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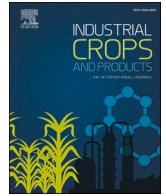
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Resin tapping: A review of the main factors modulating pine resin yield

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ABSTRACT

Pine resin is a non-wood forest product that has been used for multiple purposes since ancient times throughout the world. In recent years, resin tapping activity has increased in countries that were historically producers, but in which it had practically disappeared since the late 1980 s, and is expected to grow in importance due to its bio-product nature. The aim of this review is to provide an overview of the research work on the main factors modulating resin yield. A total of 205 papers were selected and classified according to their main topics. The species and its intraspecific genetic variation are two of the main factors influencing both the production and the quality of the resin obtained. The environmental factors most commonly studied and which in turn were the most successful when related to resin production, were temperature and water availability. Diameter at breast height was the most investigated dendrometric variable, although other variables such as total height or crown ratio were also studied, generally obtaining positive relationships between them and resin production. The resin ducts, which produce, secrete and transport resin through the tree, are the most influential anatomical variable and the focus of the anatomical research. Other factors that can modulate resin production are the presence of pests, which induce the tree's immune response, and fire, with contradictory results on their effects. Finally, the extraction method and the stimulant paste used influence resin production, research is focusing on new extraction methods and more efficient and cheaper stimulant pastes with lower proportions of sulfuric acid. Although interest in and knowledge about resin tapping has increased in recent years, research needs to further develop and deepen the relationships between resin production and the different factors involved.

1. Introduction

To defend themselves against antagonistic organisms, plants produce a wide variety of defensive substances that repel, impede or deter the progress of the invaders (Agrios, 2005). In addition, components of these substances can attract the natural predators of the invaders (Phillips and Croteau, 1999). One outstanding example of these defensive substances is resin, a viscous substance secreted by many different plant species, composed of volatile and non-volatile secondary metabolites (mainly mono and sesquiterpenes and resin acids) mixed heterogeneously in different proportions depending on the particular species. Resin is typically produced and stored in specialized cells that may form different types of structures in which resin is stored under pressure. When plant tissues are damaged, resin flows out expelling and/or capturing the aggressor. In addition, when exudation begins and the resin comes into contact with the atmosphere, the volatile compounds, evaporate, leaving a semi-crystalline mass which forms a protective

barrier that seals the wound, thus preventing further access by insects and pathogens to internal tissues (Phillips and Croteau, 1999).

Many plant taxa, including species from phylogenetically distant orders such as Asparagales, Malvales, Apiales or Coniferales, to mention just a few, produce resins as a defensive mechanism (Langenheim, 2003).

In temperate regions, the main resin-producing plants are, however, the gymnosperms, and particularly the Pinaceae family which includes up to ten genera and 230 species distributed worldwide (Wu and Hu, 1997). Within the Pinaceae family, the *Pinus* genus stands out as the one with the highest investment in resin production. In pine trees, resin is produced and accumulated at high concentrations (up to 10–20% of dry mass) in all tissues (stems, roots, branches, needles, and even cones). Pine resin is stored in specialized structures that form an interconnected three-dimensional hub of resin ducts (Vázquez-González et al., 2020). When resin canals are injured, the resin accumulated in this network of tube-like structures flows out in amounts which, depending on the

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species, can be copious.

For thousands of years, different civilisations have harvested resin from pine trees, and benefited from the different uses it has (Meiggs, 1982). The activity of resin extraction from trees is called resin tapping, and consists of making wounds in the stems of living trees and collecting the resin that flows out from the exposed resin ducts (Sharma et al., 2018b). Formerly, the practiced wounds removed not only the bark and the cambium but also thin strips of wood, causing important lesions and large impacts on tree growth and timber quality (Chen et al., 2015; Rodrigues-Corrêa et al., 2013; Rodríguez-Soalleiro et al., 2008; Zeng et al., 2021). Nowadays, wounds do not penetrate into the wood reducing the impacts in tree growth while allowing the resin flowing from the exposed resin canals in the xylem and phloem to be collected (Van der Maaten et al., 2017; Martínez-Chamorro, 2016; Tomusiak and Magnuszewski, 2009). In the early stages of civilisation resin was used for motley purposes, such as, for example, mummification processes in ancient Egypt or in traditional medicine (Michavila et al., 2017), but the real boom in the use and trade of pine resin occurred in the 15th century, with the rise of the shipbuilding industry in Europe and the use of resin for waterproofing ships (Loewen, 2005).

With the emergence of the chemical industry in the 19th century, resin found an important industrial niche that has been maintained up to date (Michavila et al., 2017). The industrial uses of oleoresin and its derivatives cover a wide range of products, some of high added value such as pharmaceuticals, cosmetics, emulsifiers, adhesives, chewing gums or paints (Pinillos et al., 2009; Neis et al., 2019b; Rodrigues-Corrêa et al., 2013). With the professionalisation of the sector, an important effort was paid to improve the tapping techniques and the efficiency of exploitations, thus leading to a continuous increase in knowledge in the different fields involved in resin production, such as new extraction methods or the use of chemical stimulants to improve production (Hodges, 1995; Parham, 1976). In traditional producing countries (e.g. Spain, USA, France, Portugal), resin production continuously increased until, approximately the 1980's, when the market was liberalised and practically monopolized by emerging producers in subtropical countries, dooming the production in traditional areas to practically disappear (Pinillos et al., 2009; Picardo, 2013; Soliño et al., 2018). The emergence of synthetic resins also contributed to the decline of resin tapping exploitations (Sebastián, J.A. (ed. lit.), Uriarte-Ayo, R. (ed. lit.), 2003). However, in the 2000 s, and as a consequence of the interest for substituting petroleum derivatives by renewable bioproducts in the industry (Aldas et al., 2020; Karademir et al., 2020) and the need to revitalize pine forests both from an economic and environmental perspective (Soliño et al., 2018), the resin tapping sector is regaining attention in different regions where it had almost disappeared, such as southwest Europe. This interest stems from the need to reduce the environmental impact of many industrial processes and their dependency on fossil nonrenewable raw materials (Demko and Machava, 2022). Pine resin is, indeed, postulated as a candidate to replace petroleum derivatives in the synthesis of many products, such as new printer inks or jet fuels based in hydrogenated turpentine, thus making them more ecofriendly and sustainable (Alonso-Esteban et al., 2022; Bolonio et al., 2022; Donoso et al., 2021; Hayta et al., 2022). This comeback of the sector is leading to a resurgence of the interest for understanding the main factors involved in pine resin production, and resin chemical properties, and practical issues related to the extraction methods to make resin tapping exploitations more profitable (Rodríguez-García et al., 2016; Rubini et al., 2021).

The general objective of the present work is to provide a systematical bibliographical review of the main factors that influence resin production and its physical and chemical properties. The specific objectives are:

- 1) To determine the main *Pinus* species, regions and temporal trends of the accumulated scientific knowledge on pine resin production and resin tapping;
- 2) To identify the most influential factors (genetic, environmental, dendrometric and phenotypic) that modulate resin production;
- 3) To compile the different methodologies currently used for

resin tapping and summarize their impact on resin yield and quality. The aim of this.

review is to provide an overview of the factors involved in the activity of resin extraction, serving both as a compilation of articles published to date, and as a starting point for future research.

2. Methods

We conducted a systematic review of scientific literature published up to the beginning of 2023 through a systematic search in the most common databases (ScholarGoogle, ScienceDirect, Springer, Web of Science, ResearchGate and SemanticScholar) using keywords and concepts related with the topic of resin tapping. The terms sought could be grouped into three blocks: *resin production*, *factors* and *statistical analysis*. The chosen terms related with the *resin production* block were: pine, *Pinus*, resin yield, oleoresin, resin production, resin flow, defenses, resin canals, resin ducts and gum. In relation to the *factor's* block, the expression and words used were: climate, genetic variation, heritability, temperature, precipitation, irradiation, water deficit, evapotranspiration, dendrometry, site index, diameter, total height, basal area, density, age, crown diameter, competition index, slenderness, bark thickness, soil properties, slope, orientation, altitude, tapping methods, wounding and stimulant paste. Finally, the terms related with the *statistical analysis* research were: regression model, statistical approach, modelling, factors, geostatistic, correlation values, Pearson, Spearman, stepwise, linear, regression, non parametric and distribution functions. A total of 49 different terms and their combinations were introduced in the distinct databases. The results were filtered in two steps, firstly by reading the abstract and conclusions, and then by reading the full paper, choosing those that had the strongest relationships with the main topics of this paper. Additional papers were identified throughout the reviewing process by referring to pertinent studies that were cited in the reviewed literature.

The selected papers were classified depending on the year of publication, the location of the study, the species used and the main topic (Fig. 1). The first group was the *Information sequence*, in which the articles were classified according to their publication year, analyzing the number of publications per year and the trend in recent years. In the second group, *Location*, the articles were classified according to the country where the study took place. This two first classification groups put into context the situation and interest in the study of resin tapping around the world. The third group, *Species*, allowed to list the world's leading pine species used for resin tapping and research and the main chemical components of the resin they produce. The fourth group, *Topics*, includes the articles exploring the behavior and influence of different factors both at the stand level (climatic, physiographic, edaphic and silvicultural) and the tree level (genetic, dendrometric, anatomic, fire and pests and extraction method) that can intervene in resin production.

3. Information sequence

The number of papers directly related to the topic of resin tapping as the main focus was scarce, so the search had to take cross-cutting paths to understand the processes and factors involved in resin production. A total of 205 papers were finally selected and classified according to the six groups defined in the Methods section (Table S1). The number of scientific publications related to the extraction of resin from pine trees showed a marked positive trend over time (Fig. 2), which was more pronounced than the general increase in publications that occurred in all scientific disciplines, such as those related to pine trees from a broad global perspective, represented by the number of publications when using the Web of Science as a filter on the topics "pine OR pinus OR pines". For this comparison, the Web of Science was used as a large collection of bibliographic databases of citations and references of scientific publications. The peak of publications related with resin tapping

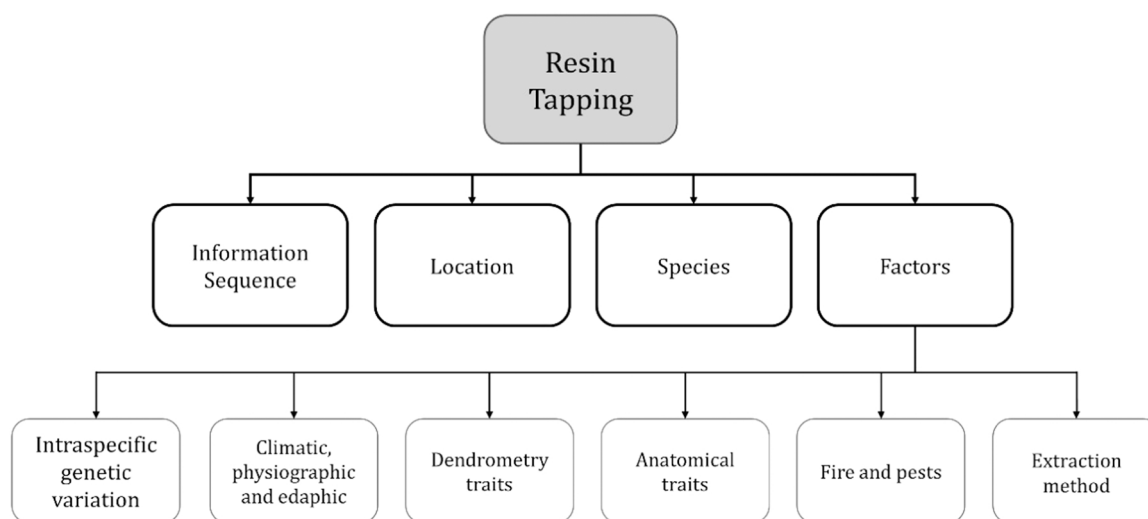


Fig. 1. Concept map of the four main groups into which the articles were grouped and the subgroups into which the articles were classified within the fourth group.

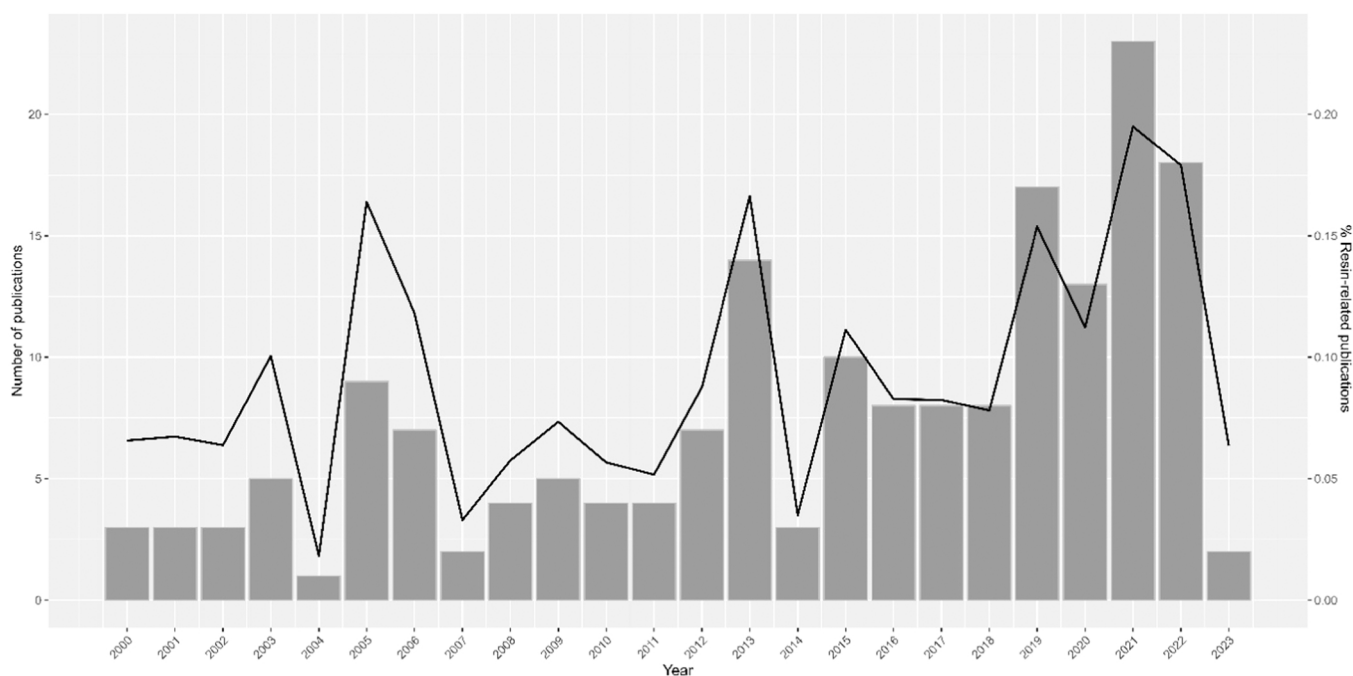


Fig. 2. Number of scientific publications related to resin tapping of pine trees from 2000 onward (barplot) and percentage of resin-related publications in the total number of publications with the words *pine*, *pinus* or *pinus* as the topic in the Web of Science (continuous line). This global trend is referred to the right y-axis which was scaled to make the value 0.05% coincident with the value 5 of the publications. Note the stepper trend in the last 3 years of the publications related to resin tapping in relation to the general rise of publications related to pine trees.

occurred at the end of the studied period with 23 publications in 2021. The increase in the number of publications may be due to the emerging interest for renewable bioresources capable of substituting petroleum derivatives, such as resin, as mentioned above (Hayta et al., 2022). Particularly, the increasing interest for resin production has prompted many research activities aimed to determine the most productive territories and fine tune management alternatives to improve production, especially in countries where the activity had previously ceased (Moreno-Fernández et al., 2021).

4. Location

Additionally to the date of the publications, the country in which the studies were carried out is also important to see which geographical

areas have the most interest in the field of study. Fig. 3 shows the

number of publications related to pine resin production according to the country where the study was carried out. The variation in the size of the dots denote the total resin production in those countries (Clopeau and Orazio, 2019; Cunningham, 2022). An important mismatch can be seen between the number of publications and the total production of resin across countries. While scientific publications related to resin are abundant in Spain, USA, and other countries with little resin production. Some other resin producing countries such as Vietnam for which no publications were found are even missing in the figure. This decompensation between the number of publications and the total production of resin can also be seen in Fig. 4, which shows the proportion of publications according to the pine species studied in each paper. Clearly, *P. pinaster* is the most studied species despite contributing little to the

area and the availability of high yielding native species, or exotic species capable of being grown in the region (Lauture, 2017). Almost 90% of the resin produced in the world comes from just four pine species (Cunningham, 2022), although many other pine species are also potentially high resin yielders (Table 1). These four species are *P. elliottii* var. *elliottii* (China and Brazil), *P. massoniana*, *P. merkusii* (Indonesia) and *P. yunnanensis* (China) (Cunningham, 2012). In addition to these four species, *P. pinaster* is widely used in the Iberian Peninsula and France (Picardo, 2013; Palma et al., 2016), *P. oocarpa* in Mexico (Reyes-Ramos et al., 2019), *P. roxburghii* in India (Sharma et al., 2018a), *P. kesiya* also in China (Wang et al., 2015), *P. nigra* ssp. *laricio* in Corsica (Rezzi et al., 2005), *P. caribaea* in Brazil and Malaysia (Jantan and Ahmad, 1999), *P. sylvestris* in north Europe and Slovenia (Rissanen et al., 2021; Zaluma et al., 2022) and *P. halepensis* in Greece and Tunisia (Aloui et al., 2022; Papadopoulos, 2013). Some hybrids between some of these species are also used for resin-tapping in different countries (Liu et al., 2022).

Resin production per individual tree is highly variable both across species but also within species (Table 1). According to the published data, some species (*P. kesiya* and *P. caribaea*) produce more resin than others (*P. sylvestris* and *P. roxburghii*). Usually, in the producer countries the tree's yield ranges between 3 and 6 kg, although there is a huge variation between productions. This variation is a consequence of different factors modulating resin production that will be discussed below. The extremely high values for some of the species (*P. yunnanensis* and *P. halepensis*) are due to a combination of these factors, mainly due to the extraction methods used.

The pine species and the geographic location not only influences resin yield but also determines the resin composition (Silvestre and Gandini, 2008). Resin is a complex mixture of turpentine (volatile fraction, mainly composed by mono and sesquiterpenes), and rosin (non-volatile fraction, mainly composed by diterpenes or resin acids)

Table 1

Most commonly pine species used for resin production, the region where resin is produced, the contribution to world resin production and the range of individual tree production according to the literature. *: Note that individual tree production depends, among other factors, on the extraction method.

Species	Region	Species		Reference (s)
		% production	Tree production* (kg/tree)	
<i>P. elliottii</i> var. <i>elliottii</i>	China, Brazil, Argentina	48.8	3–8	Neis et al. (2019a)
<i>P. massoniana</i>	China, Vietnam	19.6		
<i>P. merkusii</i>	Indonesia	14.3	2–5	Hadiyane et al. (2015)
<i>P. yunnanensis</i>	China, Vietnam	4.2	2–12 <	Wang et al. (2015)
<i>P. caribaea</i>	Brazil, Malaysia	< 13.1	4–4.5	Santos et al. (2016)
<i>P. pinaster</i>	Iberian Peninsula, France	idem	1–4	Palma et al. (2012)
<i>P. oocarpa</i>	Mexico	idem	2–3	Heinze et al. (2021)
<i>P. roxburghii</i>	India	idem	< 1–1.3	Dutt and Kumar (2020); Sharma et al. (2013a)
<i>P. kesiya</i>	China	idem	3	Yi et al. (2018)
<i>P. nigra</i> ssp. <i>Laricio</i>	Corsica, Slovenia	idem	1–2	Cannac et al. (2009); Gajšek et al. (2018)
<i>P. sylvestris</i>	North Europe, Slovenia	idem	< 1	Gajšek et al. (2018)
<i>P. halepensis</i>	Greece, Tunisia	idem	< 1–13.5	Spanos et al. (2010)

(Neis et al., 2019a; Rubini et al., 2022). Sometimes, resin is confused with oleoresin, which differs from oleoresin in that it is comparatively fluid with a higher proportion of volatile and non-volatile terpenes (Demko and Machava, 2022). From now on, both the term resin and oleoresin will be used to refer to resin, as they are used interchangeably to refer to resin. The proportion of both fractions is highly variable depending on the species, the genotype and the environmental conditions (Yi et al., 2021). As an example of this variations, Table 2 shows the proportions of mono- and diterpenes in the resin of the four most productive species and in *P. pinaster*, which is the most studied in the reviewed papers.

The differences in the total proportion of monoterpenes and diterpenes vary according to the different species, making species valid for different purposes (Rodrigues-Corrêa et al., 2013). Table 2 shows how the contents of α -pinene, the most abundant monoterpene in all cases, vary according to the species from 27.43% in *P. elliottii* to 74.3% in *P. merkusii*. The case of the β -pinene is even more variable, since in *P. elliottii* and *P. pinaster* it appears in quite high levels, while in the other three species is much less abundant. In terms of diterpenes, the values are similar among all the species, although they vary in each one, especially the levels of Levopimaric+Palustric acid and neoabietic acid.

As mentioned above, the amounts of the different fractions that make up the resin vary between species. However, there is also intraspecific variation, which can be seen in the ranges between the different fractions for the species *P. elliottii* (three areas in Jiangxi Province, China), *P. merkusii* (East and West Java and North Sumatra) and *P. pinaster* (three areas in Segovia Province, Spain + 2 seasons) in Table 2. These ranges correspond to the variation in resin composition according to location and, in the case of *P. pinaster*, according to the season in which the samples were collected. These variations are accentuated by distance and differences in the environmental characteristics in which the trees were found. For example, *P. elliottii* samples collected by Lai et al. (2020) during the months of July to September had lower proportions of alpha and beta pinene than those recorded by Rodrigues et al. (2011) during the spring in Rio Grande do Sul, Brazil. The latter work also shows how the composition of resins can vary depending on the concentration of metals used to prepare the chemical stimulants.

6. Factors

Based on published data, resin production of pine trees shows wide variability both across and within pine stands. To understand this variability, the starting point is to explore the distribution functions that best fits to this variation, and then to explore the factors behind this variation. There are few works that have explored the frequency distributions of within-site variability in resin production and the distribution of resin production variability across the territory. Gómez-García et al. (2022) modeled the distribution functions of resin production for 45 *P. pinaster* stands with different treatments in Northwest Spain using the two-parameter Weibull function and the moments-based parameter recovery method. Similarly, Nanos et al. (2000) used the two-parameter Weibull but also the Chaudhry and Ahmad's probability function to model the resin production distribution function of *P. pinaster* in the Central Plateau of the Iberian Peninsula. Both works obtained the same results, with large differences in production between and within the plots and attributing this variation to climatic, edaphic, dendrometric and silvicultural factors, as will be discussed in the following sections.

Another type of data-driven modelling that remains poorly studied, as a tool for modelling resin production is geostatistics. Nanos et al. (2001) used this technique to model resin production in the Spanish Central Plateau, studying the spatial structure of resin production of maritime pine populations at two different scales. Results showed that within-stand variation was not spatially structured, however, variation in mean plot production was spatially structured. This reinforces the fact that the variation in resin production is due to several factors such as those mentioned above.

Table 2

Variation in chemical compositions between the four species with the highest production worldwide and *P. pinaster*. *: the percentages of these species are not relative to the total but according to the fraction to which they belong (monoterpenes or diterpenes).

Chemical compositions					
<i>P. elliottii</i> var. <i>elliottii</i>	<i>P. massoniana</i>	<i>P. yunnanensis</i>	<i>P. merkusii</i> *	<i>P. pinaster</i> *	
Reference(s)	Lai et al. (2020)	Song et al. (1995)	Song et al. (1995)	Wiyono et al. (2006)	Arrabal et al. (2002)
Monoterpenes (%)					
α-Pinene	27.43–28.31	31.7	38.5	57.7–74.3	67.95–70.6
Myrcene	1.59–1.98	0.4	0.5	0.7–1	0.65–1.04
Dipentene	0.43–0.52	0.5	1.7	0.9–2.8	1.44–1.85
Camphene	0.28–0.31	0.5	0.5	0.7–1	0.58–0.67
β-Pinene	13.41–15.08	1.2	2	0.8–4.8	17.53–18.91
Diterpene (%)					
Isopimaric acid	3.93–4.01		1.4	0.88–0.97	7.86–11.18
Abietic acid	10.51–11.31	10.9	5.5	1.05–1.15	12.78–13.67
Dehydroabietic acid	3.26–3.49	1.7	2.6	1	2.53–3.60
Neoabietic acid	10.62–11.65			1.10–1.34	16.84–18.84
Pimaric acid	0.22–0.24	0.1	0.7		6.53–7.19
Pimarene	0.27–0.31				
Pimarinal	0.25–0.28				0.48–0.61
Communic acid	0.20–0.27	4.1	2.9		
Sandaracopimaric acid	0.24–0.27	1.3	1.4	0.77–0.93	1.53–1.74
Palustric + Levopimaric acid	18.08–19.24	27.5	31	0.91–0.98	38.30–42.51
15-Hydroxydehydroabietic acid	0.33–0.41				
7,13,15-Abietatrienic acid	0.26–0.41	0.7	0.6		0.53–0.72
Dehydroabietal	0.29–0.33	1.7	2.6		
7-Hydroxydehydroabietic acid	0.35–0.45	0.2	0.1		
6,8,11,13-Abietatetraenoic acid	0.27–0.29	0.2	0.3		
8,14-Dihydropimaric acid	0.27–0.3	1.7	2.6		
Monoterpenes (%)	43.42–45.32	34.3	43.7		23.01–25.68
Diterpene (%)	50.41–53.00	51.9	56.1		61.36–66.85

6.1. Intraspecific genetic variation

As is generally the case for most phenotypic traits of pine trees (Ramírez-Valiente et al., 2022), resin yield not only varied among pine species, but also shows large genetic variation within species (Lai et al., 2020). Indeed, resin yield is a trait under high genetic and heritable control (Strom et al., 2002; Vázquez-González et al., 2021). This intraspecific genetic variation occurs both across (López-Goldar et al., 2019) and within (Vázquez-González et al., 2021) pine populations. Among population variation may be the result of divergent selection processes across heterogeneous environmental conditions within the natural range of a given species (Torre et al., 2019), to correlated responses to natural selection on other functional traits (Vázquez-González et al., 2020) or to neutral processes related to the demographic history of the species (López-Goldar et al., 2019). Little information is available on the relative contribution of these evolutionary forces on the differentiation processes of resin production across populations, but, as resin flow is directly related to the phenotypic expression of plant resistance, natural selection to biotic stresses are assumed to be important (Zas et al., 2005). Within population variation in resin flow is also high, with moderately to high heritability estimates (Lai et al., 2020). Narrow-sense heritability estimates of resin yield or resin flow vary from 0.11 to 0.77 depending on the species and assessment age (Table 3). Taking advantage of this high heritability, mass selection of high-yielder individuals and their establishment in clonal banks for tree selection or seed orchards as mother trees for seed production has been or is currently in progress in USA (Mergen et al., 1955), China (Mei et al., 2021a), Brazil (Assis and Resende, 2011) and Spain (Tadesse et al., 2001). Genetic gains of these genetic improvement initiatives have been not reported yet. However, large genetic gains in terms of improved resin production can be expected from the relatively high heritability estimates.

One important point that needs especial attention in tree breeding initiatives is to discard that the genetic improvement of a given trait does not come at the expense of a deterioration in other important functional or economical traits due to genetic correlations among traits (Santos-del-Blanco et al., 2015; Suárez-Vidal et al., 2021). From a physiological level, resin is a high-carbon resource (Rissanen et al., 2021) that is

Table 3

Heritability estimates of resin flow or resin yield depending on the species and the study. *h_i*: individual narrow sense heritability. *: range for different estimates in the same genetic test but for different origins. **: Repeatability value indicating the upper limit of the *h_i*.

Heritabilities				
Species	Age	<i>h_i</i>	Reference (s)	
<i>P. elliottii</i> var. <i>elliottii</i>	27	0.11	Lai et al. (2017)	
		0.68	Li et al. (2012)	
	26	0.19–0.32	Lai et al. (2020) *	
	14	0.58–0.66	Salto et al. (2014) *	
	15	0.54–0.66		
	4	0.04–0.12	Romanelli and Sebbenn (2004) *	
	12	0.002–0.33		
	25	0.55	Roberds and Strom (2006) **	
	<i>P. merkusii</i>	7	0.15–0.65	Nugrahanto et al. (2022) *
		29–30	0.58	Susilowati et al. (2013)
13		0.52	Sukarno et al. (2015)	
12		0.52	Leksono and Hardiyanto (1996)	
<i>P. massoniana</i>		7	0.17	Zeng et al. (2013)
	9	0.2		
	11	0.13		
	13	0.18		
	15	0.18		
	20	0.17		
	24	0.31		
	26	0.22		
<i>P. pinaster</i>	8	0.47	Liu et al. (2013)	
		0.5	Tadesse et al. (2001) **	
<i>P. taeda</i>	15	0.49	Vázquez-González et al. (2021)	
	10	0.44–0.59	Roberds et al. (2003) *	
	6–7	0.12–0.30	Westbrook et al. (2013) *	
<i>P. caribaea</i>	10–20	0.64–0.71	Roberds and Strom (2006) ***	
	27	0.25	Santos et al. (2016)	
<i>P. oocarpa</i>	5	0.2	Fabián-Plesníková et al. (2022)	

produced in huge amounts in all pine tissues, including needles, and phloem and xylem in roots and stems (Wu and Hu, 1997). This massive investment in resin implies a huge sink of photoassimilates that may no longer be available for other vital functions such as growth or

reproduction. Thus, negative relationships between resin production and growth and reproduction should be expected (Vázquez-González et al., 2021). However, resin is produced in resin ducts and the number and size of resin ducts increase with tree growth, so the more the tree grows, the more resin will produce (Hood and Sala, 2015). These explanations point to opposite directions of growth-resin relationships and may explain the lack of consensus of published data. Specifically, genetic correlations between growth and resin production range from no significant (Tadesse et al., 2001; Vázquez-González et al., 2021) to positive correlations (Lai et al., 2017; Liu et al., 2013; Zeng et al., 2013). Altogether, improving resin yield without affecting growth rate and timber quality traits seems feasible. However, the relation between growth and resin production is far from being clear. In *P. pinaster*, for example, despite the lack of additive genetic correlations, growth and resin production appear to be positively related at the phenotypic level (see also *Dendrometry and phenotypic traits* section), while they are negatively correlated at the population level (i.e. fast growing populations tend to produce less resin and vice versa) (Vázquez-González et al., 2021; Zas et al., 2020). This negative correlation at the population level has been explained in terms of evolutionary constraints associated to the large costs of resin production (Vázquez-González et al., 2021). As trait to trait correlations are known to be species-, population- and environmentally-dependent, further research is still needed to depict the complete picture of the relationships between growth and resin production in pine trees.

Intraspecific genetic variation is not restricted to resin yield but also affects other relevant traits involved in resin production, such as some physical properties or its chemical composition. For example, according to McReynolds (1971) heritability estimate for viscosity for the resin of slash pine is high. The chemical composition of *P. pinaster* resin is also known to vary across populations (Arrabal et al., 2005) and within populations (Arrabal et al., 2002) with large differences in some specific terpenes between high-yielders and control trees (Arrabal et al., 2002), a result that was also observed in other pine species (Chen et al., 2006; Lai et al., 2020; Neis et al., 2019a; Zhang et al., 2016). Genetic variation in resin duct metrics is also important and has been reported in several pine species such *P. pinaster* (Vázquez-González et al., 2019), *P. radiata* (Govina et al., 2021) or *P. taeda* (Westbrook et al., 2015).

More recently, an important research effort is in course to depict the molecular basis of resin production (both quantitatively and qualitatively), with notable progress in the identification of the genes involved in resinosis (Y. Li et al., 2022; Z. Li et al., 2022; Yi et al., 2022) as well as in the physical and chemical properties of the resin (Bai, 2022; de Lima et al., 2016; Junkes et al., 2019a; Liu et al., 2020). This progress has allowed to describe molecular markers and fine tune genomics tools to identify and select high resin yielders. Selection through molecular studies at the transcriptomic level is possible and may facilitate and accelerate the otherwise complex and slow breeding cycles. The selection of genes involved in resin quality is aimed at obtaining a resin whose chemical composition is better suited to the needs of the industry rather than to improve the final quantity obtained (Ding et al., 2023). In addition to molecular studies, Shi et al. (2021) also used proteomic analysis to reveal the regulatory pathways and protein targets associated with resin biosynthesis.

Taking all these results together, genetic selection and breeding for improved resin yield emerges as one of the key tools to improve the profitability of resin tapping exploitations. In forestry, these techniques have been successfully practised for decades to improve productivity and timber quality achieving significant genetic gains (Jansson et al., 2017). Given that intraspecific genetic variation in resin-related traits is generally very large and that heritability of resin yield is higher than that of growth traits, even larger genetic gains should be expected for resin yield genetic improvement. However, up to date there are only partial studies on the genetics of resin yield and very few and inconclusive breeding initiatives that have deployed improved material to be used in reforestation. Nonetheless, advances in molecular biology tools

and progress on the identification of the genes involved in resin production and their expression (Liu et al., 2015; Mei et al., 2021b; Shi et al., 2021; Westbrook et al., 2015, 2013) will facilitate the implementation of effective breeding programs for rapid improving resin production of future plantations (Liu et al., 2019, 2020).

6.2. Climatic, physiographic and edaphic

Other factors that may affect the resin production of the pine trees are those related with the environment and, particularly with the climate, physiography and edaphic conditions of the site where the trees are established (Blanche et al., 1992). In other words, resin yield and resin components are known to be highly plastic traits to environmental variations (Sampedro et al., 2010). According to the literature, many different climatic parameters have been shown to modulate resin production (Table 4). Among them, the climatic variables that most affect resin flow and have the highest correlation values with resin production, are temperature and those related to soil water storage (Blanche et al., 1992; Lombardero et al., 2000; Lorio and Hodges, 1968; Zas et al., 2020). In most of the studies showed in Table 4, temperature affects positively resin yield while the effect of soil water storage departs from being linear, with resin yield increasing under moderate water deficit but decaying when water stress becomes more severe (Rodríguez-García et al., 2015).

In addition to these two main variables, the effects of other factors such as precipitation, potential evapotranspiration, relative humidity, accumulated water deficit and daily solar radiation were also shown to modulate resin yield in some extent (Table 4). The effect of precipitation varied across studies from negative (Neis et al., 2018) to positive correlations (Gajšek et al., 2018). Similarly in the case of relative humidity, the results of the relationship with resin yield were contradictory, with positive (Rodríguez-García et al., 2016) and negative (Sharma et al., 2018a) results, while PET tend to affect positively resin production (Rodríguez-García et al., 2015; Sharma et al., 2018a). Relationships between resin flow and the cumulative water deficit and the daily solar radiation were either negative (Gajšek et al., 2018; Rodríguez-García et al., 2015) or positive (Rodríguez-García et al., 2015; Sharma et al., 2018a; Zas et al., 2020b) results, although only the positive ones were statistically significant. Besides the variables showed in Table 4, Rodríguez-García et al. (2015) had positive relations with the mean water deficit (0.47) and the actual evapotranspiration (0.11). Due to the modulation of precipitation and temperature, resin production has a very strong seasonal component, especially in temperate and mediterranean climates. In these areas, resin tapping is typically carried out in the warmer months of the year, when temperatures are higher and water deficit is moderate (Hood and Sala, 2015; Kim et al., 2005; Kolb et al., 2019; Rodrigues-Corrêa and Fett-Neto, 2009; Tisdale and Nebeker, 1992; Touza et al., 2021; Yi et al., 2021). In non-Mediterranean and non-temperate areas, according to Rodrigues-Honda et al. (2023), water availability seems to be one of the most important factor affecting pine resin yield, as the lower the rainfall, the lower the resin yield.

Although comparatively much less studied, another group of factors that can intervene in resin yield are the physiographic factors such as altitude and slope. For altitude the results are contradictory, with positive (Lukmandaru et al., 2021) and negative (Sukamo et al., 2015) correlations between resin yield and this factor. Steeper slopes have been also shown to favored higher resin yields (Egloff et al., 2019; Luan et al., 2022).

Soil quality and nutrient availability are also expected to affect resin production as resin is highly costly to produce (Hood and Sala, 2015) and requires large amounts of resources that may ultimately depend on the availability of soil water and nutrient. The presence of clay together with intermittent flooding seems to influence the availability of water in the ground to the tree, thus stimulating resin production (Rodrigues-Honda et al., 2023). However, there seems to be no consensus within the literature about the relationship between soil resources and resin

Table 4

Correlations and simple linear regression r^2 between resin production and climatic variables. Statistically significant correlations ($p < 0.05$) are highlighted in bold. n: sample size; T: mean temperature; MaxT: maximum average temperature; MinT: minimum average temperature; P: average precipitation; PET: potential evapotranspiration; RH: relative humidity; AWD: accumulative water deficit; DSR: daily solar radiation.

Correlations (r)										
Species (n)	Country	T	MaxT	MinT	P	PET	RH	AWD	DSR	Reference (s)
<i>P. nigra</i> (58)	Slovenia	-0.59	-0.51	-0.66	0.42				-0.36	Gajšek et al. (2018)
<i>P. sylvestris</i> (39)	Slovenia	-0.2	-0.21	-0.28	-0.13				-0.09	Gajšek et al. (2018)
<i>P. ponderosa</i> (60)	USA	0.83								Gaylord et al. (2007)
<i>P. merkusii</i>	Indonesia									Lukmandaru et al. (2021)
<i>P. elliotii</i> var. <i>elliottii</i> (398)	Brazil	0.95/0.78			-0.41/-0.90					Neis et al. (2018)
<i>P. pinaster</i> (561)	Spain	0.49			0.09	0.68		-0.32	0.64	Rodríguez-García et al. (2015)
<i>P. pinaster</i> (577)	Spain	0.93					0.67			Rodríguez-García et al. (2016)
<i>P. pinaster</i> (21)	Spain	0.62						0.57		Zas et al. (2020b)
<i>P. roxburghii</i>	India		0.63	0.07	-0.05	0.46	-0.52		0.19	Sharma et al. (2018a)
Simple Linear Regression (r^2)										
<i>P. taeda</i> (30)	USA	0.66								Ruel et al. (1998)
<i>P. elliotii</i> (1620)	Brazil	0.76								Neis et al. (2018)
<i>P. ponderosa</i> (60)	USA	0.88								Gaylord et al. (2007)

production. Some authors claim that better soils increase resin production (García-Fórner et al., 2021; Knebel et al., 2008; Novick et al., 2012; Wei et al., 2014) but others found the opposite (Kytö et al., 1998; Lombardero et al., 2000; Rodrigues-Honda et al., 2023; Ruel et al., 1998; Warren et al., 1999). Most authors reporting that impoverished soils increase pine resin explain their findings in terms of growth defence balance (Loomis, 1932; Lorio, 1986) and carbon-nutrient balance (Bryant et al., 1983) hypotheses, which state that resources tend to be shifted from growth to secondary metabolite production when resource availability decreases. However, trees located in rich soils with abundant nutrients or high water availability may have, in absolute terms, more resources to invest in defence (Knebel et al., 2008; Lombardero et al., 2000; Lorio and Sommers, 1986).

In summary, the number of studies and the results obtained clearly indicate that certain climatic variables are responsible for, and therefore explain, at least part of the environmental variation in resin production. Edaphic or physiographic variables were, however, studied to a lesser extent and the obtained results are mostly inconclusive.

6.3. Dendrometry traits

As seen before, resin yield is a plastic trait highly influenced by climatic, physiographic and edaphic factors. Besides this plasticity to macroenvironmental differences, large variation in resin production is commonly reported within single pine stands, under relatively homogeneous environmental conditions (Vázquez-González et al., 2021). This variation is likely due to plasticity to microenvironmental variation, developmental plasticity and to genotypic variation within sites, and it can be modeled in terms of the variation in phenotypic traits of individual trees within stands. Several phenotypic tree characteristics (related to growth, size or morphology of the whole tree or of particular organs such as stems or leaves), have been shown to be correlated with the resin yield of individual trees (Li et al., 2022). In particular, different dendrometric measurements typically used in forest management to control tree growth have been shown to be strong determinants of resin production (Hadiyane et al., 2015; Rodrigues et al., 2008; Rodrigues-Honda et al., 2023; Rodríguez-García et al., 2014). The main dendrometric traits related to resin yield are diameter at breast height (dbh) and total height (ht), but some works also reported significant relationships between resin production and other traits such as crown

Table 5

Correlations between resin production and dasometric variables at the individual tree level. Statistically significant correlations ($p < 0.05$) are highlighted in bold. n: sample size; dbh: diameter at breast height; ht: total height; CR: crown ratio; CI: competition index; BA: basal area; V: volume; Bark: bark thickness.

Species (n)	Country	Case study	Correlations (r)							
			dbh	ht	CR	CI	BA	V	Bark	Reference (s)
<i>P. taeda</i> (45)	USA	Early summer	0.07	0.14	-0.03			-0.15		Lombardero et al. (2000)
<i>P. taeda</i> (45)	USA	Late summer	0.65	0.11	0.48			-0.61		Lombardero et al. (2000)
<i>P. pinaster</i> (26)	Spain			0.46						Rodríguez-García et al. (2014)
<i>P. pinaster</i> (44)	Portugal		0.57							García-Fórner et al. (2021)
<i>P. pinaster</i> (504)	Spain	June	0.14	0.18*						Zas et al. (2020b)
		July	0.13	0.10						
		September	0.18	0.17						
<i>P. pinaster</i> (1584–1636) (893–896)	Spain	Carbonero	0.16	0.12						Vázquez-González et al. (2021)
	Spain	Saviñao	-0.06	-0.10						Vázquez-González et al. (2021)
<i>P. caribaea</i> (96)	Brazil		0.41	0.23				0.36		Santos et al. (2016)
<i>P. oocarpa</i> (251)	Mexico		0.14		0.16		-0.78 (n = 15)			Egloff (2019)
<i>P. nigra</i> (58)	Slovenia		0.46							Gajšek et al. (2018)
<i>P. sylvestris</i> (39)	Slovenia		0.09							Gajšek et al. (2018)
<i>P. roxburghii</i>	India		0.48	0.48					0.41	Sood et al. (2019)
<i>P. merkusii</i> (10)	Indonesia		0.16	-0.03						Abdillah et al. (2020)

ratio (CR), competition index (CI) or basal area increment (BAI)(Table 5 and Table 6).

The most studied relationship is between resin yield and the diameter at breast height, for which most of the results are significantly positive (Table 5). Other factors such as total height, crown ratio, competition index, basal area, basal area increment, volume, bark and phloem thickness, radial growth, needle length and thickness, mean leaf angle and LAI have been also studied but the number of available studies is much lower. The effect of total height and crown ratio was mostly positive and significant (Rodríguez-García et al., 2014; Sood et al., 2019). The positive relationships between diameter, height and crown ratio with resin production denotes a size effect where bigger trees tend to produce more resin. This may be explained in terms of an increasing capacity to produce and accumulate more resin in larger trees due to a greater net of resin canals. Competition index and basal area were always negatively related with resin flow (Table 5). This is not surprising given the large amounts of resources needed for resin production (Egloff et al., 2019; Lombardero et al., 2000; McDowell et al., 2007).

Besides to the information presented in the Table 5 and Table 6, Lombardero et al. (2000) also explored the correlations between the inducible resin flow after mechanical wounding and different dendrometric variables in *P. taeda*. While inducible resin flow in early summer was not related to any tree trait, inducible resin flow in late summer (when conditions for tree growth were less favourable) was positively related to radial growth ($r = 0.62-0.63$) and phloem thickness ($r = 0.40$). The relationships between resin production and several other morphologic traits not included in Table 5 have been explored in a few studies. For example, Sood et al. (2019) estimated in Indian *P. roxburghii* trees the correlations between resin yield and number of branches ($r = 0.14$), needle length ($r = 0.33$), needle thickness ($r = 0.27$), leaf area index (LAI) ($r = 0.31$) and mean leaf angle ($r = 0.35$). The positive relationships with needle size and LAI have been explained in terms of increased resin flow with greater tree vigor, rather than a direct effect of the canopy characteristics on resin production. However, McDowell et al. (2007) exploring the relation between the resin yield and LAI in *P. ponderosa* found no significant relationships. Some authors have also explored whether the relationships between dasometric traits and resin flow may depart from being linear, but the results gave no support for this idea (Sood et al., 2019).

In addition to univariate approaches described up to here, other studies have tried to predict resin upon multiple linear regression models that use climatic and dasometric variables together in different combinations. These studies are summarized in Table 7. The climatic variables used in these models are temperature, precipitation (Wang et al., 2006) while those related to dendrometry were, mainly, tree diameter. Wang et al. (2006), modelling resin production in *P. kesiya* species, obtained a high predictive value ($r^2 = 0.91$) with temperature, precipitation and dbh appearing the equation with positive coefficients, meaning that they positively affect resin production. In another study with *P. oocarpa*, Reyes-Ramos et al. (2019) modeled.

resin production using climate unit, the number of tapping faces open in the tree, and the unbranched stem height. The coefficient of

Table 6

Values of r^2 of the simple linear regression models between resin production and dasometric variables. Values of statistically significant correlations ($p < 0.05$) are in bold. n: sample size; dbh: diameter at breast height; ht: total height; BA: basal area; BAI: basal area increment; Bark: bark thickness.

Simple Linear Regressions (r^2)							
Species (n)	Country	dbh	ht	BA	BAI	Bark	Reference (s)
<i>P. pinaster</i> (26)	Spain	0.38					Rodríguez-García et al. (2014)
<i>P. pinaster</i> (100)	Spain	0.24/0.23					García-Mejome et al. (2019)
<i>P. pinaster</i> (150)	Spain	0.46		0.36	0.84		Martínez-Chamorro et al. (2016)
<i>P. ponderosa</i>	USA						McDowell et al. (2007)
<i>P. halepensis</i> (195)	Greece	0.31					Spanos et al. (2010)
<i>P. nigra</i> (58)	Slovenia	0.21					Gajšek et al. (2018)
<i>P. sylvestris</i> (39)	Slovenia	0.01					Gajšek et al. (2018)
<i>P. roxburghii</i>	India	0.22	0.48			0.16	Sood et al. (2019)

Table 7

Values of r^2 of other regression models between resin production and dasometric variables.

Multiple Regressions (r^2)				
Species	Country	Variable	r^2	Reference (s)
<i>P. kesiya</i>	China	Temperature, precipitation, dbh	0.91	Wang et al. (2006)
<i>P. oocarpa</i>	Mexico	Climatic unit, number of tapping faces open in the tree, unbranched stem height	0.68	Reyes-Ramos et al. (2019)
<i>P. pinaster</i>	Spain	Age, Slenderness	0.45	Zas et al. (2020)
<i>P. caribaea</i>	Brazil	dbh, total height, C	0.75	Brito et al. (1982)

determination was, in this case, $r^2 = 0.68$. Zas et al. (2020) predicted resin flow in.

P. pinaster using tree age and tree slenderness as the independent variables, and explained the obtained.

model in terms of the positive relationship between tree age and abundance of resin canals and the effect of tree competition on tree slenderness. Finally, Brito et al. (1982) utilised the diameter, the total height and the average of the lengths of the exudation lines of the north and south faces for predict resin yield in *P. caribaea*.

Given the general positive relationships between the dendrometric measurements and resin production summarized here, simple and classical dendrometric traits may be valid tools or at least help for estimating resin production of individual trees of forest stands.

6.4. Anatomical traits

From an anatomical perspective, the phenotypic elements that intervene most in resin yield were the resin ducts (Lin et al., 2002; Neis et al., 2019a; Rigling et al., 2003). These tube-like structures that are distributed in axial and radial directions, in different tissues (cortex and xylem) and organs (stems, roots, needles, cones) (Krekling et al., 2000; Wu and Hu, 1997), accumulate under pressure the resin synthesized in the epithelial cells that conform the canals (Krokene and Nagy, 2012). Higher inner volume of the resin canal network is thus assumed to be directly related with the potential to produce resin. In addition, the differentiation of resin canals may be induced in response to damage of the cambium by frosty, mechanical, chemical, or pathogenic origin (Cabrita, 2021). The so called traumatic resin ducts (Eyles et al., 2010; Krokene and Nagy, 2012) enhance the defensive status of pine trees preventing the progression of the damage. As resin tapping implies large traumatism in the trunks, new traumatic resin ducts are assumed to be differentiated in response to tapping with these new canals likely contributing to increase resin yield, at least in the following tapping campaigns (Touza et al., 2021). Different characteristics of the resin duct network have been associated with resin flow or resin yield (Esteban et al., 2012; Lai et al., 2017). The results of this association are shown in Table 8.

The results shown in Table 8 show mostly positive significant

Table 8

Correlations and simple linear regressions between resin production and resin ducts (RD) and traumatic ducts (TD) characteristics. Significant correlations are highlighted in bold. r: value of correlations.

Species	Country	Case study	Correlations (r)		
			Variable	r	Reference (s)
<i>P. taeda</i>	USA	Early summer	RD density (RD/cm ²)	0.03	Lombardero et al. (2000)
		Early summer	Number RD (RD/year)	0.25	
		Late summer	RD density (RD/cm ²)	-0.41	
		Late summer	Number RD (RD/year)	0.31	
<i>P. pinaster</i>	Portugal	PCO	Average RD size (mm ²)	0.51	García-Fornier et al. (2021)
		PCO	RD production (RD)	0.58	
		PCO	RD area (mm ²)	0.70	
		PCO	RD density (RD/mm ²)	-0.21	
		PCO	Relative RD area (%)	0.19	
		VPA	Average RD size (mm ²)	0.03	
		VPA	RD production (RD)	0.62	
		VPA	RD area (mm ²)	0.56	
		VPA	RD density (RD/mm ²)	0.31	
		VPA	Relative RD area (%)	0.31	
		<i>P. elliottii</i> var. <i>elliottii</i>	Spain		
Brazil			RD diameter (mm)	0.64	
Axial RD frequency (RD/mm RD volume (mm ³))				0.49	
RD area (mm ²)				0.39	
Simple Linear Regression (r ²)					
<i>P. pinaster</i>	Spain		RD frequency (RD/mm ²)	0.23	Rodríguez-García et al. (2014)
<i>P. oocarpa</i>	Mexico	Progenies	TD area (mm ²)	0.53	Fabián-Plesniková et al. (2022)
		Mother trees	TD diameter (mm)	0.50	
		Progenies	TD area (mm ²)	0.69	
		Mother trees	TD diameter (mm)	0.63	

correlations, although in some few study cases the relations are not significant or even significantly negative. The highest positive correlation values have been obtained for the size measurements (ducts area or mean duct diameter), but resin duct density was also positively related with resin production in some cases (Neis et al., 2019a; Rodríguez-García et al., 2014). Taking all together, although there is evidences supporting the general idea that the greater the number and size of resin ducts, the more resin, the relationships were, in general, less strong than expected. Other physical factors related to the resin ducts that can also affect the resin flow are the viscosity (Hodges et al., 1981) and the pressure (Rissanen et al., 2016) at which the resin is subjected when it circulates through the resin duct network. Resin viscosity has been shown to be variable depending on the season (McReynolds, 1971) and the resin chemical components (Cabrita, 2021). Resin pressure is a factor that varies daily and seasonality because it is directly related to temperature and water turgor in tissues surrounding the resin ducts (Rissanen et al., 2021, 2019, 2016).

6.5. Fires and pests

Resin ducts, which support the production of resin and, thus, together with the bark, tree first defences against external factors (Franceschi et al., 2005; Valor et al., 2021), are highly responsive to externalities, including fire (Hood et al., 2015; Lombardero et al., 2006; Vázquez-González et al., 2020), pests (Kolb et al., 2019; Lombardero et al., 2006; Santoro et al., 2001) and pathogens (Luchi et al., 2005; Nagy et al., 2006). These topics have been widely studied within the plant defence field, but not that much in relation to resin production and resin tapping. For example, important research efforts have been paid to understand the role of resin canals and their inducibility upon damage or fire in the resistance to bark beetle attacks in the USA (Lombardero et al., 2006; Santoro et al., 2001; Wallin et al., 2003). According to some authors, low-intensity fires have been shown to increase resin flow by inducing the differentiation of resin ducts (Cannac et al., 2009; Hood et al., 2015; Prasetya et al., 2017; Roberds and Strom, 2006; Vázquez-González et al., 2020) and reducing resin viscosity (Davis et al., 2011), but others have shown that the effects of fire are not reflected in resin yield (Perrakis and Agee, 2006; Rodríguez-García et al., 2018).

Resin production also increases after mechanical wounding (Hood and Sala, 2015; Knebel et al., 2008; Li et al., 2022; Ruel et al., 1998), pathogen infection (Knebel et al., 2008; Luchi et al., 2005; Phillips and Croteau, 1999), or pest attack (Franceschi et al., 2005; Kane and Kolb, 2010; Phillips and Croteau, 1999), with this increase being part of the immunological induced response to these attacks.

6.6. Extraction method

A number of factors related to the tapping procedure itself can largely vary the amount of raw material a resin harvester can collect. These factors include the extraction method, the frequency of the grooves and the use of stimulant pastes. Generally, extraction methods consist of making incisions by removing strips of bark and phloem from living pine trees, cutting and causing the formation of new resin canals, thus triggering resin production. According to Cunningham (2009), there are currently four methods of extraction that are widespread in the world, two with the application of chemical stimulants and two without. The methods using chemical stimulation are the “bark streak” or “American” method, widely used in Brazil and Argentina (Candaten et al., 2021; Füller et al., 2016; Rodrigues et al., 2008) and variants used mainly in the Mediterranean area (Spain, Portugal and France) (Serrano et al., 2013; Torrijos et al., 2013), and the “Mazek” or “Rill” method (Sharma et al., 2018b), extended in India and Indonesia. In the “American” method, a horizontal groove of 2–3 cm wide and a length of about one third of the tree perimeter is made every 14 days (Rodríguez-García et al., 2014). In the “Mazek” method, a V-shaped upward groove of 2–3 mm wide is made every 3–7 days (Cunningham, 2012). The methods that do not use chemical stimulation are the “Chinese” method (Wei et al., 2014), used in China, and the “Hughes” or “French” method, developed in the 19th century in France and currently only used in Indonesia and Mexico (Hartiningtias et al., 2020; Reyes-Ramos et al., 2019). The “Chinese” method consists of making a V-shaped downward groove every day by cutting approximately half the circumference of the tree, in the “Hughes” method an 8–10 cm groove is cut every 10–15 days (Cunningham, 2009; Williams et al., 2017).

Other methods less commonly used than the above are the “Borehole” (Hodges, 1995; Sharma et al., 2013a; Sukarno et al., 2015) and

"EuroGem" (Picardo, 2013; Rubini et al., 2022) methods, extraction systems that collect the resin in a closed container. In the first method, a hole 15 cm deep and 2.5 cm in diameter is drilled into the trees (Sharma et al., 2018b), in the second method a circular disc of bark and phloem 8 cm in diameter is extracted from the trunk of the trees (Picardo, 2013). In order to improve the ergonomics of the tapping work, innovation attempts to mechanize the debarking and drilling processes and to collect and transport the resin production through the forest are also in progress (Gurau et al., 2021; Rodríguez-García et al., 2016; Serrano et al., 2013; Yovi et al., 2021).

Within each of these methods, resin production can largely vary depending on the size (length and width) and the direction of the incisions (Gómez-García et al., 2017; Jimeno and Crespo, 2013; Rodríguez-Soalleiro et al., 2008; Rodríguez-García et al., 2016; Sharma et al., 2013b). The timing of the interventions is other important variable with major impacts on resin yield. Groove frequency largely varies according to the stimulant paste used and the labour costs in the region (Touza et al., 2021). According to the literature the time between successive grooves in open-container methods, can range from two to fourteen days (Heinze et al., 2021; Pinillos et al., 2009; Martínez-Chamorro et al., 2019b; Yi et al., 2021). It is also important to note the disadvantage of the "Rill" and Chinese methods, as the wound needs to be renewed every few days. In addition, some of available methods are more damaging to the tree than others. This is the case of the "Hugues" and borehole methods, in which strips of wood are removed, making resin extraction incompatible with subsequent timber harvesting.

In remote times, no stimulants were used during the resin tapping process. However, the incorporation of stimulant pastes produced a drastic increase in the production of resin and the profitability of the exploitations. These chemical stimulants applied after the mechanical wounding induce a slow necrosis of living cells, which favours the resin production of the remaining living cells (Wolter et al., 1980), increasing the amount of resin generated and preventing wound healing, thus prolonging the exudation process. Stimulant sprays were first used in Germany, USSR and USA to increase resin production in the 1930's, but it wasn't until 1964 when R.W. Clements developed a stimulant in the form of a viscous and sticky paste, that the use of stimulant pastes was generalized thus reducing the hazards derived from the use of sprays (Parham, 1976).

The main pastes used today are based on different proportions of sulfuric acid, potassium, salicylic acid, Ethephon, Ethrel, benzoic acid, neftalene acetic acid, paraquat, copper and 2-Chloroethyl phosphonic Acid (CEPA) (Füller et al., 2016; Neis et al., 2018; Rodrigues-Corrêa et al., 2013; Rodrigues-Corrêa and Fett-Neto, 2013, 2012; Silverman et al., 2005; García-Mejome et al., 2019; García-Mejome et al., 2020; Martínez et al., 2013). Among the above compounds, salicylic acid, is a phytohormone involved in signaling the induced response to biotic damage, and Ethephon, Ethrel and CEPA are synthetic precursors of ethylene, which is also a phytohormone involved in the signaling of defensive responses to mechanical and biotic stimuli (Rodrigues-Corrêa and Fett-Neto, 2012). Several studies have compared the different yields of the above-mentioned stimulant compounds (Junkes et al., 2019b; Neis et al., 2018; Liu et al., 2022; Rodrigues et al., 2011, 2008; Rodrigues-Corrêa and Fett-Neto, 2013, 2009). Current trends in the formulation of stimulant pastes are more in line with ecofriendly trends, trying to reduce the proportion of sulfuric acid. This is why it is increasingly common to use pastes with a higher proportion of other components, such as citric acid or methyl jasmonate, the last being another phytohormone involved in the signaling of induced response to biotic damage (López-Villamor et al., 2021; Michavila et al., 2021; Vázquez-González et al., 2022).

7. Conclusion

After this bibliographical review, it can be stated that the subject of resin extraction has experienced a growing trend in publications in the

last years, with the three main producing countries (China, Brazil and Indonesia), plus USA and Spain, contributing the most to the scientific production. This increasing interest for resin production is likely linked to the current need to find natural resources capable of substituting petroleum derivatives, and how to optimise their production. Up to date, the different studies carried out have produced results that are not very homogeneous in terms of the variables that intervene in resin production and how they do so. What is clearly deduced from the revised literature is that resin production is extremely variable both genetically and plastically. At the genetic level, variation in resin production and resin composition occurs both across and within species, and across and within populations with resin yield showing moderate to high heritability estimates. The significance of attaining enhanced management over tree productivity and resin composition is growing, driven by the diverse applications it offers. Consequently, initiatives such as transcriptomic-level molecular studies are gaining prominence, as they enable the identification of genes associated with these traits. At the environmental level, resin production varies in response to multiple abiotic and biotic factors.

The environmental variables modulating resin production on which most of the research effort has focused is temperature with positive correlations in the majority of the studies consulted, and water availability, as key factors involved in resin production. The influence of temperature and water availability on resin production explains the seasonal nature of resin tapping activities.

Variation in resin production also occurred within environmentally homogeneous stands. Several phenotypic traits at the individual tree level have been shown to explain this variation. Diameter at breast height is the trait that most frequently correlated (positive) with resin production, although other dasometric traits related to tree size such as tree height and crown radius are also typically positively related. From a mechanistic point of view resin duct characteristics are the main factors determining resin productivity. Research related to extraction methods and different stimulants has increased in recent years, looking for new extraction methods and pastes with lower sulfuric acid content.

Despite the increasing interest for pine resin production and the relatively abundant scientific literature that has been produced up to date, conclusions on the sources of variation of resin production are far from being definitive. More research effort is still needed at least on 1) exploring in greater depth the correlations between the different variables involved in resin production, 2) new resin tapping methods and pastes should be further investigated, in order to automatize resin extraction and obtain a higher resin quality, 3) new statistical modelling approaches, as machine learning or deep learning, should be tested to see if it is possible to obtain more robust and statistically significant models to predict resin production potential of individual trees and pine stands and 4) implementing all this knowledge in accessible tools for forest managers who are interested in this type of use.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.indcrop.2023.117105](https://doi.org/10.1016/j.indcrop.2023.117105).

References

- Abdillah, E., Muharyani, N., Na'lem, M., 2020. The characteristics of *Pinus mercusii* resin productivity flow pattern. IOP Conf. Ser.: Earth Environ. Sci. 528 (1), 012031 <https://doi.org/10.1088/1755-1315/528/1/012031>.
- Agrios, G.N., 2005. How plants defend themselves against pathogens. Plant Pathol. 207–248. <https://doi.org/10.1016/B978-0-08-047378-9.50012-9>.
- Aldas, M., Pavon, C., López-Martínez, J., Arrieta, M.P., 2020. Pine resin derivatives as sustainable additives to improve the mechanical and thermal properties of injected moulded thermoplastic starch. Appl. Sci. 10 (7), 2561. <https://doi.org/10.3390/app10072561>.
- Alonso-Esteban, J.I., Carocho, M., Barros, D., Velho, M.V., Heleno, S., Barros, L., 2022. Chemical composition and industrial applications of maritime pine (*Pinus pinaster* Ait.) bark and other non-wood parts. Rev. Environ. Sci. Bio/Technol. 1–51, 022–09624-1. <https://doi.org/10.1007/s11157>.
- Aloui, F., Baraket, M., Jedidi, S., Hmaidi, B., Salem, E.B., Jdai, N., Taghouti, I., Nasr, Z., Abbes, C., 2022. Assessment of biological activities of resin extracted from Tunisian pine forests. Pak. J. Bot. 54 (2) [https://doi.org/10.30848/pjb2022-2\(45\)](https://doi.org/10.30848/pjb2022-2(45)).
- Arrabal, C., Cortijo, M., Simón, B.F.D., García-Vallejo, M.C., Cadaña, E., 2002. *Pinus pinaster* oleoresin in plus trees. Holzforschung 56 (3), 261–266. <https://doi.org/10.1515/HF.2002.043>.
- Arrabal, C., Cortijo, M., Simón, B.F.D., Vallejo, M.C.G., Cadaña, E., 2005. Differentiation among five Spanish *Pinus pinaster* provenances based on its oleoresin terpenic composition. Biochem. Syst. Ecol. 33 (10), 1007–1016. <https://doi.org/10.1016/J.BSE.2005.03.003>.
- Assis, T.F., Resende, M.D.V., 2011. Genetic improvement of forest tree species. Crop Breed. Appl. Biotechnol. 11 (spe), 44–49. <https://doi.org/10.1590/S1984-70332011000500007>.
- Bai, Q., 2022. Comparative transcriptomics of *Pinus massoniana* organs provides insights on terpene biosynthesis regulation. Physiol. Plant. 174 (5), e13791 <https://doi.org/10.1111/pp1.13791>.
- Blanche, C.A., Lorio, P.L., Sommers, R.A., Hodges, J.D., Nebeker, T.E., 1992. Seasonal cambial growth and development of loblolly pine: Xylem formation, inner bark chemistry, resin ducts, and resin flow. For. Ecol. Manag. 49 (1–2), 151–165. [https://doi.org/10.1016/0378-1127\(92\)90167-8](https://doi.org/10.1016/0378-1127(92)90167-8).
- Bolonio, D., Sánchez-Canales, M., Jiménez-Oyola, S., Ortega, M.F., Donoso, D., García-Martínez, M.J., Lapuerta, M., Canoira, L., 2022. Techno-economic, life cycle, and environmental cost assessment of biojet fuel obtained from *Pinus pinaster* by turpentine hydrogenation. Sustainable. Energy Fuels 6 (10), 2478–2489. <https://doi.org/10.1039/D2SE00275B>.
- Brito, J.O., Barrichelo, L.E., Couto, H.T.Z., do, Capitani, L.R., Neves, M. de, A., 1982. Método rápido para estimar a produção de resina em árvores de *Pinus*. IPEF: Instituto de Pesquisas e Estudos Florestais ESALQ-USP. São Paulo, Braz., Cir. Tec. 148, 1–9.
- Bryant, J.P., Chapin, F.S., Klein, D.R., 1983. Carbon/Nutrient balance of boreal plants in relation to vertebrate herbivory. Oikos 40 (3), 357. <https://doi.org/10.2307/3544308>.
- Cabrita, P., 2021. A model for resin flow. In: Ramawat, K.G., Ekiert, H.M., Goyal, S. (Eds.), Plant Cell and Tissue Differentiation and Secondary Metabolites: Fundamentals and Applications. Springer, pp. 117–144. https://doi.org/10.1007/978-3-030-30185-9_5.
- Candaten, L., Lazarotto, S., Zwetsch, A.P.R., Rieder, E., Silva, M.D., da, Machado, G., Balbinot, R., Trevisan, R., 2021. Resinagem de pinus no Brasil: Aspectos gerais, métodos empregados e mercado. Evangelista, Wescley (org.). Produtos Florestais Não Madeireiros: tecnologia, mercado, pesquisas e atualidades. Científica. <https://doi.org/10.37885/210504772>.
- Cannac, M., Barboni, T., Ferrat, L., Bighelli, A., Castola, V., Costa, J., Trecul, D., Morandini, F., Pasqualini, V., 2009. Oleoresin flow and chemical composition of Corsican pine (*Pinus nigra* subsp. *laricio*) in response to prescribed burnings. For. Ecol. Manag. 257 (4), 1247–1254. <https://doi.org/10.1016/j.foreco.2008.11.017>.
- Chen, F., Yuan, Y., Yu, S., Zhang, T., 2015. Influence of climate warming and resin collection on the growth of Masson pine (*Pinus massoniana*) in a subtropical forest, southern China. Trees 29 (5), 1423–1430. <https://doi.org/10.1007/s00468-015-1222-3>.
- Chen, H., Tang, M., Gao, J., Chen, X., Li, Z., 2006. Changes in the composition of volatile monoterpenes and sesquiterpenes of *Pinus armandi*, *P. tabulaeformis*, and *P. bungeana* in Northwest China. Chem. Nat. Compd. 42 (5), 534–538. <https://doi.org/10.1007/S10600-006-0208-1>.
- Clopeau, A., Orazio, C., 2019. El mercado internacional de la resina. Tierra De. Pinares 2, 23–26.
- Cunningham, A., 2009. Estado actual de la resinación en el mundo. Proceedings XIII Congreso Forestal Mundial. Buenos Aires, Argentina, p. 7.
- Cunningham, A., 2012. Pine resin tapping techniques used around the world. ISBN 9788130804934. In: Arthur Germano Fett-Neto; Kelly Cristine da Silva Rodrigues-Corrêa. (Eds.). Pine Resin: Biology, Chemistry and Applications. 1ed. Kerala: Research Signpost, 1–8.
- Cunningham, A., 2022. Visión internacional sobre el mercado de la miera. Proceedings JORNADA TÉCNICA EL SECTOR RESINERO NACIONAL Un Oficio Profesional. Innovador y de Calidad.
- Davis, T.S., Jarvis, K., Parise, K., Hofstetter, R.W., 2011. Oleoresin exudation quantity increases and viscosity declines following a fire event in a ponderosa pine ecosystem. J. Ariz. - Nev. Acad. Sci. 43 (1), 6–11. <https://doi.org/10.2181/036.043.0102>.
- Demko, J., Machava, J., 2022. Tree resin, a macroergic source of energy, a possible tool to lower the rise in atmospheric CO₂ levels. Sustainability 14 (6), 3506. <https://doi.org/10.3390/SU14063506>.
- Ding, X., Li, Y., Zhang, Y., Diao, S., Luan, Q., Jiang, J., 2023. Genetic analysis and elite tree selection of the main resin components of slash pine. Front. Plant Sci. 14, 174. <https://doi.org/10.3389/FPLS.2023.1079952>.
- Donoso, D., Ballesteros, R., Bolonio, D., García-Martínez, M.J., Lapuerta, M., Canoira, L., 2021. Hydrogenated turpentine: a biobased component for jet fuel. Energy Fuels 35 (2), 1465–1475. <https://doi.org/10.1021/acs.energyfuels.0c03379>.
- Dutt, B., Kumar, R., H., V., 2020. Assessing the potential half-sib progenies of *Pinus roxburghii* Sargent for oleoresin yield. Int. J. Chem. Stud. 8, 2037–2039. <https://doi.org/10.22271/chemi.2020.v8.i1ad.8567>.
- Egloff, P., 2019. Tapping *Pinus oocarpa*-Assessing drivers of resin yield in natural stands of *Pinus oocarpa*. Master's Thesis, Wageningen University & Research, Wageningen, The Netherlands, 1–29.
- Esteban, L.G., Martín, J.A., Palacios, P., de, Fernández, F.G., 2012. Influence of region of provenance and climate factors on wood anatomical traits of *Pinus nigra* Arn. subsp. *salsmannii*. Eur. J. For. Res. 131 (3), 633–645. <https://doi.org/10.1007/S10342-011-0537-X>.
- Eyles, A., Bonello, P., Ganley, R., Mohammed, C., 2010. Induced resistance to pests and pathogens in trees. New Phytol. 185 (4), 893–908. <https://doi.org/10.1111/J.1469-8137.2009.03127.X>.
- Fabián-Plesniková, I., Sáenz-Romero, C., Terrazas, T., Reyes-Ramos, A., Martínez-Trujillo, M., Cruz-De-León, J., Sánchez-Vargas, N.M., 2022. Traumatic ducts size varies genetically and is positively associated to resin yield of *Pinus oocarpa* open-pollinated progenies. Silvae Genet. 71 (1), 10–19. <https://doi.org/10.2478/SG-2022-0002>.
- Franceschi, V.R., Krokene, P., Christiansen, E., Krokene, T., 2005. Anatomical and chemical defenses of conifer bark against bark beetles and other pests. New Phytol. 167 (2), 353–376. <https://doi.org/10.1111/J.1469-8137.2005.01436.X>.
- Füller, T.N., Lima, J.C. de, Costa, F., Rodrigues-Corrêa, K.C.S., Fett-Neto, A.G., 2016. Stimulant paste preparation and bark streak tapping technique for pine oleoresin extraction. In: Fett-Neto, A.G. (Ed.), Biotechnology of Plant Secondary Metabolism: Methods in Molecular Biology 1405 © Springer Science+Business Media New York. https://doi.org/10.1007/978-1-4939-3393-8_2.
- Gajšek, D., Brečelj, M., Jarni, K., Brus, R., 2018. Resin yield of *Pinus nigra* and *Pinus sylvestris* in the Slovenian Karst. Acta Silvae Et. Ligni 115, 21–28. <https://doi.org/10.20315/asetl.115.2>.
- García-Fórner, N., Campelo, F., Carvalho, A., Vieira, J., Rodríguez-Pereiras, A., Ribeiro, M., Salgueiro, A., Silva, M.E., Louzada, J.L., 2021. Growth-defence trade-offs in tapped pines on anatomical and chemical production. For. Ecol. Manag. 496, 119406 <https://doi.org/10.1016/j.foreco.2021.119406>.
- García-Mejome, A., Martínez-Chamorro, E., Fernández, E., Gómez-García, E., 2019. Estudio para mejorar la productividad de miera con el sistema de resinación de pica de corteza en pinares atlánticos de *Pinus pinaster* Ait. Proceedings XII Congreso de Economía Agraria (AEEA 2019) Lugo. España, pp. 701–704.
- García-Mejome, A., Martínez-Chamorro, E., Blanco, E.F., Gómez-García, E., 2020. Análisis de producciones y rendimientos del sistema de resinación de pica de corteza con estimulación química de doble cara ancha en masas de *Pinus pinaster* Ait. Cuyo objetivo principal es la producción de madera. Recur. Rurais 16, 5–10. <https://doi.org/10.15304/rr.016972>.
- Gaylord, M.L., Kolb, T.E., Wallin, K.F., Wagner, M.R., 2007. Seasonal dynamics of tree growth, physiology, and resin defenses in a northern Arizona ponderosa pine forest. Can. J. For. Res. 37 (7), 1173–1183. <https://doi.org/10.1139/X06-309>.
- Gómez-García, E., Martínez-Chamorro, E., García-Mejome, A., Lorenzo, M.J.R., 2022. Modelling resin production distributions for *Pinus pinaster* Ait. Stands in NW Spain. Ind. Crop. Prod. 176, 114316 <https://doi.org/10.1016/j.indcrop.2021.114316>.
- Gómez-García, E., Lorenzo, M.J.R., Folgoso, A.Q., Martínez-Chamorro, E., 2017. Instalación de ensayos para determinar las posibilidades del aprovechamiento resinero en Galicia. In: Proceedings 7º Congreso Forestal Español. Plasencia, Cáceres, España, 8.
- Govina, J.K., Apolaza, L.A., Altaner, C.M., 2021. Variation and genetic parameters of axial resin canal features in clones and families of *Pinus radiata*. New For. 52 (1), 167–176. <https://doi.org/10.1007/S11056-020-09780-8>.
- Gurau, V., Ragland, B., Cox, D., Michaud, A., Busby, L., 2021. Robot operations for pine tree resin collection. Technologies 9 (4), 79. <https://doi.org/10.3390/technologies9040079>.
- Hadiyane, A., Sulistyawati, E., Asharina, W.P., Dungani, R., 2015. A study on production of resin from *Pinus merkusii* Jungh. et de Vriese in the Bosscha observatory area, West Java-Indonesia. Asian J. Plant Sci. 14 (2), 89–93. <https://doi.org/10.3923/ajps.2015.89.93>.
- Hartiningtias, D., Fulé, P.Z., Gunawan, A.A., 2020. Wildfire effects on forest structure of *Pinus merkusii* in Sumatra, Indonesia. For. Ecol. Manag. 457, 117660 <https://doi.org/10.1016/J.FORECO.2019.117660>.
- Hayta, P., Oktav, M., Duru, Ö.A., 2022. An ecological approach to printing industry: Development of ecofriendly offset printing inks using vegetable oils and pine resin as renewable raw materials and evaluation of printability. Color Res. Appl. 47 (1), 164–171. <https://doi.org/10.1002/col.22708>.

- Heinze, A., Kuyper, T.W., Barrios, L.E.G., Marcial, N.R., Bongers, F., 2021. Tapping into nature's benefits: values, effort and the struggle to co-produce pine resin. *Ecosyst. People* 17 (1), 69–86. <https://doi.org/10.1080/26395916.2021.1892827>.
- Hodges, A.W., 1995. Management Strategies for a Borehole Resin Production System in Slash Pine. University of Florida.
- Hodges, J.D., Elam, W.W., Bluhm, D.R., 1981. Influence of resin duct size and number on oleoresin flow in the southern pines. Res. Note SO-266. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 3. <https://doi.org/10.2737/SO-RN-266>.
- Hood, S., Sala, A., 2015. Ponderosa pine resin defenses and growth: Metrics matter. *Tree Physiol.* 35 (11), 1223–1235. <https://doi.org/10.1093/treephys/tpv098>.
- Hood, S., Sala, A., Heyerdahl, E.K., Boutin, M., 2015. Low-severity fire increases tree defense against bark beetle attacks. *Ecology* 96 (7), 1846–1855. <https://doi.org/10.1890/14-0487.1>.
- Jansson, G., Hansen, J.K., Haapanen, M., Kvaalen, H., Steffenrem, A., 2017. The genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland. *Scand. J. For. Res.* 32 (4), 273–286. <https://doi.org/10.1080/02827581.2016.1242770>.
- Jantan, I., Ahmad, A.S., 1999. Oleoresins of Three Pinus Species from Malaysian Pine Plantations. ASEAN Review of Biodiversity and Environmental Conservation (ARBEC).
- Jimeno, A.D.D., Crespo, A.S., 2013. Mejoras tecnológicas en procesos de resinación y campañas experimentales. In: II International Symposium on Natural Resins. Pp. 90–103.
- Junkes, C.F., de, O., de Araújo Júnior, A.T., de Lima, J.C., de Costa, F., Füller, T., de Almeida, M.R., Neis, F.A., Rodrigues-Corrêa, K.C.S., Fett, J.P., Fett-Neto, A.G., 2019a. Resin tapping transcriptome in adult slash pine (*Pinus elliottii* var. *elliottii*). *Ind. Crop. Prod.* 139, 111545 <https://doi.org/10.1016/j.indcrop.2019.111545>.
- Junkes, C.F., de, O., Duz, J.V.V., Kerber, M.R., Wieczorek, J., Galvan, J.L., Fett, J.P., Fett-Neto, A.G., 2019b. Resinosis of young slash pine (*Pinus elliottii* Engelm.) as a tool for resin stimulant paste development and high yield individual selection. *Ind. Crop. Prod.* 135, 179–187. <https://doi.org/10.1016/j.indcrop.2019.04.048>.
- Kane, J.M., Kolb, T.E., 2010. Importance of resin ducts in reducing ponderosa pine mortality from bark beetle attack. *Oecologia* 164 (3), 601–609. <https://doi.org/10.1007/s00442-010-1683-4>.
- Karademir, A., Aydemir, C., Yenidogan, S., Kandirmaz, E.A., Kiter, R.G., 2020. The use of natural (*Pinus pinaster*) resin in the production of printing ink and the printability effect. *Color Res. Appl.* 45 (6), 1170–1178. <https://doi.org/10.1002/COL.22534>.
- Kim, J.C., Kim, K.J., Kim, D.S., Han, J.S., 2005. Seasonal variations of monoterpene emissions from coniferous trees of different ages in Korea. *Chemosphere* 59 (11), 1685–1696. <https://doi.org/10.1016/j.chemosphere.2004.10.048>.
- Knebel, L., Robison, D.J., Wentworth, T.R., Klepzig, K.D., 2008. Resin flow responses to fertilization, wounding and fungal inoculation in loblolly pine (*Pinus taeda*) in North Carolina. *Tree Physiol.* 28 (6), 847–853. <https://doi.org/10.1093/treephys/28.6.847>.
- Kolb, T., Keefover-Ring, K., Burr, S.J., Hofstetter, R., Gaylord, M., Raffa, K.F., 2019. Drought-mediated changes in tree physiological processes weaken tree defenses to bark beetle attack. *J. Chem. Ecol.* 45 (10), 888–900. <https://doi.org/10.1007/S10886-019-01105-0>.
- Krekling, T., Franceschi, V.R., Berryman, A.A., Christiansen, E., 2000. The structure and development of polyphenolic parenchyma cells in Norway spruce (*Picea abies*) bark. *Flora* 195 (4), 354–369. [https://doi.org/10.1016/S0367-2530\(17\)30994-5](https://doi.org/10.1016/S0367-2530(17)30994-5).
- Krokene, P., Nagy, N.E., 2012. Anatomical aspects of resin-based defenses in pine. ISBN 9788130804934. In: Arthur Germano Fett-Neto; Kelly Cristine da Silva Rodrigues-Corrêa. (Eds.). Pine Resin: Biology, Chemistry and Applications. 1ed. Kerala: Research Signpost. 67–86.
- Kytö, M., Niemelä, P., Annala, E., 1998. Effects of vitality fertilization on the resin flow and vigour of scots pine in Finland. *For. Ecol. Manag.* 102 (2–3), 121–130. [https://doi.org/10.1016/S0378-1127\(97\)00150-3](https://doi.org/10.1016/S0378-1127(97)00150-3).
- Lai, M., Dong, L., Yi, M., Sun, S., Zhang, Y., Fu, L., Xu, Z., Lei, L., Leng, C., Zhang, L., 2017. Genetic variation, heritability and genotype × environment interactions of resin yield, growth traits and morphologic traits for *Pinus elliottii* at three progeny trials. *Forests* 8 (11). <https://doi.org/10.3390/f8110409>.
- Lai, M., Zhang, L., Lei, L., Liu, S., Jia, T., Yi, M., 2020. Inheritance of resin yield and main resin components in *Pinus elliottii* Engelm. At three locations in southern China. *Ind. Crop. Prod.* 144, 112065 <https://doi.org/10.1016/j.indcrop.2019.112065>.
- Lainez, M., González, J.M., Aguilar, A., Vela, C., 2018. Spanish strategy on bioeconomy: towards a knowledge based sustainable innovation. *N. Biotechnol.* 40, 87–95. <https://doi.org/10.1016/J.NBT.2017.05.006>.
- Langenheim, J.H., 2003. Plant Resins: Chemistry, Evolution, Ecology, and Ethnobotany. Timber Press., Portland, OR, USA.
- Lauture, M.J., 2017. Reinventing oleoresin collection in the southeast USA: Evaluation of chemical inducers, stand management, tree characteristics, and genetics.
- Leksono, B., Hardiyanto, E.B., 1996. Genetic variation of oleoresin yield of *Pinus merkusii* Jungh et de Vriese. In: Dieters, M. et al. (Ed.), Tree Improvement for Sustainable Tropical Forestry. Proceedings QFRI-IUFRO Conference. 202–203.
- Li, Y., Jiang, J., Luan, Q., 2012. Determination and genetic analysis of resin productivity, resin density and turpentine content in half-sib families of slash pine. *J. Beijing For. Univ.* 34 (4), 48–51.
- Li, Y., Sun, H., Paula Protásio, T., de, Hein, P.R.G., Du, B., 2022. The mechanisms and prediction of non-structural carbohydrates accretion and depletion after mechanical wounding in slash pine (*Pinus elliottii*) using near-infrared reflectance spectroscopy. *Plant Methods* 18 (1), 1–13 <https://doi.org/10.1186/S13007-022-00939-2/>.
- Li, Z., Shen, L., Hou, Q., Zhou, Z., Mei, L., Zhao, H., Wen, X., 2022. Identification of genes and metabolic pathways involved in resin yield in masson pine by integrative analysis of transcriptome, proteome and biochemical characteristics. *Int. J. Mol. Sci.* 23 (19), 11420. <https://doi.org/10.3390/ijms231911420>.
- de Lima, J.C., de Costa, F., Füller, T.N., Rodrigues-Corrêa, K.C.D.S., Kerber, M.R., Lima, M.S., Fett, J.P., Fett-Neto, A.G., 2016. Reference genes for qPCR analysis in resin-tapped adult slash pine as a tool to address the molecular basis of commercial resinosis. *Front. Plant Sci.* 7, 849. <https://doi.org/10.3389/FPLS.2016.00849>.
- Lin, J., Hu, Y., He, X., Ceulemans, R., 2002. Systematic survey of resin canals in Pinaceae. Source: *Belgian Journal of Botany* 135(2), 3–14.
- Liu, J.J., Williams, H., Zamany, A., Li, X.R., Gellner, S., Snieszko, R.A., 2019. Development and application of marker-assisted selection (MAS) tools for breeding of western white pine (*Pinus monticola* Douglas ex D. Don) resistance to blister rust (*Cronartium ribicola* J.C. Fisch.) in British Columbia. *Can. J. Plant Pathol.* 42, 250–259. <https://doi.org/10.1080/07060661.2019.1638454>.
- Liu, J.J., Snieszko, R.A., Sissons, R., Krakowski, J., Alger, G., Schoettle, A.W., Williams, H., Zamany, A., Zitomer, R.A., Kegley, A., 2020. Association mapping and development of marker-assisted selection tools for the resistance to white pine blister rust in the Alberta limber pine populations. *Front. Plant Sci.* 11, 1404. <https://doi.org/10.3389/fpls.2020.557672>.
- Liu, Q., Zhou, Z., Fan, H., Liu, Y., 2013. Genetic variation and correlation among resin yield, growth, and morphologic traits of *Pinus massoniana*. *Silvae Genet.* 62 (1–2), 38–44. <https://doi.org/10.1515/sg-2013-0005>.
- Liu, Q., Zhou, Z., Wei, Y., Shen, D., Feng, Z., Hong, S., 2015. Genome-wide identification of differentially expressed genes associated with the high yielding of oleoresin in secondary xylem of masson pine (*Pinus massoniana* Lamb) by transcriptomic analysis. *PLoS ONE* 10 (7), e0132624. <https://doi.org/10.1371/JOURNAL.PONE.0132624>.
- Liu, Q., Xie, Y., Liu, B., Huanhuanyin, Zhou, Z., Feng, Z., Chen, Y., 2020. A transcriptomic variation map provides insights into the genetic basis of *Pinus massoniana* Lamb. Evolution and the association with oleoresin yield. *BMC Plant Biol.* 20 (1), 1–14. <https://doi.org/10.1186/S12870-020-02577-Z>.
- Liu, Y., Wang, Z., Zhao, F., Zeng, M., Li, F., Chen, L., Wu, H., Che, X., Li, Y., Deng, L., Zhong, S., Guo, W., 2022. Efficient resin production using stimulant pastes in *Pinus elliottii* × *P. caribaea* families. *Sci. Rep.* 12 (1), 13129. <https://doi.org/10.1038/s41598-022-17329-2>.
- Loewen, B., 2005. Resinous paying materials in the French Atlantic, AD 1500–1800. History, technology, substances. *Int. J. Naut. Archaeol.* 34 (2), 238–252. <https://doi.org/10.1111/j.1095-9270.2005.00057.x>.
- Lombardero, M.J., Ayres Jr, M.P., Ruel, J.J., P.L.L., 2000. Environmental effects on constitutive and inducible resin defences of *Pinus taeda*. *Ecol. Lett.* 3 (4), 329–339. <https://doi.org/10.1046/j.1461-0248.2000.00163.x>.
- Lombardero, M.J., Ayres, M.P., Ayres, B.D., 2006. Effects of fire and mechanical wounding on *Pinus resinosa* resin defenses, beetle attacks, and pathogens. *For. Ecol. Manag.* 225 (1–3), 349–358. <https://doi.org/10.1016/j.foreco.2006.01.010>.
- Loomis, W.E., 1932. Growth-differentiation balance vs. Carbohydrate-nitrogen ratio. *Proc. Am. Soc. Hortic. Sci.* 240–245.
- López-Goldar, X., Villari, C., Bonello, P., Borg-Karlson, A.K., Grivet, D., Sampedro, L., Zas, R., 2019. Genetic variation in the constitutive defensive metabolome and its inducibility are geographically structured and largely determined by demographic processes in maritime pine. *J. Ecol.* 107 (5), 2464–2477. <https://doi.org/10.1111/1365-2745.13159>.
- López-Villamor, A., Zas, R., Pérez, A., Cáceres, Y., Silva, M.N., da, Vasconcelos, M., Vázquez-González, C., Sampedro, L., Solla, A., 2021. Traumatic resin ducts induced by methyl jasmonate in *Pinus* spp. *Trees* 35 (2), 557–567. <https://doi.org/10.1007/s00468-020-02057-9>.
- Lorio, P.L., 1986. Growth-differentiation balance: A basis for understanding southern pine beetle-tree interactions. *For. Ecol. Manag.* 14 (4), 259–273. [https://doi.org/10.1016/0378-1127\(86\)90172-6](https://doi.org/10.1016/0378-1127(86)90172-6).
- Lorio, P.L., Hodges, J.D., 1968. Microsite effects on oleoresin exudation pressure of large loblolly pines. *Ecology* 49 (6), 1207–1210. <https://doi.org/10.2307/1934519>.
- Lorio, P.L., Sommers, R.A., 1986. Evidence of competition for photosynthates between growth processes and oleoresin synthesis in *Pinus taeda* L. *Tree Physiol.* 2 (1–2–3), 301–306. <https://doi.org/10.1093/treephys/2.1-2-3.301>.
- Luan, Q., Diao, S., Sun, H., Ding, X., Jiang, J., 2022. Prediction and comparisons of turpentine content in slash pine at different slope positions using near-infrared spectroscopy. *Plants* 11 (7), 914. <https://doi.org/10.3390/plants11070914>.
- Luchi, N., Ma, R., Capretti, P., Bonello, P., 2005. Systemic induction of traumatic resin ducts and resin flow in ustrian pine by wounding and inoculation with *Sphaeropsis sapinea* and *Diplodia scrobiculata*. *Planta* 221 (1), 75–84. <https://doi.org/10.1007/s00425-004-1414-3>.
- Lukmandaru, G., Amri, S., Sunarta, S., Listyanto, T., Pujiarti, R., Widyorini, R., 2020. Oleoresin yield of *Pinus merkusii* trees from East Banyumas. IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing. <https://doi.org/10.1088/1755-1315/449/1/012024>.
- Lukmandaru, G., Amri, S., Sunarta, S., Listyanto, T., Pujiarti, R., Widyorini, R., 2021. The effect of stimulants and environmental factors on resin yield of *Pinus merkusii* tapping. *BioResources* 16 (1), 163–175. <https://doi.org/10.15376/biores.16.1.163-175>.
- Martínez, M.O., Salazar, B.G., Suárez, M.Á., Camacho, P., Martínez, S., 2013. Guía básica de trabajos de resinación en pinares. PRODESE (Ed.).
- Martínez-Chamorro, E., 2016. Revisión de las primeras experiencias de resinación en Galicia (1950-1970). *Recur. Rurais* 12, 13–22.
- Martínez-Chamorro, E., Riesco, G., García-Méijome, A., Gómez, E., Rodríguez, R., 2019a. Propuesta de modelo selvícola combinando producción de madera y resina para pinares atlánticos de *Pinus pinaster*. In: In: Proceedings XII Congreso de Economía Agraria (AEAA 2019), pp. 709–712. Lugo, España.

- Martínez-Chamorro, E., Rozados, M.J.L., García-Méijome, A., García, E.G., 2019b. Adaptación del aprovechamiento resinero en masas de *Pinus pinaster* Ait. destinadas a la producción de madera de sierra en Galicia. *Montes* 137, 32–36.
- McDowall, N.G., Adams, H.D., Bailey, J.D., Kolb, T.E., 2007. The role of stand density on growth efficiency, leaf area index, and resin flow in southwestern ponderosa pine forests. *Can. J. For. Res.* 37 (2), 343–355. <https://doi.org/10.1139/X06-233>.
- McReynolds, R.D., 1971. Heritability and seasonal changes in viscosity of slash pine oleoresin. Res. Note SE-155. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 4, 155.
- Mei, L., Wen, X., Fan, F., Yang, Z., Xie, W., Hong, Y., 2021a. Genetic diversity and population structure of masson pine (*Pinus massoniana* Lamb.) superior clones in south China as revealed by EST-SSR markers. *Genet. Resour. Crop Evol.* 68, 1987–2002. <https://doi.org/10.1007/S10722-021-01112-9z>.
- Mei, L., Yan, Y., Li, Z., Ran, J., Shen, L., Wu, R., Hou, Q., Shen, T., Wen, X., Yang, Z., Feng, Y., 2021b. Identification of the diterpenoid biosynthesis genes and their expression status in relation to oleoresin yield of masson pine. *Ind. Crop. Prod.* 170, 113827 <https://doi.org/10.1016/j.indcrop.2021.113827>.
- Meiggs, R., 1982. *Trees and Timber in the Ancient Mediterranean World*. Clarendon Press.
- Mergen, F., Hoekstra, P.E., Echols, R.M., 1955. Genetic control of oleoresin yield and viscosity in slash pine. *For. Sci.* 1 (1), 19–30. <https://doi.org/10.1093/FORESTSCIENCE/1.1.19>.
- Michavila, S., Moreno-González, V., Labarga, D., Martínez, E., Acebes, J.L., 2017. El hombre y la resina de pino: Desde su uso pasado hasta la actualidad con especial atención en España. *AmbioCiencias* 15, 21–30.
- Michavila, S., Rodríguez-García, A., Rubio, F., Gil, L., Lopez, R., 2021. Salicylic and citric acid as promising new stimulants for resin tapping in maritime pine (*Pinus pinaster* Ait.). *For. Syst.* 29, eSC07. <https://doi.org/10.5424/fs/2020293-16737>.
- Moreno-Fernández, D., Zavala, M.A., Madrigal-González, J., Seijo, F., 2021. Resilience as a moving target: An evaluation of last century management strategies in a dry-edge maritime pine ecosystem. *Forests* 12 (9). <https://doi.org/10.3390/f12091151>.
- Nagy, N.E., Krokene, P., Solheim, H., 2006. Anatomical-based defense responses of scots pine (*Pinus sylvestris*) stems to two fungal pathogens. *Tree Physiol.* 26 (2), 159–167. <https://doi.org/10.1093/treephys/26.2.159>.
- Nanos, N., Tadesse, W., Montero, G., Gil, L., Alia, R., 2000. Modelling resin production distributions for *Pinus pinaster* Ait using two probability functions. *Ann. For. Sci.* 57 (4), 369–377. <https://doi.org/10.1051/forest:2000128>.
- Nanos, N., Tadesse, W., Montero, G., Gil, L., Alia, R., 2001. Spatial stochastic modeling of resin yield from pine stands. *Can. J. For. Res.* 31 (7), 1140–1147. <https://doi.org/10.1139/cjfr-31-7-1140>.
- Neis, F.A., Costa, F., de, Füller, T.N., Lima, J.C., de, Silva Rodrigues-Corrêa, K.C.S., Fett, J.P., Fett-Neto, A.G., 2018. Biomass yield of resin in adult *Pinus elliottii* Engelm. Trees is differentially regulated by environmental factors and biochemical effectors. *Ind. Crop. Prod.* 118, 20–25. <https://doi.org/10.1016/j.indcrop.2018.03.027>.
- Neis, F.A., Costa, F., de, Almeida, M.R., de, Colling, L.C., Oliveira Junkes, C.F., de, Fett, J.P., Fett-Neto, A.G., 2019a. Resin exudation profile, chemical composition, and secretory canal characterization in contrasting yield phenotypes of *Pinus elliottii* Engelm. *Ind. Crop. Prod.* 132, 76–83. <https://doi.org/10.1016/j.indcrop.2019.02.013>.
- Neis, F.A., Costa, F., de, Araújo, A.T., de, Fett, J.P., Fett-Neto, A.G., 2019b. Multiple industrial uses of non-wood pine products. *Ind. Crop. Prod.* 130, 248–258. <https://doi.org/10.1016/j.indcrop.2018.12.088>.
- Novick, K.A., Katul, G.G., McCarthy, H.R., Oren, R., 2012. Increased resin flow in mature pine trees growing under elevated CO₂ and moderate soil fertility. *Tree Physiol.* 32 (6), 752–763. <https://doi.org/10.1093/treephys/tpri133>.
- Nugrahanto, G., Na'iem, M., Indrioko, S., Faridah, E., Widiyatno, W., Abdillah, E., 2022. Genetic parameters for resin production of *Pinus merkusii* progeny test collected from three landraces in Banyumas Barat Forest District, Indonesia. *Biodiversitas J. Biol. Divers.* 23 (4) <https://doi.org/10.13057/biodiv/d230436>.
- Palma, A., Pestana, M., Azevedo, A., 2012. Pine resin sector in Portugal-weaknesses and challenges. *Forest. Ideas* 18 (1), 10–18.
- Palma, A., Pereira, J.M., Soares, P., 2016. Resin tapping activity as a contribution to the management of maritime pine forest. *For. Syst.* 25 (2), eSC11. <https://doi.org/10.5424/fs/2016252-08925>.
- Papadopoulos, A.M., 2013. Resin tapping history of an aleppo pine forest in central Greece. *Open For. Sci. J.* 6 (1), 50–53. <https://doi.org/10.2174/1874398601306010050>.
- Parham, M.R., 1976. Stimulation of oleoresin yield in conifers. *Outlook Agric.* 9 (2), 76–81. <https://doi.org/10.1177/003072707600900207>.
- Perrakis, D.D., Agee, J.K., 2006. Seasonal fire effects on mixed-conifer forest structure and ponderosa pine resin properties. *Can. J. For. Res.* 36 (1), 238–254. <https://doi.org/10.1139/x05-212>.
- Phillips, M.A., Croteau, R.B., 1999. Resin-based defenses in conifers. *Trends Plant Sci.* 4 (5), 184–190. [https://doi.org/10.1016/S1360-1385\(99\)01401-6](https://doi.org/10.1016/S1360-1385(99)01401-6).
- Picardo, Á., 2013. La resinación en España y en el mundo en 2013: Situación y perspectivas, II Simposio Internacional de Resinas Naturales, 30–54, Segovia, España.
- Pinillos, F.M., Picardo, Á., Allué-Andrade, M., Soria, E., Sanz, A., 2009. La resina: Herramienta de conservación de nuestros pinares. CESEFOR (Ed).
- Prasetya, C.D., Syaifina, L., Santosa, G., 2017. The effect of various types of forest fires on pine resin productivity in Gunung Walat University Forest, Sukabumi, Indonesia. *Biodiversitas J. Biol. Divers.* 18 (1), 476–482. <https://doi.org/10.13057/biodiv/d180158>.
- Ramírez-Valiente, J.A., Blanco, L.S., del, Alía, R., Robledo-Arnuncio, Juan, J., Climent, J., 2022. Adaptation of Mediterranean forest species to climate: Lessons from common garden experiments. *J. Ecol.* 110 (5), 1022–1042. <https://doi.org/10.1111/1365-2745.13730>.
- Reyes-Ramos, A., León, J.C., de, Martínez-Palacios, A., Lobit, P.C.M., Ambríz-Parra, J.E., Sánchez-Vargas, N.M., 2019. Ecological and dendrometric characters in which influence resin production of *Pinus oocarpa* of Michoacán, Mexico. *Madera Y Bosques* 25 (1). <https://doi.org/10.21829/myb.2019.2511414>.
- Rezzi, S., Bighelli, A., Castola, V., Casanova, J., 2005. Composition and chemical variability of the oleoresin of *Pinus nigra* ssp. *laricio* from Corsica. *Ind. Crop. Prod.* 21 (1), 71–79. <https://doi.org/10.1016/j.indcrop.2003.12.008>.
- Rigling, A., Ehlhart, H.B., Eker, O.U.B., Forster, T., Schweingruber, F.H., 2003. Effects of irrigation on diameter growth and vertical resin duct production in *Pinus sylvestris* L. on dry sites in the central alps, Switzerland. *For. Ecol. Manag.* 175 (1–3), 285–296. [https://doi.org/10.1016/S0378-1127\(02\)00136-6](https://doi.org/10.1016/S0378-1127(02)00136-6).
- Rissanen, K., Hölttä, T., Vanhatalo, A., Aalto, J., Nikinmaa, E., Rita, H., Bäck, J., 2016. Diurnal patterns in scots pine stem oleoresin pressure in a boreal forest. *Plant Cell Environ.* 39 (3), 527–538. <https://doi.org/10.1111/pce.12637>.
- Rissanen, K., Hölttä, T., Barreira, L.F.M., Hyytiäinen, N., Kurtén, T., Bäck, J., 2019. Temporal and spatial variation in scots pine resin pressure and composition. *Front. For. Glob. Change* 2. <https://doi.org/10.3389/ffgc.2019.00023>.
- Rissanen, K., Hölttä, T., Bäck, J., Rigling, A., Wermelinger, B., Gessler, A., 2021. Drought effects on carbon allocation to resin defences and on resin dynamics in old-grown scots pine. *Environ. Exp. Bot.* 185, 104410 <https://doi.org/10.1016/j.envenpbot.2021.104410>.
- Roberds, J.H., Strom, B.L., 2006. Repeatability estimates for oleoresin yield measurements in three species of the southern pines. *For. Ecol. Manag.* 228 (1–3), 215–224. <https://doi.org/10.1016/j.foreco.2006.03.005>.
- Roberds, J.H., Strom, B.L., Hain, F.P., Gwaze, D.P., McKeand, S.E., Lott, L.H., 2003. Estimates of genetic parameters for oleoresin and growth traits in juvenile loblolly pine. *Can. J. For. Res.* 33 (12), 2469–2476. <https://doi.org/10.1139/x03-186>.
- Rodrigues, K.C.S., Azevedo, P.C.N., Sobreiro, L.E., Pelissari, P., Fett-Neto, A.G., 2008. Oleoresin yield of *Pinus elliottii* plantations in a subtropical climate: effect of tree diameter, wound shape and concentration of active adjuvants in resin stimulating paste. *Ind. Crop. Prod.* 27 (3), 322–327. <https://doi.org/10.1016/j.indcrop.2007.11.010>.
- Rodrigues, K.C.S., Apel, M.A., Henriques, A.T., Fett-Neto, A.G., 2011. Efficient oleoresin biomass production in pines using low cost metal containing stimulant paste. *Biomass Bioenergy* 35 (10), 4442–4448. <https://doi.org/10.1016/j.biombioe.2011.08.021>.
- Rodrigues-Corrêa, K.C.S., Fett-Neto, A.G., 2009. Oleoresin yield of *Pinus elliottii* in a subtropical climate: seasonal variation and effect of auxin and salicylic acid-based stimulant paste. *Ind. Crop. Prod.* 30 (2), 316–320. <https://doi.org/10.1016/j.indcrop.2009.06.004>.
- Rodrigues-Corrêa, K.C.S., Fett-Neto, A.G., 2012. Physiological control of pine resin production. ISBN 9788130804934. Arthur Germano Fett-Neto; Kelly Cristine da Silva Rodrigues-Corrêa. (Eds.). *Pine Resin: Biology, Chemistry and Applications*, first ed. Research Signpos, Kerala, pp. 25–48.
- Rodrigues-Corrêa, K.C.S., Fett-Neto, A.G., 2013. Seasonality and chemical elicitation of defense oleoresin production in field-grown slash pine under subtropical climate. *Theoretical and Experimental. Plant Physiol.* 25 (1), 56–61.
- Rodrigues-Corrêa, K.C.S., Lima, J.C., de, Fett-Neto, A.G., 2013. Oleoresins from pine: production and industrial uses, natural products: phytochemistry, botany and metabolism of alkaloids. Phenolics and Terpenes. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-22144-6_175.
- Rodrigues-Honda, K.C.S., Junkes, C.F., de, O., Lima, J.C., de, Waldow, V., de, A., Rocha, F.S., Sausen, T.L., Bayer, C., Talamini, E., Fett-Neto, A.G., 2023. Carbon sequestration in resin-tapped slash pine (*Pinus elliottii* Engelm.) Subtropical Plantations. *Biology* 12 (2), 324. <https://doi.org/10.3390/biology12020324>.
- Rodríguez-García, A., López, R., Martín, J.A., Pinillos, F., Gil, L., 2014. Resin yield in *Pinus pinaster* is related to tree dendrometry, stand density and tapping-induced systemic changes in xylem anatomy. *For. Ecol. Manag.* 313, 47–54. <https://doi.org/10.1016/j.foreco.2013.10.038>.
- Rodríguez-García, A., Martín, J.A., López, R., Mutke, S., Pinillos, F., Gil, L., 2015. Influence of climate variables on resin yield and secretory structures in tapped *Pinus pinaster* Ait. in central Spain. *Agric. For. Meteorol.* 202, 83–93. <https://doi.org/10.1016/j.agrformet.2014.11.023>.
- Rodríguez-García, A., Martín, J.A., López, R., Sanz, A., Gil, L., 2016. Effect of four tapping methods on anatomical traits and resin yield in maritime pine (*Pinus pinaster* Ait.). *Ind. Crop. Prod.* 86, 143–154. <https://doi.org/10.1016/j.indcrop.2016.03.033>.
- Rodríguez-García, A., Madrigal, J., González-Sancho, D., Gil, L., Guijarro, M., Hernando, C., 2018. Can prescribed burning improve resin yield in a tapped *Pinus pinaster* stand? *Ind. Crop. Prod.* 124, 91–98. <https://doi.org/10.1016/j.indcrop.2018.07.049>.
- Rodríguez-Soalleiro, R.J., Serrada, R., Lucas, J.A., Alejano, R., Rio, M., Torres, E., Cantero, A., 2008. Selvicultura de *Pinus pinaster* Ait. subsp. *mesogeensis* Fieschi & Gausson. Compendio De Selvicultura Aplicada En España. INIA 399–430.
- Romanelli, R.C., Sebbenn, A.M., 2004. Parâmetros genéticos e ganhos na seleção para produção de resina em *Pinus elliottii* var *elliottii*, no sul do estado de São Paulo. *Rev. do Inst. Florest.* 16 (1), 11–23.
- Rubini, M., Feuillerat, L., Cabaret, T., Leroyer, L., Leneveu, L., Charrier, B., 2021. Comparison of the performances of handheld and benchtop near infrared spectrometers: application on the quantification of chemical components in maritime pine (*Pinus pinaster*) resin. *Talanta* 221, 121454. <https://doi.org/10.1016/j.talanta.2020.121454>.
- Rubini, M., Clopeau, A., Sandak, J., Dumarcay, S., Sandak, A., Gerard, P., Charrier, B., 2022. Characterization and classification of *Pinus* oleoresin samples according to *Pinus* species, tapping method, and geographical origin based on chemical

- composition and chemometrics. *Biocatal. Agric. Biotechnol.* 42, 102340 <https://doi.org/10.1016/j.bcab.2022.102340>.
- Ruel, J.J., Ayres, M.P., Peter, L., Lorio, Jr, 1998. Loblolly pine responds to mechanical wounding with increased resin flow. *Can. J. For. Res.* 28 (4), 596–602. <https://doi.org/10.1139/x98-030>.
- Salto, C., Harrant, L., López, J., Marcó, M.A., 2014. Parámetros genéticos y ganancia genética en producción de resina en *Pinus elliottii* var. *elliottii* (Englem.) En Argentina. In: Proceedings of the VI Reunión GEMFO, 10.
- Sampedro, L., Moreira, X., Llusia, J., Peñuelas, J., Zas, R., 2010. Genetics, phosphorus availability, and herbivore-derived induction as sources of phenotypic variation of leaf volatile terpenes in a pine species. *J. Exp. Bot.* 61 (15), 4437–4447. <https://doi.org/10.1093/jxb/erq246>.
- Santoro, A.E., Lombardero, M.J., Ayres, M.P., Ruel, J.J., 2001. Interactions between fire and bark beetles in an old growth pine forest. *For. Ecol. Manag.* 144 (1–3), 245–254. [https://doi.org/10.1016/S0378-1127\(00\)00389-3](https://doi.org/10.1016/S0378-1127(00)00389-3).
- Santos, W.D., Souza, D.C.L., Moraes, M.L.T.D., Aguiar, A.V.D., 2016. Genetic variation of wood and resin production in *Pinus caribaea* var. *hondurensis* Barret & Golfari. *Silvae Genet.* 65 (1), 31–37. <https://doi.org/10.1515/sg-2016-0004>.
- Santos-del-Blanco, L., Alía, R., González-Martínez, S.C., Sampedro, L., Lario, F., Climent, J., 2015. Correlated genetic effects on reproduction define a domestication syndrome in a forest tree. *Evolut. Appl.* 8 (4), 403–410. <https://doi.org/10.1111/EVA.12252>.
- Sebastián, J.A. (ed. lit.), Uriarte-Ayo, R. (ed. lit.), 2003. Historia y economía del bosque en la Europa del sur (siglos XVIII-XX), Historia y economía del bosque en la Europa del Sur (Siglos XVIII-XX). Prentice Universitarias de Zaragoza. <https://doi.org/10.26754/uz.84-7733-649-0>.
- Serrano, E.P., Ortiz, R.B., Gómez, A.A., 2013. Evaluación de la producción de miera obtenida según diferentes métodos de resinación en un monte de la serranía baja de cuenca. In: Proceedings 6^o Congreso Forestal Español, Vitoria-Gasteiz, España, 10.
- Sharma, K.R., Lekha, C., Parmar, Y.S., 2013a. Tapping of *Pinus roxburghii* (chir pine) for oleoresin in Himachal Pradesh, India. *Advances in Forestry Letters (AFL)*.
- Sharma, S.C., Prasad, N., Sharma, K.R., Chandrlekha, 2013b. Development and evaluation of freshening tools for enhancing resin yield from chir pine (*Pinus roxburghii*) using bore hole method of resin tapping. *Agricultural Engineering Today* 37 (2), 42–50.
- Sharma, K.R., Kumar, R., Dutt, B., Attri, V., 2018a. Effect of morphological and environmental factors on oleoresin yield in *Pinus roxburghii* Sargent. *Bulletin of Environment. Pharmacol. Life Sci.* 7, 75–78.
- Sharma, S.C., Prasad, N., Pandey, S.K., Giri, S.K., 2018b. Status of resin tapping and scope of improvement: A review. *Agricultural mechanization in Asia. Afr. Lat. Am.* 49, 16–26.
- Shi, L., Chen, J., Zhang, Q., Bai, Q., 2021. TMT-based comparative proteomic analysis reveals regulatory pathways and protein targets associated with resin biosynthesis in *Pinus massoniana*. *Ind. Crops Prod.* 172, 114077 <https://doi.org/10.1016/j.indcrop.2021.114077>.
- Silverman, F.P., Petracek, P.D., Fledderman, C.M., Ju, Z., Heiman, D.F., Warrior, P., 2005. Salicylate activity. 1. Protection of plants from paraquat injury. *J. Agric. Food Chem.* 53 (25), 9764–9768. <https://doi.org/10.1021/jf0513819>.
- Silvestre, A.J.D., Gandini, A., 2008. Terpenes: Major sources, properties and applications. In: Belgacem, M.N., Gandini, A. (Eds.), *Monomers, Polymers and Composites from Renewable Resources*. Elsevier, Amsterdam, pp. 17–38. <https://doi.org/10.1016/B978-0-08-045316-3.00002-8>.
- Soliño, M., Yu, T., Alía, R., Auñón, F., Bravo-Oviedo, A., Chambel, M.R., Miguel, J., de Río, M., del Justes, A., Martínez-Jauregui, M., Montero, G., Mutke, S., Ruiz-Peinado, R., Barrio, J.M.G. del, 2018. Resin-tapped pine forests in Spain: Ecological diversity and economic valuation. *Sci. Total Environ.* 625, 1146–1155. <https://doi.org/10.1016/j.scitotenv.2018.01.027>.
- Song, Z., Liang, Z., Liu, X., 1995. Chemical characteristics of oleoresins from Chinese pine species. *Biochem. Syst. Ecol.* 23 (5), 517–522.
- Sood, Y., Mahajan, P.K., Bharti, Gupta, R.K., 2019. Correlation and regression studies on estimation of resin yield in *Pinus roxburghii*. *Indian J. Pure Appl. Biosci.* 7 (6), 63–66. <https://doi.org/10.18782/2582-2845.7438>.
- Spanos, K., Gaitanis, D., Spanos, I., 2010. Resin production in natural Aleppo pine stands in northern Evia, Greece. *Web Ecol.* 10 (1), 38–43. <https://doi.org/10.5194/we-10-38-2010>.
- Strom, B.L., Goyer, R.A., Ingram, L.L., Boyd, G.D.L., Lott, L.H., 2002. Oleoresin characteristics of progeny of loblolly pines that escaped attack by the southern pine beetle. *For. Ecol. Manag.* 158 (1–3), 169–178. [https://doi.org/10.1016/S0378-1127\(00\)00710-6](https://doi.org/10.1016/S0378-1127(00)00710-6).
- Suárez-Vidal, E., Sampedro, L., Climent, J., Voltas, J., Sin, E., Notivol, E., Zas, R., 2021. Direct and correlated responses to artificial selection for growth and water-use efficiency in a Mediterranean pine. *Am. J. Bot.* 108 (1), 102–112. <https://doi.org/10.1002/ajb2.1599>.
- Sukarno, A., Hardiyanto, E., Marsoem, S., Na'iem, M., 2015. Oleoresin production, turpentine yield and components of *Pinus merkusii* from various Indonesian provenances. *J. Trop. For. Sci.* 27 (1), 136–141.
- Susilowati, A., Siregar, I.Z., Supriyanto, S., Wahyudi, I., Corryanti, C., 2013. Genetic variation, heritability and correlation between resin production character of *Pinus merkusii* high resin yielder (hry). *Biotropia* 20 (2), 122–133.
- Tadesse, W., Auñón, F.J., Pardos, J.A., Gil, L., Alía, R., 2001. Evaluación precoz de la producción de miera en *Pinus pinaster* Ait. *For. Syst.* 10 (1), 141–150. <https://doi.org/10.5424/717>.
- Tisdale, R.A., Nebeker, T.E., 1992. Resin flow as a function of height along the bole of loblolly pine. *Can. J. Bot.* 70 (12), 2509–2511. <https://doi.org/10.1139/b92-309>.
- Tomusiak, R., Magnuszewski, M., 2009. Effect of resin tapping on radial increments of scots pine (*Pinus sylvestris* L.). *TRACE* 7, 151–157.
- Torre, A.R.D.L., Wilhite, B., Neale, D.B., Slotte, T., 2019. Environmental genome-wide association reveals climate adaptation is shaped by subtle to moderate allele frequency shifts in loblolly pine. *Genome Biol. Evol.* 11 (10), 2976–2989. <https://doi.org/10.1093/GBE/evz220>.
- Torrijos, Y.A., Crespo, A.S., Iglesias, E.M., Herrero, F.M.P., Relaño, R.L., Esteban, E.T., Peña, S.V., 2013. Tiempos y rendimientos del método de resinación mediante pica de corteza tradicional ascendente. In: Proceedings 6^o Congreso Forestal Español, Vitoria-Gasteiz, España, 14.
- Touza, R., Lema, M., Zas, R., 2021. Timing of resin-tapping operations in maritime pine forests in northern Spain. *For. Syst.* 30 (3), eSC05. <https://doi.org/10.5424/fs/2021303-18414>.
- Valor, T., Hood, S.M., Piqué, M., Larrañaga, A., Casals, P., 2021. Resin ducts and bark thickness influence pine resistance to bark beetles after prescribed fire. *For. Ecol. Manag.* 494, 119322 <https://doi.org/10.1016/j.foreco.2021.119322>.
- Van der Maaten, E., Mehl, A., Wilmking, M., Van der Maaten-Theunissen, M., 2017. Tapping the tree-ring archive for studying effects of resin extraction on the growth and climate sensitivity of scots pine. *For. Ecosyst.* 4 (1) <https://doi.org/10.1186/s40663-017-0096-9>.
- Vázquez-González, C., López-Goldar, X., Zas, R., Sampedro, L., 2019. Neutral and climate-driven adaptive processes contribute to explain population variation in resin duct traits in a Mediterranean pine species. *Front. Plant Sci.* 10, 1613. <https://doi.org/10.3389/fpls.2019.01613>.
- Vázquez-González, C., Zas, R., Erbilgin, N., Ferrenberg, S., Rozas, V., Sampedro, L., 2020. Resin ducts as resistance traits in conifers: Linking dendrochronology and resin-based defences. *Tree Physiol.* 40 (10), 1313–1326. <https://doi.org/10.1093/TREEPHYS/TPAA064>.
- Vázquez-González, C., López-Goldar, X., Alía, R., Bustingorri, G., Lario, F.J., Lema, M., Mata, R., de la, Sampedro, L., Touza, R., Zas, R., 2021. Genetic variation in resin yield and covariation with tree growth in maritime pine. *For. Ecol. Manag.* 482, 118843 <https://doi.org/10.1016/j.foreco.2020.118843>.
- Vázquez-González, C., Sampedro, L., López-Goldar, X., Solla, A., Vivas, M., Rozas, V., Lombardero, M.J., Zas, R., 2022. Inducibility of chemical defences by exogenous application of methyl jasmonate is long-lasting and conserved among populations in mature *Pinus pinaster* trees. *For. Ecol. Manag.* 518, 120280 <https://doi.org/10.1016/J.FORECO.2022.120280>.
- Wallin, K.F., Kolb, T.E., Skov, K.R., Wagner, M.R., 2003. Effects of crown scorch on ponderosa pine resistance to bark beetles in northern Arizona. *Environ. Entomol.* 32 (3), 652–661. <https://doi.org/10.1603/0046-225X-32.3.652>.
- Wang, H.L., Yang, W.Y., Gao, C.J., Kun, L., Xiong, H., Yang, F.C., 2015. Anatomical comparison of resin canals in *Pinus yunnanensis* with different oleoresin yield. *For. Res.* 28 (3), 352–357.
- Wang, Z., Calderon, M.M., Carandang, M.G., 2006. Effects of resin tapping on optimal rotation age of pine plantation. *J. For. Econ.* 11 (4), 245–260. <https://doi.org/10.1016/J.JFE.2005.10.001>.
- Warren, J.M., Allen, H.L., Booker, F.L., 1999. Mineral nutrition, resin flow and phloem phytochemistry in loblolly pine. *Tree Physiol.* 19 (10), 655–663. <https://doi.org/10.1093/treephys/19.10.655>.
- Wei, R.P., Yang, R., Wei, Q., 2014. Effect of lime application to acidic soils on oleoresin yield tapped from pine plantations in south China. *Open J. For.* 04 (04), 390–397. <https://doi.org/10.4236/ojf.2014.44044>.
- Westbrook, J.W., Resende, M.F.R., Munoz, P., Walker, A.R., Wegrzyn, J.L., Nelson, C.D., Neale, D.B., Kirst, M., Huber, D.A., Gezan, S.A., Peter, G.F., Davis, J.M., 2013. Association genetics of oleoresin flow in loblolly pine: Discovering genes and predicting phenotype for improved resistance to bark beetles and bioenergy potential. *New Phytol.* 199 (1), 89–100. <https://doi.org/10.1111/nph.12240>.
- Westbrook, J.W., Walker, A.R., Neves, L.G., Munoz, P., Resende, M.F.R., Neale, D.B., Wegrzyn, J.L., Huber, D.A., Kirst, M., Davis, J.M., Peter, G.F., 2015. Discovering candidate genes that regulate resin canal number in *Pinus taeda* stems by integrating genetic analysis across environments, ages, and populations. *New Phytol.* 205 (2), 627–641. <https://doi.org/10.1111/nph.13074>.
- Williams, R., Nauman, C., Zhu, J., 2017. The effects of resin tapping on the radial growth of masson pine trees in south China—a case study. *Agric. Res. Technol.: Open Access J.* 8 (2), 25–28. <https://doi.org/10.19080/ARTOAJ.2017.08.55732>.
- Wiyono, B., Tachibana, S., Tinambunan, D., 2006. Chemical composition of Indonesian *Pinus merkusii* turpentine oils, gum oleoresins and rosins from Sumatra and Java. *Pak. J. Biol. Sci.* 9 (1), 7–14. <https://doi.org/10.3923/PJBS.2006.7.14>.
- Wolter, K.E., Peters, W.J., Roberts, D.R., McReynolds, R.D., Broomfield, J., Crews, E.R., 1980. Process for increasing oleoresin synthesis in *Pinus* species.
- Wu, H., Hu, Z.H., 1997. Comparative anatomy of resin ducts of the Pinaceae. *Trees - Struct. Funct.* 11 (3), 135–143. <https://doi.org/10.1007/s004680050069>.
- Yi, M., Jia, T., Dong, L., Zhang, L., Leng, C., Liu, S., Lai, M., 2021. Resin yield in *Pinus elliottii* Engelm. is related to the resin flow rate, resin components and resin duct characteristics at three locations in southern China. *Ind. Crop. Prod.* 160, 113141 <https://doi.org/10.1016/j.indcrop.2020.113141>.
- Yi, M., Zhang, L., Cheng, Z., Hu, R., Gao, Y., Jin, C., Yuan, S., Sun, S., Lai, M., 2022. Identification of key genes for oleoresin biosynthesis in high and low oleoresin-yielding slash pine based on transcriptome analysis. *Forests* 13 (8), 1337. <https://doi.org/10.3390/f13081337>.
- Yi, W., Xiaolong, Y., Mei, H., Jiang, L., Juan, W., 2018. Transcriptome and gene expression analysis revealed mechanisms for producing high oleoresin yields from simao pine (*Pinus kesiya* var. *langbianensis*). *Plant Omics J.* 11 (01), 42–49. <https://doi.org/10.21475/poj.11.01.18.pne1085>.
- Yovi, E.Y., Prasetyana, D., Nirmalasari, N.A., 2021. Work measurement study on motor-manual pine tapping operation: the application of the concept of lean manufacturing and allowances. *Indones. J. For. Res.* 8 (1), 111–125. <https://doi.org/10.20886/IJFR.2021.8.1.111-125>.

- Zaluma, A., Strike, Z., Rieksts-Riekstin, R., Gaitnieks, T., Vasaitis, R., 2022. Long-term pathological consequences of resin tapping wounds on stems of scots pine (*Pinus sylvestris* L.). *Trees* 36 (5), 1507–1514. <https://doi.org/10.1007/s00468-022-02307-y>.
- Zas, R., Sampedro, L., Prada, E., Fernández-López, J., 2005. Genetic variation of *Pinus pinaster* Ait. seedlings in susceptibility to the pine weevil *Hyllobius abietis* L. *Ann. For. Sci.* 62 (7), 681–688. <https://doi.org/10.1051/forest:2005064>.
- Zas, R., Quiroga, R., Touza, R., Vázquez-González, C., Sampedro, L., Lema, M., 2020. Resin tapping potential of Atlantic maritime pine forests depends on tree age and timing of tapping. *Ind. Crop. Prod.* 157, 112940 <https://doi.org/10.1016/j.indcrop.2020.112940>.
- Zas, R., Touza, R., Sampedro, L., Lario, F.J., Bustingorri, G., Lema, M., 2020b. Variation in resin flow among maritime pine populations: Relationship with growth potential and climatic responses. *For. Ecol. Manag.* 474, 118351 <https://doi.org/10.1016/j.foreco.2020.118351>.
- Zeng, L.H., Zhang, Q., He, B.X., Lian, H.M., Cai, Y.L., Wang, Y.S., Luo, M., 2013. Age trends in genetic parameters for growth and resin-yielding capacity in masson pine. *Silvae Genet.* 62 (1–2), 7–18. <https://doi.org/10.1515/sg-2013-0002>.
- Zeng, X., Ni, P., Li, Y., Wang, W., Sun, S., Wang, Y., Chang, Y., Tao, X., Hou, M., Liu, X., 2021. Short-term resin tapping activities had a minor influence on physiological responses recorded in the tree-ring isotopes of Chinese pine (*Pinus tabulaeformis*). *Dendrochronologia* 70, 125895. <https://doi.org/10.1016/j.dendro.2021.125895>.
- Zhang, S., Jiang, J., Luan, Q., 2016. Genetic and correlation analysis of oleoresin chemical components in slash pine. *Genet. Mol. Res.* 15 (3) <https://doi.org/10.4238/gmr.15038982>.