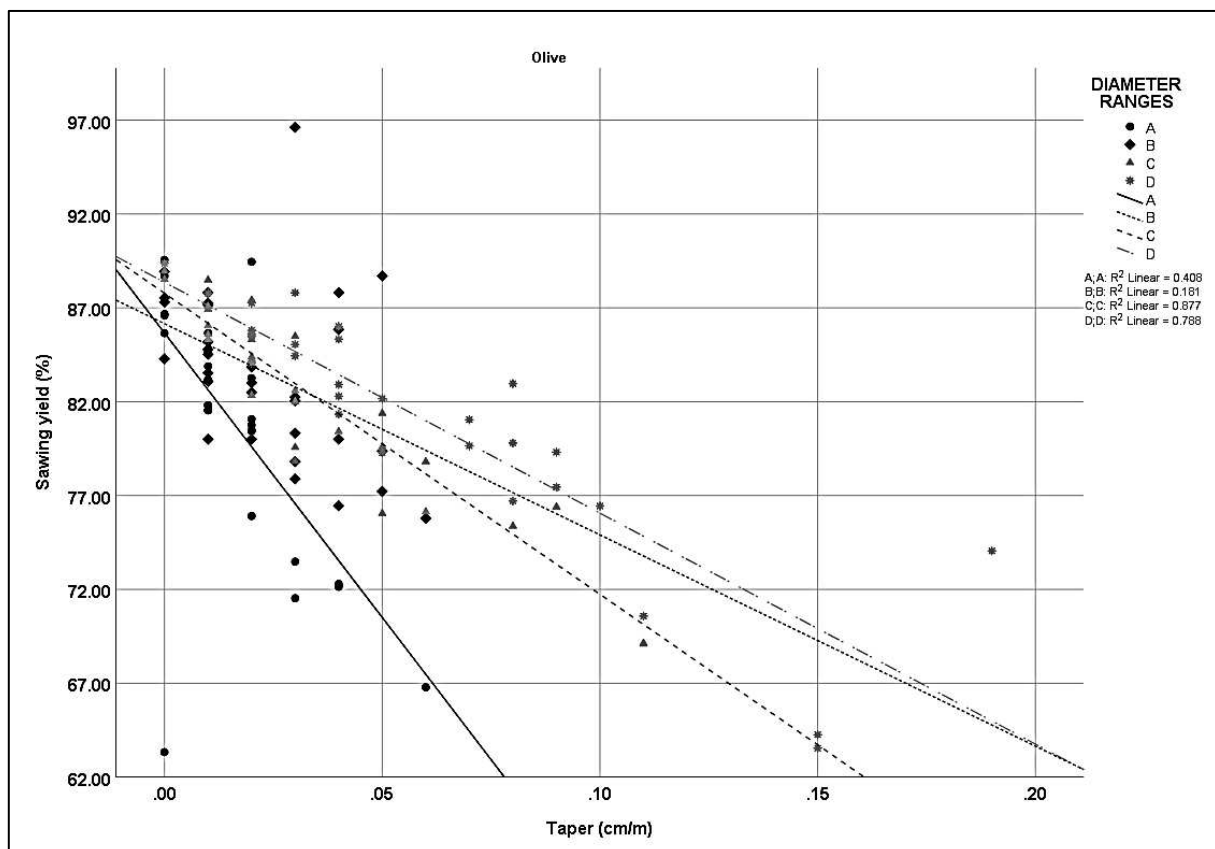


Fig. 1 Linear correlation between taper defect and sawing yield for olive logs.

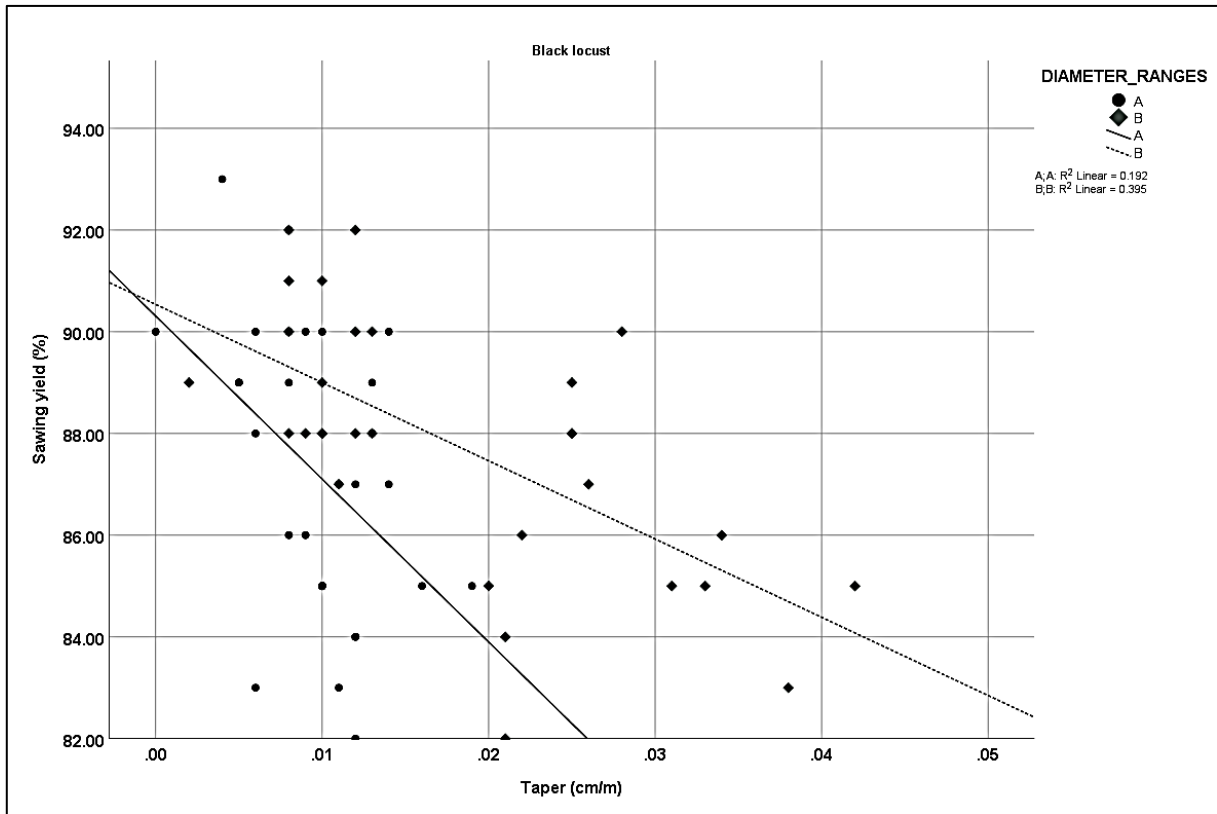
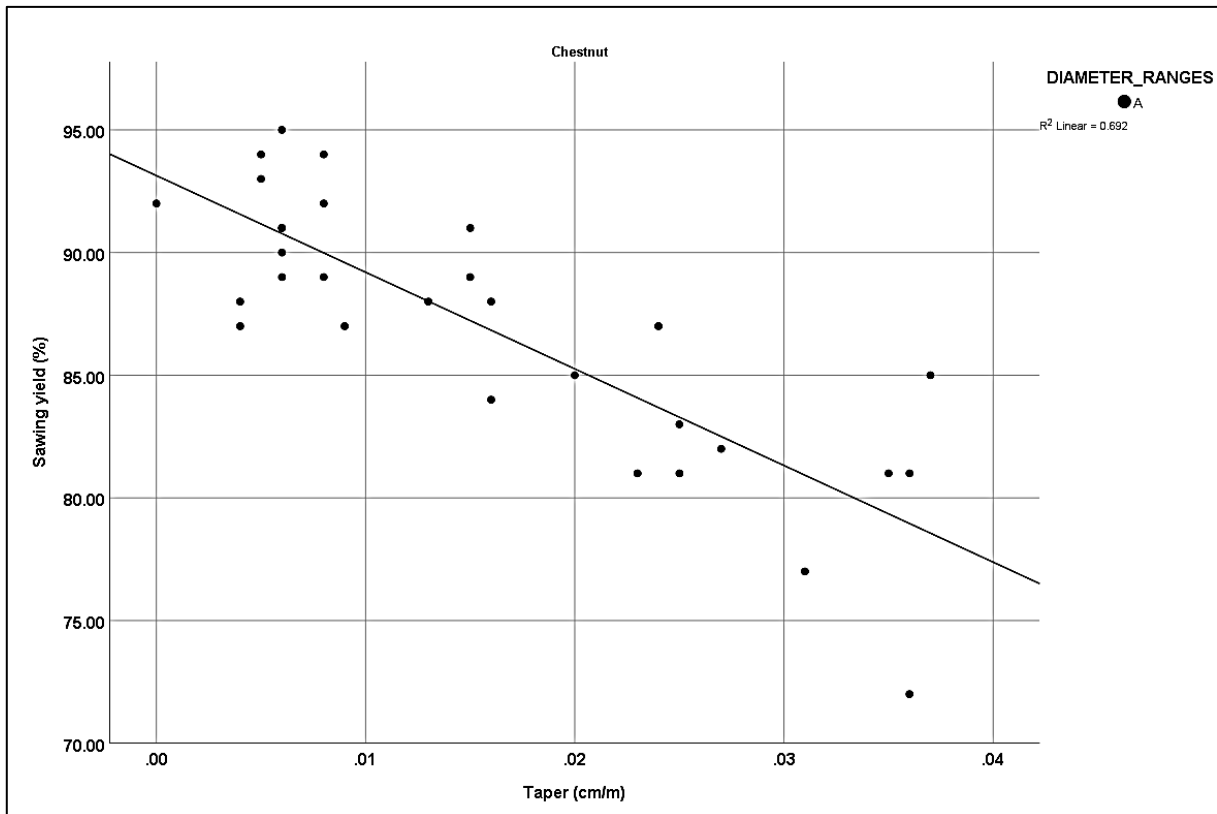


Fig. 2 Linear correlation between taper defect and sawing yield for black locust logs.



**Fig. 3** Linear correlation between taper defect and sawing yield for chestnut logs.

#### 4. Discussion

The findings that the dimensional variables such as the average diameter and the volume of logs, generally affect the sawing yield, align with the observations of Melo et al. (2019), who noted that higher yields associated with larger diameters are not always guaranteed in cases where the diameter cannot be fully utilized or where logs present significant defects. This exception was also evident in the present study, emphasizing the critical role of log quality in optimizing yield.

Among the defects, the taper is the one that more than the others examined in this research reduces the potential sawing yield. This result could be linked to the fact that taper is the most widespread type of defect among the examined logs. The other defects, generating considerable waste but only for a small number of logs, were not proven to have a significant impact on the sawing yield. Furthermore, in many cases, the concomitant presence of multiple defects on the same log could have influenced the result of the analysis. Moreover, olive tree logs often do not have regular cylindrical shapes, so high volumes do not always correspond to high levels of sawing yield. In order to obtain commercially marketable assortments, the logs must undergo several cuts that will inevitably produce a quantity of waste wood that is greater the further the log moves away from the ideal cylindrical shape, suggesting that yield could be improved by selecting logs with fewer shape deformities. The inverse relationship between taper and yield was particularly evident, demonstrating that taper limits the number of boards obtainable, especially in smaller-diameter classes.

The choice of the type of cut could also have determined the influence of different defects on the sawing yield. In fact, by proceeding with cuts parallel to the longitudinal axis of the logs - live sawing -, at higher values of average diameter, higher sawing yields are obtained. The tapering defect significantly reduces the yield, which reduces one of the two extreme diameters of the log, resulting in a reduction in the number of obtainable boards.

Table 8. Sawing yield values of hardwood species from various studies.

Type of wood	Yield (%)	Source
Eucalypt (diameter 25-30 cm)	53.60	Batista et al. (2015)
Pedunculate oak (diameter 30-39 cm)	62.24	Selver et al. (2023)
Teak hardwood	68.20	Bouaphavong et al. (2023)
Hardwoods	63–69	Johansson and Sandberg (2010)
Pedunculate and Sessile oak	60	Nylinder and Woxblom (2005)

To the best of the authors' knowledge, there are no scientific studies evaluating sawing yields for the species considered in this study, but the values obtained reflect what has been found in research carried out over the last 20 years on hardwoods (Table 8). In fact, the cutting yields here were very similar to those found for hardwood in general (Johansson and Sandberg, 2010), oak wood (Nylinder and Woxblom, 2005; Riesco Muñoz et al., 2013), and teak wood (Bouaphavong et al., 2023). An interesting comparison emerges, in particular, with the results obtained by Riesco Muñoz et al. where both studies identified the diameter of the logs as a key variable for predicting the timber yield, suggesting that large logs allow for a higher volumetric recovery. However, the comparison between the two studies highlights that the type of sawn product also influences the final yield. In the oak study, the final products were quartersawn planks, which require specific dimensions and quality, while in our case the focus on boards contributed to a higher average yield (about 70%).

The results were intermediate when observing eucalyptus wood (Batista et al., 2015). It should be considered that the authors had only monitored small-diameter logs (25-30 cm), and the cuts were performed with a circular saw, which, being equipped with a toothed disc that determines a greater cutting thickness than a band blade, causes a greater production of sawdust, with a consequent reduction in yield. The use of suitable cutting technology, such as the band saw used in this study, also facilitates greater yield efficiency, especially for larger diameters. This research suggests that, despite the olive, black locust and chestnut species being less commonly studied, they offer a competitive yield potential that reinforces their suitability for use in commercial sawing applications. Other studies have also observed that the presence of defects negatively affects yield (Carpenter et al., 1989; Ištvančić et al., 2011; Missanjo and Magodi, 2015).

Riesco Muñoz et al. (2013) observed that defects other than taper such as an increase in the amount of bark and heartwood, especially in lower quality logs, had a greater impact on overall yield, reducing the quality of timber intended for structural uses, such as quartersawn planks. This difference can be attributed not only to the species,

1 but also to the final products considered in the two studies: in this scientific work, the final products are boards,  
2 which tolerate a greater variety in defects, while in the study by Riesco Muñoz et al. (2013), which focused on  
3 quartersawn planks, the defects, as well as the cutting method, must be more rigorously controlled, since they  
4 directly affect the structural use of the wood. Some scientific works have observed how the cutting patterns  
5 influence the sawing yield (Wang SJ, 1988; Popadić et al., 2009; Popadić et al., 2014; Missanjo and Magodi, 2015).  
6 In several cases, the decision regarding the cut is random, leading to a low yield of sawn wood (Biasi and Rocha  
7 2001; Buehlmann and Thomas, 2002). The choice of an appropriate log breakdown method for each species is  
8 necessary to valorize timber and optimize the production at the sawmill (Bonato Junior et al., 2017; Popadić et al.,  
9 2014; Santos et al., 2019). Popadić et al. (2009, 2014) observed that live sawing has a negative impact on the yield,  
10 but the results obtained by Riesco Muñoz et al. (2013) confirm its effectiveness in maximizing yield, giving in the  
11 case of oak, the best results for large logs, with a maximum yield of 55.3%. In this work, live sawing proved to be  
12 especially useful for species such as chestnut and black locust, ensuring greater stability in yield, helping optimise  
13 the production of boards, a product with less stringent requirements in terms of size and quality than those obtained  
14 analyzed by Riesco Muñoz et al. (2013). A live sawing performed parallel to the trunk axis, as was used in the  
15 present work, could lead to an increase in the sawing yield for the raw product (sawn boards), as was also observed  
16 by Klement et al. (2023) for hardwood.  
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## 20 5. Conclusion

21 Several factors may influence lumber yield, such as the final size of the pieces, the number of cuttings, the  
22 machinery used, the specialized workforce employed, the sawing methods (Ferreira et al., 2004) and the log  
23 dimensions (Vital, 2008), in addition to the parameters related to log quality (Garcia et al., 2012). This study has  
24 explored and analyzed the impacts of defects on three Mediterranean wood species, confirming that sawing yield  
25 is strongly influenced by the intrinsic characteristics of the logs and their diameters. Taper emerged as the defect  
26 with the greatest impact on yield, especially for olive and chestnut logs, as it significantly limits the yield of  
27 obtainable boards and therefore reduces production efficiency. Despite the presence of defects such as ovality, the  
28 yield stability observed for black locust and chestnut demonstrates their strong potential for use in commercial  
29 applications, which is comparable to that of other more widely studied hardwood species. The sawing method used  
30 here proved to be effective for large-diameter logs, especially for olive, although further optimization is needed  
31 for irregularly shaped logs. Looking to the future, the adoption of innovative technologies, which have already  
32 been adopted in many industrialized countries, such as computer vision systems and predictive analytics based on  
33 artificial intelligence, could significantly improve sawing yields, reducing waste and maximizing the value of  
34 Mediterranean wood species. Exploiting these advances, in combination with the predictive models proposed in  
35 this work, would allow for more sustainable responses to the growing demand for wood, enhancing local resources  
36 and promoting a more environmentally friendly forestry economy in the Mediterranean basin.  
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## 5. Conclusion and Future Perspectives

This PhD thesis has developed three main strands on the wood supply chain in the Plain of Gioia Tauro, focusing on logging operations, knowledge of olive wood and sawing yields during the first transformation phases. In particular, the main objective of this study was to define a series of actions aimed at fostering the development of new and innovative production processes in the different phases of olive wood harvesting and processing.

The first activity focused on studying the productivity of two highly specialised forestry machines (skidder and harvester) found in Calabria. The importance of this study was to establish whether these two machines, under Calabrian forestry conditions, increase the productivity of forestry operations. It was observed how:

- The use of the skidder offers high productivity compared to other extraction machines (such as the agricultural tractor), which makes it very suitable for logging operations in Mediterranean coniferous forests.
- The harvester, compared to classic felling, depeeling and limbing methods, is a highly productive machine that requires professional planning and management to improve productivity.

These machines are perfectly adaptable to the orography of the Calabrian terrain. In addition, optimised planning of harvesting and forwarding routes, based on terrain characteristics and viability maps, is an essential factor in improving productivity, minimising impact on the land and increasing safety.

Given the immense olive-growing heritage in the Plain of Gioia Tauro, it was only right to dwell on the evaluation of olive wood in order to increase scientific knowledge. First, an in-depth qualitative analysis was carried out on the anatomy of the two olive cultivars present in the area: '*Ottobratica*' and '*Sinopolese*' (second activity). The objective was to perform the first studies on the anatomical properties of this still little-known species in order to increase and

explore the suitability of this wood for different uses. The results illustrated that the wood of both cultivars had a complex, often irregular anatomical structure. The only small difference found was in the parenchymatous rays: some of them had one to three rows, visible in tangential sections. Both cultivars have starch in the parenchyma cells. The '*Ottobratica*' cultivar appears to have a higher amount of granular deposits.

Subsequently, the study of the third activity focused on determining the physical properties, testing the mechanical properties of small specimens of light wood, and comparing the results between the two cultivars and between the branches and stem wood in the same cultivars. The study attempted to broaden the notions related to the wood obtainable from the extraordinary pruning of olive trees. In fact, considering the lack of information on this wood species, the results gathered from this study can enrich the interest in forest olive trees. The study reveals the possibility of using the woody branches to obtain similar products made from the stem. Furthermore, the commercial use of wood branches may represent a valuable opportunity for the local rural economy when stems are not suitable. In conclusion, knowledge about the performance of olive wood will increase its use in multiple sectors and ensure a more conscious use of wood resources.

The fourth activity was aimed at analysing the influence of steam treatment at low temperatures and with different durations on the physical-mechanical properties of olive wood. The study revealed that heat treatment can add potential value to olive wood, making it more effectively usable in the production of interior products (flooring, furniture, etc.). In addition, the results of this study contribute to a better understanding of the potential use of this species, which has gained more and more ground in the market in recent years. Steam treatment can be a valuable integrating element for local wood processors in the creation of interior products.

In the Plain of Gioia Tauro there are numerous sawmills where almost all the wood from the various forestry uses is conveyed. Among the species used,

the olive tree is of particular interest. This species (and others) has a great variety of defects that affect sawing yields. In the fifth activity, the distribution of defects on logs of different species and diameter classes was analysed. In addition, the impact of defects on the sawing yield obtained when sawing three different species of wood in a medium-sized sawmill was investigated. Finally, an attempt was made to predict the sawing yield from defective logs of different diameter classes. From what emerges from this study, the sawing yield is strongly influenced by the intrinsic characteristics of the logs and their diameters. Tapering emerged as the defect with the greatest impact on yield (particularly for olive and chestnut logs). Despite the presence of defects such as ovality, the yield stability observed for black locust and chestnut demonstrates their strong potential for use in commercial applications. The sawing method used proved effective for large-diameter logs, particularly olive, although further optimisation is needed for irregularly shaped logs.

Summing up:

- **SRO<sub>2.1</sub>**. The machines examined are highly performing and adaptable to the orographic conditions of the territory. In addition, both studies contribute to implementing the knowledge of these (still little studied) machines in the territory.
- **SRO<sub>2.2</sub>**. The qualitative anatomical study of the two olive cultivars (*'Ottobratica'* and *'Sinopolese'*) contributes to the understanding of the species. This is due to the lack of studies that address the anatomical investigation of secular olive trees.
- **SRO<sub>2.3</sub>**. This study, along with the anatomical study, sought to expand the notions related to olive wood. Integrating it with the knowledge of the physical-mechanical performance of olive wood.
- **SRO<sub>2.4</sub>**. The study revealed that steaming treatment can add potential value to olive wood, making it more effectively usable in the production of interior and exterior products.
- **SRO<sub>2.5</sub>**. The sawing method used has proven effective for large-diameter

logs, particularly olive trees, although further optimisation is required for irregularly shaped logs.

The results obtained in this PhD may be useful for all sectors of the forestry-wood sector. In fact, the results obtained in terms of forest mechanisation can be extended to other types of forests in Calabria and/or southern Italy that have similar characteristics to the studies conducted. Moreover, the results obtained from the study of olive wood could be of support in both first and second/third transformation. Finally, sawmills could adopt innovative technologies to significantly improve cutting yields, reducing waste and maximising the value of Mediterranean wood species. Exploiting these advances, in combination with the predictive models proposed in this paper, would enable more sustainable responses to the growing demand for wood, enhancing the value of local resources.

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# DM 1061 del 10 agosto 2021

Dottorati PON - Bando 2021 - Ciclo 37 (XXXVII)

Azione IV.4 - Dottorati e contratti di ricerca su tematiche dell'innovazione

Azione IV.5 - Dottorati su tematiche Green



UNIONE EUROPEA  
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Coordinatore	Prof. Leonardo Schena
Corso di Dottorato in	Scienze Agrarie, Alimentari e Forestali – <i>Curriculum Scienze Forestali</i>
Ciclo	XXXVII
Codice borsa e n.	Codice: DOT1647787 – Borsa N°1
CUP	C35F21001330002
Tipologia Green/Innovazione	Innovazione
Titolo Progetto	Study of the forest-wood supply chain for the enhancement of local wood resources in the rural area of the plain of Gioia Tauro