Seasonal Resin Production in *Pinus pinaster* Ait. Plantations: Dendrometric and Meteorological Influences

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The relationship between dendrometric and meteorological parameters and resin production in *Pinus pinaster* plantations was studied using data from 90 trees collected between June and October. Resin production was measured every 15 days over a five-month period to explore how environmental factors influence resin production rates. The correlation between diameter at breast height (DBH) ranging from 20 cm to 49 cm and total and average resin production was examined, with the goal to optimize resin harvesting practices and to understand the ecological significance of resin in these plantations. The bi-monthly resin production was tested using the open wound tapping method over a five-month period beginning in June. Through regression models, significant seasonal variability in resin production was observed. Specifically, higher resin yields were recorded in June (354 g) and lower yields in October (53.5 g). The impact of DBH, tree height, basal area, and volume on resin yield were also assessed. Descriptive statistics, correlation, and regression analyses elucidated the relationships between tree metrics, meteorological factors, and resin production. This study contributes new insights into how tree characteristics influence resin production and how this relationship is modulated by seasonal changes. Such findings can inform sustainable forest management practices and improve resin harvesting methods.

DOI: 10.15376/biores.20.1.548-565

Keywords: Pinus pinaster plantation; Non-timber forest product; Resin yield; Bark streak tapping

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INTRODUCTION

Resin production from trees is a significant ecological and economic activity, particularly in forest ecosystems dominated by species such as *Pinus pinaster* Ait. (maritime pine) (Soliño *et al*. 2018; López-Álvarez *et al.* 2023b). Pines produce resin, a versatile raw material that, when fractionated, yields distinct components such as rosin and turpentine, each with unique industrial applications (da Silva Rodrigues-Corrêa *et al*. 2013). Rosin is widely used in adhesives, inks, and varnishes, while turpentine is valuable in the chemical and pharmaceutical industries (Sarria-Villa *et al*. 2021). Additionally, wood resin has potential applications in bioenergy and the development of biodegradable batteries, underscoring its significant untapped potential (Neis *et al*. 2019). This valuable forest product is used in various industries, including pharmaceuticals, adhesives, and varnishes (Neis *et al*. 2019; da Silva Júnior *et al*. 2020). Therefore, understanding the factors influencing resin production in *Pinus pinaster* is essential for enhancing resin yield and ensuring sustainable management of forest resources. Effective resin harvesting practices contribute to the economic viability of forest enterprises (Soliño *et al*. 2018).

Pinus pinaster is extensively studied within its natural range, particularly in Spain and Portugal, where significant research is ongoing (López-Álvarez *et al*. 2023a). Known for its resin-producing capabilities (Tadesse *et al*. 2002; López-Álvarez *et al*. 2023b), this species is also significant in Türkiye's afforestation efforts, where it is preferred due to its adaptability and rapid growth rate. *Pinus pinaster* plantations in Türkiye contribute to timber production, soil stabilization, and coastal erosion prevention. Although not endemic to Türkiye, it has been successfully introduced and cultivated due to its resilience and economic value. Management practices have helped sustain resin production in *Pinus pinaster* forests despite global socioeconomic and climatic changes (Moreno-Fernández *et al*. 2021).

Resin production in *Pinus pinaster* is influenced by intrinsic factors, such as tree size (Moura *et al*. 2023) and health, and extrinsic factors, such as environmental conditions. Tree size, particularly diameter at breast height (DBH) (Yu *et al*. 2020; Garcia-Forner *et al*. 2021; Sabo *et al*. 2022), tree height (Rodríguez-García *et al*. 2014), and tree age (Zas *et al*. 2020a), are generally positively correlated with resin production in *Pinus pinaster*. As the DBH increases, resin yield also increases (Rodríguez-García *et al*. 2014; López-Álvarez *et al*. 2023a, Caglayan *et al*. 2024). Resin production slows tree growth, creating a trade-off between growth rate and tree size (Génova *et al*. 2014). However, this reduction in growth does not stop trees entirely; they adapt to the slower growth while maintaining their functions (Kopaczyk *et al*. 2023).

Additionally, seasonal changes can significantly affect resin production, with factors, such as temperature and precipitation, playing crucial roles. Meteorologic parameters, including temperature, wind speed, and precipitation, are known to impact physiological processes in trees, which in turn affect resin secretion (Caglayan *et al*. 2024). For instance, higher temperatures can enhance metabolic activities, leading to increased resin production. Conversely, wind speed might negatively impact resin yield by causing physical damage or increasing water loss through evapotranspiration. Studies in Spain by Rodríguez-García *et al*. (2015, 2016) and Zas *et al*. (2020) show positive correlations between *Pinus pinaster* growth and temperature. The influence of other climatic factors is also highlighted, such as precipitation, potential evapotranspiration, relative humidity, and available water deficit on resin production (López-Álvarez *et al*. 2023a).

Despite the extensive research on *Pinus pinaster*, the combined influence of dendrometric parameters (such as DBH) and meteorologic factors (including temperature and wind speed) on resin production remains poorly understood. There is a notable gap in comprehensive studies that integrate these variables to provide a holistic understanding of resin yield determinants in *Pinus pinaster*, especially in non-native plantations like those in Türkiye. Addressing this gap is crucial for understanding how these trees perform in different environmental contexts and optimizing resin harvesting practices globally.

This study aimed to provide a comprehensive evaluation of resin yield in *Pinus pinaster* plantations. Through conducting a detailed correlation and regression analysis, this research aims to provide insights into the optimal conditions for resin harvesting. The findings are expected to contribute to better management practices in *Pinus pinaste*r plantations, ensuring that resin production is ecologically sustainable. Moreover, understanding the ecological significance of resin in forest ecosystems can help in developing strategies for forest conservation and management. Given that *Pinus pinaster* resin production ranges from 1.0 to 4 kg per tree (Palma *et al.* 2012), predicting resin yield accurately could have significant economic and ecological benefits.

This study investigated the bi-monthly resin production of *Pinus pinaster* plantations using the bark streak tapping method over a five-month period beginning in June. The study's objectives were multifaceted. First, it sought to understand how tree size impacts resin yield by examining parameters such as DBH, tree height, basal area, and volume. Larger trees are generally expected to produce more resin due to their greater capacity for photosynthesis and resource allocation. Second, the study aims to explore the seasonal variability of resin production by analyzing data collected across different months, specifically June, July, August, September, and October. To achieve this, the study involved the analysis of data collected from 90 trees. In doing so, the impact of DBH, tree height, basal area, and volume on resin yield was assessed. Descriptive statistics, correlation, and regression analyses elucidate the relationships between dendrometric, meteorologic factors, and resin production. The author hypothesized that larger trees, exposed to higher temperatures and lower wind speeds, would exhibit greater resin production.

EXPERIMENTAL

Study Area

The Enez Forest Management Unit is located in the Marmara region of Türkiye. Geographically, it spans between 26°2'10" and 26°22'25" East longitude, and 40°35'20" and 40°46'40" North latitude (Fig. 1). The elevation within this area ranges from zero to 373 m above sea level, covering an area of 549 ha. In this region, the rotation age for *Pinus pinaster* is 30 years, with resin production permitted until three years before the final harvest.

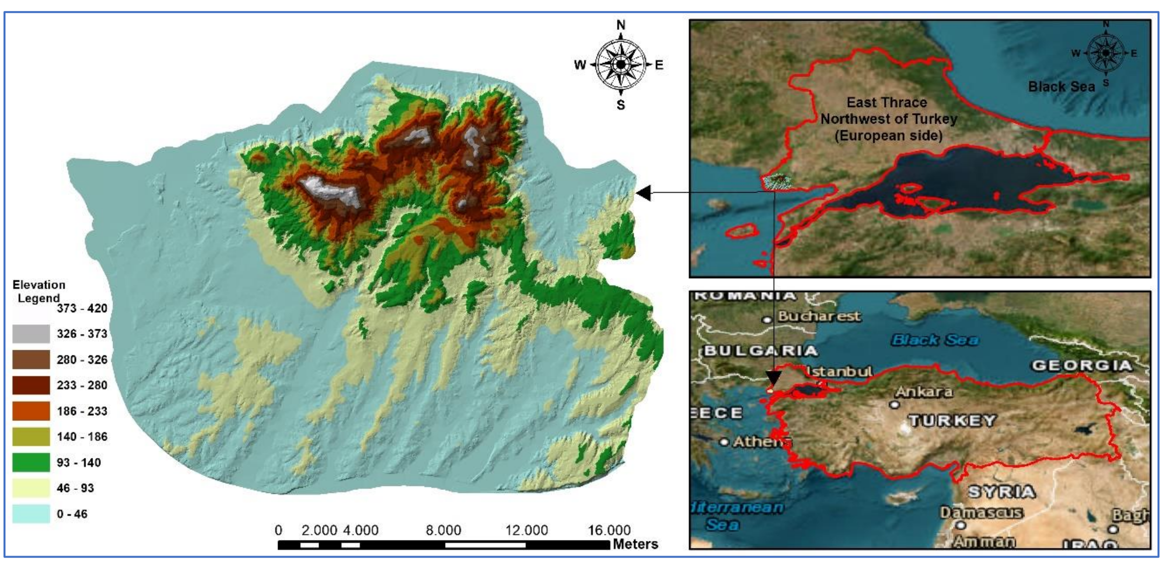

Fig. 1. The study area, Enez forest management unit, Edirne, Türkiye

Pinus pinaster, commonly known as maritime pine, is native to the western Mediterranean region, including areas such as Spain, Portugal, and North Africa. Although not indigenous to Türkiye, it has been introduced there for plantation purposes due to its adaptability and rapid growth rate. Consequently, *Pinus pinaster* plantations have been established for various functions, including timber production, soil stabilization, and as windbreaks to protect against coastal erosion. The species' ability to thrive in Mediterranean climates has facilitated its successful cultivation in regions outside its native range (Elvira-Recuenco *et al*. 2014). In Türkiye, these plantations contribute to afforestation efforts and commercial forestry enterprises, supporting both environmental and economic goals (GDF *et al*. 2013). Overall, the introduction and management of *Pinus pinaster* in Türkiye demonstrate its importance in achieving sustainable forestry and enhancing the region's ecological stability.

Data Collection

Data were collected from 90 *Pinus pinaster* trees within the Enez Forest Management Unit. The study was conducted over a five-month period, from June to October, with resin production measurements taken at the end of the period using the bark streak tapping method. This method involves making incisions in the tree bark to facilitate resin flow, which is then collected and measured.

Figure 2a illustrates the study area where the resin tapping experiment was conducted. The plot shows a typical section of the forest used in the study, highlighting the environment and the distribution of trees subjected to the resin tapping process. Additionally, Fig. 2b shows a single tree with multiple resin collection bags attached. Throughout the five months, new wounds were made on the tree bark every 15 days, and resin was collected in plastic bags. The image displays 10 resin-filled bags, demonstrating the cumulative resin yield over the specified period.

Fig. 2. Sample plots (a) and plastic resin bags (b) from June to October

Resin Extraction Process

For this study, a detailed resin extraction process was employed on *Pinus pinaster* trees, involving several key steps. First, the bark was carefully removed using a scraper on the south-eastern side of the tree to one-third of its diameter without reaching the wood layer (Fig. 3a). Next, a 5-cm-wide wound was made, starting 20 cm above the base, and extending to one-third of the bark's thickness (Fig. 3b). To enhance resin flow, approximately 0.5 g of acid paste was applied to the upper part of the wound (Fig. 3c). A commercial acid paste used for resin production from *Pinus pinaster* plantations in Türkiye was utilized. Acid-based pastes significantly increase resin yield (Lukmandaru *et al*. 2021), particularly the combination of sulfuric acid and Ethephon, which boosted oleoresin production by approximately 2 times. Similarly, stimulant pastes, such as salicylic acid, have also demonstrated effectiveness in enhancing resin yield (Lema *et al*. 2024), highlighting the value of these treatments in optimizing resin extraction. Following this, a transparent plastic bag was then attached beneath the wound using staples to collect the resin (Fig. 3d). In this study, new tappings were made every 15 days, and at the end of the study period, the resin collected in the bags representing 15-day intervals was weighed.

(a) (b) (c) (d)

Fig. 3. Steps in resin extraction process: (a) bark removal, (b) wound opening, (c) acid application, and (d) attaching plastic bag

Statistical Analysis

Descriptive statistics were computed to summarize the dendrometric and meteorologic data. Correlation analysis was performed to examine the relationships between the parameters and resin yield. To address potential heteroskedasticity in the data, a Weighted Least Squares (WLS) regression analysis was conducted. The predictors included DBH, average temperature, and wind speed, while resin yield served as the dependent variable. Additionally, factor analysis was conducted to better understand the relationships among the parameters. All statistical analyses were performed using SPSS 29 (IBM Corp., Armonk, NY, USA).

Dendrometric data

Key descriptive statistics for the dendrometric parameters showed that DBH ranged from 20 cm to 49 cm, with a mean of 31.1 cm (Table 1). Tree height ranged between 12 m and 18 m, averaging 14.7 m. The basal area had a mean of 774 cm^2, and the tree volume averaged 0.55 m^3. The average resin yield per tree per wound was 212 g.

Table 1. Descriptive Statistic for Dendrometric Parameters

Variables	Minimum	Maximum	Mean	Std. Dev.
DBH (cm)	20	49	31.09	5.559
Tree Height (m)	12	18	14.7	1.608
Basal Area (cm^2)	314	1884	774	285
Volume (m^3)	0.23	1	0.55	0.198
Average Resin (g)	0	1371	212	178

Meteorological data

The provided data encompasses various environmental factors recorded at the Ipsala meteorological station in 2023, alongside measurements of average resin production from trees planted in June. The factors include monthly precipitation, average temperatures (including minimum and maximum values), wind speed, and relative humidity. Additionally, average resin production in grams is listed for each month from June to October (Table 2).

Table 2. Descriptive Statistic for Meteorological Parameters

Variables	Min.	Max.	Mean	Std. Dev.
Precipitation (mm)	0.0	7.8	4.868	2.959
Min temperature (°C)	8.0	15.5	13.037	2.641
Avg. temperature (°C)	18.2	26.8	23.474	3.100
Max. temperature (°C)	28	38.8	35.197	3.764
Wind speed (m/s)	4.4	5.8	5.062	0.642
Humidity (%)	59.1	71.7	63.818	4.4383
Vapor pressure (hPa)	14.5	20.1	17.596	2.021
Average resin (g)	0	1371	211	178

Precipitation varied across the months, with the highest recorded in October (7.8 mm) and the lowest in August (0 mm). Average temperatures ranged from 18.2 °C in October to 26.8 °C in July. Minimum temperatures varied from 8 °C in October to 15.5 °C in August, while maximum temperatures ranged from 28 °C in October to 38.8 °C in August.

Resin production showed a corresponding decline, starting at 354 g in June and dropping to 53.5 g in October (Fig. 4). The highest resin production occurred in June, with average temperatures at 22.2 °C, while the lowest was in October, with average temperatures at 18.2 °C. Both minimum and maximum temperatures followed similar trends, with resin production decreasing as temperatures became extreme, either high or low. Wind speed was highest in August and September (5.8 m/s) and lowest in June and July (4.4 m/s). Resin production decreased as wind speed increased, particularly noticeable in August and September. Vapor pressure, measured in hPa, peaked in July at 20.1 hPa and was lowest in October at 14.5 hPa. Higher vapor pressure in July coincided with a high resin yield (313 g), while the lowest vapor pressure in October aligned with the lowest resin yield. Relative humidity was highest in October (71.7%) and lowest in July (59.9%). Higher relative humidity in October did not correspond with higher resin production, which was at its lowest. Conversely, the relatively lower humidity in June and July coincided with higher resin yields.

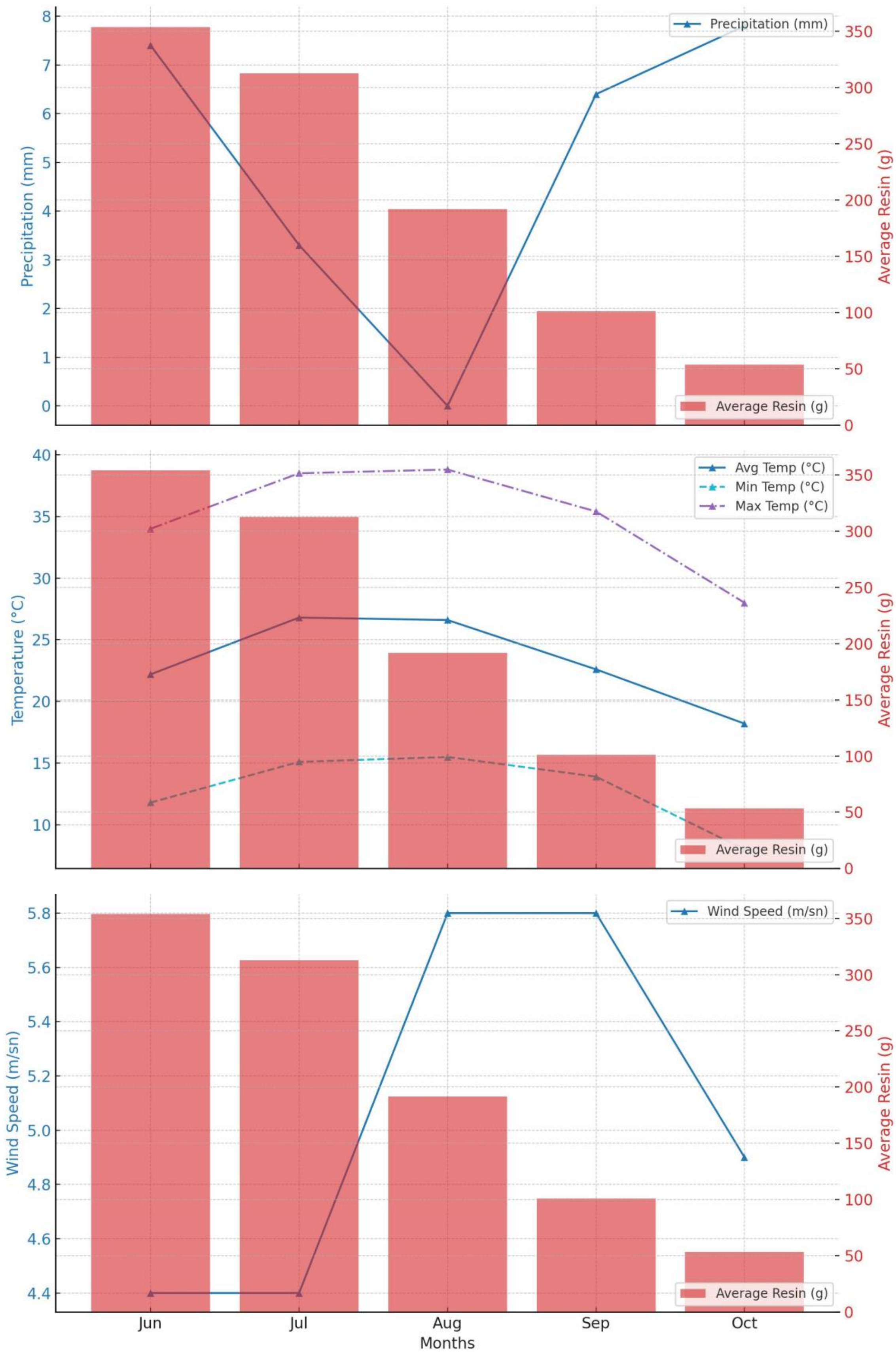

Fig. 4. Monthly meteorological overview for the study area

Factor analysis

The communalities of the variables used in Principal Component Analysis (PCA) are shown in Table 3. Communalities indicate the proportion of each variable's variance explained by the extracted components. High extraction values, close to 1.000, suggest that most of the variance in these variables is accounted for by the principal components. For example, "Average_Temperature" and "Wind_speed" have extraction values of 1.000 and 0.998, respectively, indicating that nearly all their variance is explained by the components.

Table 3. Communalities of Variables in Principal Component Analysis

Variable	Initial	Extraction
DBH	1.000	0.956
Basal area	1.000	0.947
Volume	1.000	0.975
Tree height	1.000	0.816
Precipitation	1.000	0.828
Vapor pressure	1.000	0.987
Average temperature	1.000	1.000
Wind speed	1.000	0.998
Humidity	1.000	0.993
Min temperature	1.000	0.946
Max temperature	1.000	0.971
Extraction Method: Principal Component Analysis		

Table 4 provides an overview of the total variance explained by the principal components extracted through PCA. Component 1 had an initial eigenvalue of 5.679, explaining 51.6% of the variance. After extraction, it retained the same eigenvalue and percentage of variance. With rotation, the total variance explained by Component 1 was 50.8%. Component 2 had an initial eigenvalue of 3.673, accounting for 33.4% of the variance, with the cumulative variance reaching 85.019%. After extraction and rotation, Component 2 explained 33.6% of the variance, contributing to a cumulative 84.436%. Component 3 started with an eigenvalue of 1.066, explaining 9.7% of the variance, and maintains this value post-extraction. With rotation, Component 3 explained 10.276% of the variance, bringing the cumulative total to 94.7%.

Table 4. Total Variance Explained by the Principal Components Extracted through PCA

Component	Initial Eigenvalues	Extraction Sums of Squared Loadings	Rotation Sums of Squared Loadings
	Total	% of Variance	Cumulative %
1	5.679	51.626	51.626
2	3.673	33.394	85.019
3	1.066	9.692	94.712

The rotated component matrix (Table 5), obtained using Varimax (SPSS 29, IBM Corp., Armonk, NY, USA) with Kaiser normalization, presents the loadings of each variable on the three principal components extracted through PCA. Component 1 was strongly influenced by the vapor pressure (0.981), average temperature (0.999), humidity (-0.988), minimum temperature (0.957), maximum temperature (0.983), and precipitation (-0.865). Component 2 showed strong loadings for dendrometric parameters such as DBH (0.978), basal area (0.973), volume (0.987), and tree height (0.903). Component 3 was primarily influenced by wind speed (0.989). These rotated loadings help better interpret the structure of the data, showing that Component 1 was primarily associated with temperature and humidity-related variables, Component 2 with dendrometric parameters, and Component 3 with wind speed.

Table 5. Rotated Component Matrix

Variable	Component 1	Component 2	Component 3
DBH (cm)	-0.023	0.978	0.001
Basal area (cm^2)	-0.021	0.973	0.000
Volume (m^3)	-0.026	0.987	0.000
Tree height (m)	-0.020	0.903	-0.001
Precipitation (mm)	-0.865	0.008	-0.282
Vapor pressure (hPa)	0.981	-0.020	-0.156
Avg. temperature (ºC)	0.999	-0.024	-0.037
Wind speed (m/s)	0.144	0.002	0.989
Humidity (%)	-0.988	0.024	-0.124
Min. temperature (ºC)	0.957	-0.028	0.170
Max. temperature (ºC)	0.983	-0.028	0.058
Extraction Method: Principal Component Analysis Rotation Method: Varimax with Kaiser Normalization			
a. Rotation converged in 4 iterations			

RESULTS

Dendrometric Data

The correlation analysis in Table 6 shows significant relationships between dendrometric parameters and resin yield. The DBH was strongly correlated with tree height ($r = 0.799$, $p < 0.01$), basal area ($r = 0.993$, $p < 0.01$), and volume ($r = 0.959$, $p < 0.01$). Tree height also showed strong correlations with basal area ($r = 0.796$, $p < 0.01$) and volume ($r = 0.890$, $p < 0.01$). Basal area was highly correlated with volume ($r = 0.945$, $p < 0.01$). Moreover, resin yield exhibited moderate positive correlations with DBH ($r = 0.338$, $p < 0.01$), tree height ($r = 0.262$, $p < 0.01$), basal area ($r = 0.337$, $p < 0.01$), and volume ($r = 0.318$, $p < 0.01$). These significant correlations indicate that larger trees, as measured by DBH, height, basal area, and volume, tended to yield more resin.

Table 6. Correlation of Dendrometric Variable with Average Resin

	DBH	Tree Height	Basal Area	Volume	Average Resin
DBH	1	0.799**	0.993**	0.959**	0.338**
Tree Height		1	0.796**	0.890**	0.262**
Basal Area			1	0.945**	0.337**
Volume				1	0.318**
Average Resin				.	1

Meteorologic Data

There was no significant correlation between precipitation and resin yield ($r = -0.085$, $p = 0.078$), indicating that precipitation levels do not directly influence the amount of resin produced. However, precipitation showed strong negative correlations with minimum, average, and maximum temperatures ($r = -0.780$, -0.857, and -0.802, respectively), suggesting that wetter conditions are associated with lower temperatures. Precipitation was also positively correlated with humidity (r = 0.855) and negatively correlated with vapor pressure (r = -0.848), showing that high precipitation led to higher humidity and lower vapor pressure.

All temperature variables (minimum, average, and maximum) showed significant positive correlations with resin yield, especially average temperature (r = 0.309) and maximum temperature (r = 0.291). This suggests that higher temperatures promote resin production. Additionally, there was a strong interrelationship between minimum, average, and maximum temperatures, with very high correlations among them (ranging from 0.949 to 0.989), indicating that temperature variations are consistent across different metrics.

Wind speed had a moderate negative correlation with resin yield (r = -0.428), indicating that higher wind speeds reduced resin production. This could be because wind increases water loss from trees or affects resin flow dynamics.

Humidity was negatively correlated with resin yield (r = -0.234), meaning that higher humidity levels were associated with reduced resin production. This could be due to the effect of moisture levels on resin flow or tree physiology. Humidity also showed strong negative correlations with temperature variables and vapor pressure, which is consistent with the idea that humid conditions are typically cooler and associated with lower vapor pressure. Vapor pressure was positively correlated with resin yield (r = 0.342), suggesting that higher vapor pressure, which often accompanies higher temperatures, promoted greater resin production.

Table 7. Correlation of Meteorological Data

Variables	Preci-pitation	Min. Temp.	Avg. Temp.	Max. Temp.	Wind Speed	Humidity	Vapor Pressure	Resin Yield
Precipitation	1	-0.780**	-0.857**	-0.802**	-0.386**	0.855**	-0.848**	-0.085
Min. Temp.		1	0.949**	0.989**	0.316**	-0.987**	0.888**	0.221**
Avg. Temp.			1	0.980**	0.107*	-0.983**	0.987**	0.309**
Max. Temp.				1	0.205**	-0.992**	0.937**	0.291**
Wind speed					1	-0.269**	-0.017	-0.428**
Humidity						1	-,942**	-0.234**
Vapor pressure							1	0.342**
Resin yield								1
** Correlation is significant at the 0.01 level (2-tailed)								
* Correlation is significant at the 0.05 level (2-tailed)								

Results of Regression Analysis with Factor Scores

In the regression analysis, three variables were entered: the regression factor (REGR) scores for the three components identified in the PCA. These variables are labeled as REGR factor score 1 for analysis 1, REGR factor score 2 for analysis 1, and REGR factor score 3 for analysis 1. No variables were removed from the model. The method used for the regression analysis was the ‘Enter’ method, meaning that all the requested variables were included in the model. The dependent variable in this analysis was resin yield. The inclusion of factor scores derived from PCA allows for a simplified yet comprehensive model to assess the relationship between the components and resin yield. Through incorporating these factor scores, the model effectively captures the underlying patterns and relationships among the variables, providing a more robust understanding of how the identified components influence resin yield.

Regression Analysis Summary

The regression analysis indicated a moderate positive correlation between the predictors and resin yield, with an R value of 0.657 and an R^2 of 0.432, explaining 43.2% of the variance in resin yield. The model was statistically significant ($F(3, 423) = 107.199$, $p < 0.001$). The unstandardized coefficients for the predictors were as follows: 53.741 for REGR factor score 1 ($t = 8.232$, $p < 0.001$), 59.528 for REGR factor score 2 ($t = 9.118$, $p < 0.001$), and -85.291 for REGR factor score 3 ($t = -13.065$, $p < 0.001$). This suggests that the first two components positively influenced resin yield, while the third component had a negative impact.

Table 8. Summary of the Regression Analysis with Factor Scores Predicting Resin Yield

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.657[a]	0.432	0.428	134.428
a. Predictors: (Constant), REGR factor score 3 for analysis 1, REGR factor score 2 for analysis 1, REGR factor score 1 for analysis 1				

Table 9. Regression Coefficients Predicting Resin Yield

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	211.098	6.521		32.374	0.000
	REGR factor score 1	53.741	6.528	0.302	8.232	0.000
	REGR factor score 2	59.528	6.528	0.334	9.118	0.000
	REGR factor score 3	-85.291	6.528	-0.479	-13.065	0.000
a. Dependent Variable: Resin yield						

Based on the provided regression coefficients, the equation predicting resin yield can be written as,

$$R_i = 211.098 + \ (53.741 \times Factor_1) + (59.528 \times Factor_2) - (85{,}291 \times Factor_3)$$

where $R_i$represents the resin yield, $Factor_1$ is the first factor score, $Factor_2$ is the second factor score, and $Factor_3$ is the third factor score.

Regression Analysis with Original Variables

The regression analysis demonstrated a moderate positive correlation between the predictors (DBH, average temperature, and wind speed) and resin yield, with an R value of 0.661 and an R^2 of 0.437, indicating that 43.7% of the variance in resin yield was explained by these predictors (Table 10). The model was statistically significant ($F(3, 423) = 109.376$, $p < 0.001$). The unstandardized coefficients were as follows: 11.383 for DBH ($t = 9.725$, $p < 0.001$), 21.587 for average temperature ($t = 10.228$, $p < 0.001$), and -129.780 for wind speed ($t = -12.752$, $p < 0.001$). This suggests that DBH and average temperature positively influence resin yield, while wind speed had a negative impact.

Table 10. Summary of the Linear Regression Model Predicting Resin Yield

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.661[a]	0.437	0.433	134.1557

a. Predictors: (Constant), Wind speed, DBH, Average Temperature
b. Dependent Variable: Resin yield

Table 11. Regression Coefficients Predicting Resin Yield

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.448	77.975		0.096	0.924
	DBH	11.383	1.170	0.355	9.725	0.000
	Average temperature	21.587	2.111	0.376	10.228	0.000
	Wind speed	-129.780	10.177	-0.468	-12.752	0.000

a. Dependent Variable: Resin yield

The regression equation used to estimate resin yield is given by,

$$R_{ij} = 7.448 + (11.383 \times DBH_i) + (21.587 \times T_j) - (129.780 \times W_j)$$

where R_{ij} denotes the resin yield from the tree i in month j, DBH_i denotes the diameter at breast height of the tree i (cm), T_j represents the average temperature (°C) for month j, W_j is the wind speed in m/s for month j.

In constructing this regression model, the independent variables were selected based on their factor loadings and interpretability. Although factor analysis suggests that maximum temperature had a high loading, it is often more challenging to explain and use in practical applications. Therefore, average temperature (T_j) was selected, as it provides a simpler and more straightforward variable for temperature representation. Similarly, while other variables might have shown high factor loadings, DBH was chosen due to its ease of measurement and significant correlation with resin yield. This decision ensures that the model remains practical and applicable for forest managers and researchers working in the field.

Weighted Least Squares (WLS) Regression Analysis

Due to the presence of heteroskedasticity in the data, a WLS regression analysis was conducted. The model showed a strong correlation between the predictors (DBH, average temperature, and wind speed) and resin yield, with an R value of 0.708 and an R^2 of 0.501, indicating that 50.1% of the variance in resin yield is explained by these predictors (Table 12). The model is statistically significant ($F(3, 423) = 141.580$, $p < 0.001$). The unstandardized coefficients were as follows: 9.951 for DBH ($t = 11.421$, $p < 0.001$), 24.162 for average temperature ($t = 13.705$, $p < 0.001$), and -122.849 for wind speed ($t = -13.230$,

$p < 0.001$). These results suggest that DBH and average temperature positively influenced resin yield, while wind speed has a negative impact.

Table 12. Summary of the Weighted Least Squares Regression Model Predicting Resin Yield

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.708	0.501	0.497	1.3522

a. Predictors: (Constant), Wind speed, DBH, Average Temperature
b. Dependent Variable: Resin yield
c. Weighted Least Squares Regression - Weighted by Weight

Table 13. Regression Coefficients Predicting Resin Yield

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-45.014	61.788		-0.729	0.467
	DBH	9.951	0.871	0.394	11.421	0.000
	Average temperature	24.162	1.763	0.499	13.705	0.000
	Wind speed	-122.849	9.286	-0.484	-13.230	0.000

Coefficients [a,b]
a. Dependent Variable: Resin
b. Weighted Least Squares Regression - Weighted by Weight

The WLS regression analysis resulted in a predictive model that explains the relationship between various dendrometric and meteorological variables and resin yield from *Pinus pinaster*. The model's equation was highly significant, with a p-value less than .001, indicating the substantial impact of these factors on resin production. The equation was as follows,

$$R_{ij} = -45.014 + (9.951 \times DBH_i) + (24.162 \times T_j) - (122.849 \times W_j)$$

where R_{ij} denotes the resin yield from the tree i in month j, DBH_i denotes the diameter of the tree i (cm), T_j represents the average temperature (°C) for month j, W_j is the wind speed (m/s) for month j.

DISCUSSION

Three different models were developed in this study to predict resin yield. The first model utilized factor scores obtained through factor analysis to reduce multicollinearity among variables, offering an aggregated view of the influence of multiple predictors on resin yield. The second model was developed using the regression method, providing a baseline estimation of the direct effects of dendrometric and meteorological variables. The third model employed the WLS approach, which accounts for heterogeneity within the dataset by applying varying weights to observations. The WLS model demonstrated the highest explanatory power (R^2=0.501) and the lowest standard error (1.3522), indicating that it offers improved performance in predicting resin yield. Together, these models provide complementary perspectives, enhancing our understanding of the complex factors influencing resin production.

These results shed light on the relationship between dendrometric and meteorologic parameters and resin production, providing valuable insights into predicting resin yield in *Pinus pinaster* plantations. The primary research question addressed in this study was how tree size, particularly DBH, and environmental factors, such as temperature and wind speed, influence resin production.

As hypothesized, the results demonstrated a significant positive correlation between DBH and resin production in *Pinus pinaster*. The positive correlation suggests that larger trees, with their more extensive network of resin ducts (Elvira-Recuenco *et al*. 2014), and increased photosynthetic capacity, can produce and transport more resin. This finding aligns with Rodríguez-García (2014), who also reported that larger trees generally have a higher capacity for resin biosynthesis due to their more developed vascular systems. Additionally, trees that show positive trends in growth and resin duct area may allocate more resources to resin production as a defense mechanism against herbivores and pathogens, reducing their probability of mortality (Slack *et al*. 2021). Similar findings were reported by Caglayan *et al*. (2024), who observed that larger DBH in *Pinus brutia* plantations also significantly correlated with increased resin yield, reinforcing the importance of tree size in resin production across different species.

The current findings on the positive relationship between temperature and resin yield are consistent with those reported by Rodríguez-García *et al*. (2015) and López-Álvarez *et al*. (2023a). These studies similarly observed that higher temperatures promote resin biosynthesis, possibly by enhancing metabolic activities within the tree. Caglayan *et al*. (2024) also highlighted the critical role of average temperature in *Pinus brutia*, where higher temperatures were positively associated with resin production. However, the negative impact of wind speed observed in this study contrasts with some previous studies, which found no significant effect or different impacts on resin production. This discrepancy may be due to regional variations in environmental conditions and tree responses (Dorado-Liñán *et al*. 2019), highlighting the need for site-specific management strategies. Future studies focusing on detailed temperature thresholds could further elucidate the potential for a specific trigger temperature in the onset of resin flow, while also considering whether sustained high temperatures might impact resin properties, such as viscosity and flowability, through seasonal chemical changes. Annual variations in weather conditions could influence these processes, highlighting the need for ongoing research to better understand temperature effects on resin production dynamics.

While the observed positive correlations between DBH, temperature, and resin production are consistent with prior studies, the overall low correlations in Table 6 for dendrometric parameters and in Table 7 for meteorological parameters with resin yield indicate that these variables alone are insufficient to fully explain the complexity of resin production. Although larger tree size and favorable temperatures support increased resin biosynthesis, resin production is ultimately influenced by a more intricate network of genetic traits (López-Álvarez *et al*. 2023a), age (Zas *et al*. 2020a), microenvironmental conditions, and additional environmental factors (Caglayan *et al*. 2024). Thus, a more comprehensive understanding of resin production requires incorporating these environmental and physiological interactions into the analyses.

The observed trade-off between growth and resin production under high wind conditions suggests a physiological adaptation to minimize water loss and maintain hydraulic function (Dorado-Liñán *et al*. 2019). In windy conditions, trees may prioritize maintaining structural integrity and moderating water loss through reduced transpiration (Ellison *et al*. 2017), potentially limiting the resources available for other physiological processes such as resin production. Understanding these trade-offs is crucial for forest managers aiming to balance tree growth and resin yield.

From a forest management perspective, these findings underscore the importance of considering both tree size and local meteorological conditions when selecting trees for tapping. Similar results were found by Rodríguez-García *et al*. (2015), who observed that climate variables significantly influence resin yield and secretory structures in tapped *Pinus pinaster*. Predicting resin yield requires a nuanced understanding of these factors to ensure sustainable and efficient harvesting practices. Managers should prioritize larger trees in areas with favorable temperature conditions and moderate wind speeds to maximize resin production while maintaining tree health. While this study focused on measurements at the individual tree level, factors such as canopy closure and sunlight exposure are typically influenced by stand-level characteristics, including stand density and structure. Future studies could explore the effect of a tree's competitive position within the stand such as canopy closure and access to sunlight on resin yield.

The results from this study highlight the significant influence of temperature and wind speed on resin yield. Higher temperatures likely enhance resin biosynthesis and flow, aligning with the physiological processes that increase metabolic activities in trees. Conversely, strong winds may lead to physical damage or increased water loss through evapotranspiration, negatively impacting resin production.

The implications for seasonal variability in resin production are significant. This study suggests that resin tapping operations might benefit from adjusting tapping intensity and timing based on seasonal temperature and wind patterns. For instance, during warmer months with moderate winds, increased tapping intensity may be feasible, whereas in hotter or windier periods, reducing tapping intensity could help minimize tree stress and maintain long-term productivity.

Future research should investigate whether continual tapping affects heartwood formation and internal resin accumulation, potentially impacting tree health and resin yield. Additionally, analyzing the chemical composition of the collected resin would provide deeper insights into its quality and potential applications, expanding our understanding of resin's industrial value.

In summary, this study has elucidated the significant positive correlation between DBH and resin production in *Pinus pinaster*, driven by biological mechanisms related to tree size and efficiency in nutrient transport. The findings also reveal the critical roles of temperature and wind speed in influencing resin yield, with practical implications for optimizing resin harvesting strategies. Understanding these dynamics is essential for developing sustainable forestry practices that balance resin production with tree health and ecological stability. Future research should further explore the interactive effects of multiple environmental factors and expand the geographic scope of studies to refine management practices across different regions and climatic conditions.

Through leveraging these insights, forest managers can better predict and enhance resin yields, contributing to the economic viability and sustainability of *Pinus pinaster* plantations. This study's findings not only enhance our understanding of resin production dynamics but also provide a foundation for future research aimed at improving resin harvesting methods and forest management practices globally.

CONCLUSIONS

1. The regression and weighted least squares (WLS) analyses revealed that 43.7% to 50.1% of the variance in resin yield could be explained by the predictors studied, indicating a strong model fit. The regression equations developed provide practical tools for predicting resin yield based on tree and environmental parameters, facilitating better management decisions.
2. A positive correlation was found between diameter at breast height (DBH) and resin yield in *Pinus pinaster* plantations. Higher temperature positively influenced resin production, while wind speed negatively affected it. These findings suggest that forest managers should prioritize larger trees in areas with moderate temperatures and lower wind speeds to maximize resin production while maintaining tree health.
3. Seasonal variability in resin production was observed, with significant changes over time. This suggests that tapping intensity and timing should be adjusted based on seasonal climatic conditions to optimize resin yield and ensure sustainability. The study provides practical recommendations for improving resin harvesting practices and supporting the sustainable management of *Pinus pinaster* plantations.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used OpenAI's ChatGPT by OpenAI to assist with language clarity, structuring, and academic expression. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Article submitted: September 19, 2024; Peer review completed: October 26, 2024; Revised version received and accepted: November 1, 2024; Published: November 19, 2024.
DOI: 10.15376/biores.20.1.548-565