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Role of Soil and Environmental Factors in Predicting Physical and Mechanical Properties of Black Alder Wood: CCA Aided MLR Modeling Approach

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Abstract: This study aimed to determine and model the relationships between some physical and mechanical properties of wood and physical and chemical properties of the soil, soil nutrient cations, and environmental factors in *Alnus glutinosa* subsp. *barbata* stands naturally growing in the Artvin region. Canonical Correlation Analysis (CCA) was employed to identify the relationships between the dependent and independent variables. Stepwise Multiple Linear Regression (MLR) Analysis was used to model the physical and mechanical properties. According to the CCA analysis results, a strong relationship was determined between MOR, MOE, and OWD and chemical soil properties such as pH, Mg, and K (CCA1, r = 0.89). In addition, a significant relationship was determined between CPG and DB and moisture and topographic factors such as AWC, FC, WP, and ALT (CCA2, r = 0.52). As a result of the MLR analysis, the model created for compressive strength parallel to grain explained 55% of the variance (R^2 = 0.552, RMSE = 35.66); The models created for oven-dry wood density and modulus of elasticity explained 54% (R^2 = 0.541, RMSE = 0.0352) and 38% (R^2 = 0.386, RMSE = 530.99) of the variance, respectively.

Keywords: Artvin; CCA; MLR; nutrient; soil properties. © 2025 ACG Publications. All rights reserved.

1. Introduction

Although wood's physical and mechanical properties depend on species characteristics, climatic conditions, and genetic factors, they are directly influenced by the chemical and physical components of the soil environment where the tree grows. Recent studies have shown that macronutrients and microelements, pH level, and organic matter ratios can play decisive roles in wood structure [1, 2]. These effects can be concretely observed through nutrient uptake and cell wall development mechanisms, especially in qualities such as wood density, elasticity, and specific gravity. Soil properties, such as organic matter (OM) content, pH, and available water capacity (AWC), directly affect the growth potential of trees as well as the quality parameters of the wood [3, 4].

Trees are influenced by physiographic, edaphic, and biotic factors during their growth process, resulting in variation in wood properties [5-8]. These factors directly affect wood's growth rate, composition, structural organization, and technological properties [9]. Indeed, some studies have shown

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that the chemical composition of soil can affect wood density and strength, while its physical properties can affect cellulose and fiber yield [10, 11].

Climatic factors have a significant impact on annual ring width and radial growth indicators. Parameters like average temperature and precipitation directly influence the cambial activity of trees [12-17]. Additionally, conditions such as low temperatures, snow cover, strong winds, and a short growing season at high altitudes restrict radial growth and cause variations in wood density and anatomical structure [18, 19]. It has been reported that trees grow faster in nutrient- and water-rich environments with low competition, and that their structural properties, such as fiber organization and density, may change [20, 21].

The technological value of wood is shaped by a combination of its anatomical and physico-mechanical properties. Properties such as oven-dry wood density (OWD), shrinkage coefficient, fiber saturation point, modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength parallel to the grain direction (CPG) and dynamic bending (DB) have a decisive role on the durability, workability and performance of wood [3, 4, 22, 23, 24]. The relationship between these properties and environmental variables is critical for the quality classification of forest products and the planning of industrial use areas.

In this context, the study focuses on *Alnus glutinosa* subsp. *barbata* (Black Alder) grows naturally in Turkey's Eastern Black Sea Region. This species is known for its smooth-stemmed, light-colored, homogeneous-textured, light and medium-strength wood structure. It is widely used in plywood, medium-density fiberboard, packaging, and furniture [22, 25, 26]. However, due to its rapid growth traits, the wood density and specific mechanical properties of this species can vary significantly depending on environmental factors [27, 28, 29].

Arhavi district of Artvin province, the field area of this study, is a region where *A. glutinosa* subsp. *barbata* grows naturally and is particularly notable for its high rainfall (2590 mm/year), mild temperature (10.9 °C), long and humid vegetation period, and average soil AWC (17.3%) [29]. These environmental conditions cause alder to grow rapidly and form large annual rings; however, this growth pattern leads to a decline in some traits, such as OWD [28].

In this study, it was aimed to determine and model the relationships between physical and mechanical properties of wood and soil parameters (organic matter, pH, tissue composition, nutrients) and climatic variables (temperature, precipitation, altitude) in alder (*Alnus glutinosa* subsp. *barbata*) stands growing in the Arhavi region. Modeling studies to predict wood properties are crucial for forest management, matching species to appropriate growing environments, and guiding genetic breeding practices [23, 30]. Such studies often focus on morphological and environmental variables such as individual tree form, leaf distribution, and climatic factors, but soil components are given limited consideration in most models [30, 31, 32]. This research aims to address this gap and statistically explain the effect of soil chemical properties on structural wood properties such as wood density, elasticity, and flexural strength through MLR and CCA. Accurate prediction of these variables is important for predicting wood quality, planning appropriate growing areas, and developing sustainable forestry practices. The results suggest that soil factors should be taken into account when modeling environmental variables for alder and general forestry planning.

2. Materials and Methods

2.1. Research Area

The research area is located in the Eastern Black Sea Region, within the borders of Arhavi Central Forest Management Directorate, affiliated to Arhavi Forest Management Directorate, between 41°18'10" - 41°31'51" east longitudes and 41°15'39" - 41°24'40" north latitudes. This area is situated in the Colchis subsection of the European-Siberian flora region and boasts a rich flora. While agricultural areas, alder, hazelnut, and tea plants are found in the altitude zone up to 500 meters, alder is the dominant species in the range of 500-1000 meters, mixed with chestnut, hornbeam, and elm. Eagle fern, elderberry, boxwood, and rhododendron are common in the lower flora. Alder is mainly found in stream beds above 1000 meters [33].

The region is in the Eastern Black Sea climate zone, with mild winters, cool summers, and high yearly rainfall [34]. When evaluated according to the Thornthwaite method, it was determined that the research area has a “very humid” climate type [35]. When examined geologically, the research area belongs to the Mesozoic era, and basaltic-andesitic volcanic rocks are common in the Arhavi region [36].

2.2. Methodological Framework for Field Research

Field studies were conducted in 17 pilot plots within natural *Alnus glutinosa* subsp. *barbata* stands. Each sample plot recorded local site factors, including elevation, slope, and aspect. A soil profile was excavated in each plot, and disturbed soil samples were collected from the 0-10 cm, 10-30 cm, and 30-50 cm depths of the profile. A total of 51 disturbed soil samples were obtained from these profiles. A sample tree with a homogeneous, regular trunk and normal crown development was selected from each trial area in terms of diameter and length distribution. TS 4176 standards were used to select sample trees [68]. Diameter, height, and age measurements were made for 4-6 trees in each sample area. In addition to these measurements, cylindrical sections 1.5 m long with a trunk height of 2-4 m were taken from the selected trees for physical and mechanical analyses, numbered, and transported to the cutting workshop. To perform physical and mechanical analyses of alder wood, 340 samples were studied for OWD, 252 for MOR and MOE, 340 for CPG, and 439 for DB.

2.3. Soil Analyses

Mechanical analysis was performed using the Bouyoucos hydrometer method [37, 38], field capacity (FC), wilting point (WP) and AWC using a ceramic plate pressure device [37, 39], soil reaction (pH) using the glass electrode method [37], OM content using the Walkley-Black wet combustion method [40], exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Fe^{2+} and Mn^{2+}) in soil samples were extracted with 1 N neutral ammonium acetate solution, the resulting suspension was filtered through Whatman 42 filter paper and the analyses were performed using the Shimadzu AA-6601 Atomic Absorption Spectrophotometer [41].

2.4. Physical and Mechanical Wood Analyses

In order to determine the physical and mechanical wood properties, wood samples were brought into compliance with the standards TS 2471 [42], TS 2472 [43] and TS 53 [44] for OWD, TS 2595 [25] for CPG, TS 2474 [26] and TS 2478 [45] for bending strength and modulus of elasticity in bending, and TS 2470 [46] and TS 2477 [47] for MOR. Then, OWD (kg/cm^3), CPG (kp/cm^2), MOR (kgf/cm^2), and DB (kpm/cm^2) were calculated from these samples [48-50]. The air-dry wood density (AWD) and OWD were calculated using the following formulas, respectively:

$$\rho_{12} = M_{12} / V_{12} \quad (g/cm^3)$$

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Where: ρ_{12} = air-dry specific gravity (g/cm^3), M_{12} = air-dry mass (g), V_{12} = air-dry volume (cm^3), ρ_0 = oven-dry specific gravity (g/cm^3), Mo = oven-dry mass (g), Vo = oven-dry volume (cm^3). CPG was calculated as:

$$\sigma\ B// = Fmax / ab \quad (kp/cm^2)$$

Where: σ B// = compressive strength parallel to the grain (kp/cm^2), Fmax = maximum load at failure (kp), a and b = cross-sectional dimensions of the test specimens (cm). MOR and MOE were calculated using the following formulas, respectively:

$$\sigma_e = 3FL / 2ab^2 \quad (kgf/cm^2)$$

$$E = FL^3 / 4a^3be \quad (kgf/cm^2)$$

Where: σ_e = bending strength (kgf/cm^2), F = maximum load at failure (kgf), L = span length between support points (cm), a = specimen width (cm), b = specimen thickness (cm), E = modulus of elasticity (kgf/cm^2), F = load in the elastic deformation region (kgf), L = span length between support points (cm), a = specimen width (cm), b = specimen thickness (cm), e = amount of bending (deflection) (cm). DB was calculated using the following formula:

$$\sigma ş = W / (ab) \quad (kpm/cm^2)$$

Where: σş = shock resistance (kpm/cm^2), W = energy absorbed during fracture (kpm), a = specimen width (cm), b = specimen thickness (cm).

2.5. Statistical Analysis

This study applied MLR and CCA methods to determine the effects of soil and environmental variables obtained from sample areas of the Arhavi region on wood's physical and mechanical properties. Statistical analyses were performed in SPSS and Python environments. Each analysis aimed to determine multivariate relationships and visually evaluate the model's structure. To prepare the dataset for statistical analysis, all explanatory and response variables were systematically coded and organized (Table 1).

The MLR analyses were applied separately to the physical and mechanical properties of wood, OWD, MOR, MOE, DB, and CPG. As explanatory variables, nutrients (Ca, Mg, K, Na, Fe, and Mn), soil properties (SAND, SILT, CLAY, FC, AWC, OM, and pH), and environmental factors (ALT, SLP, ASP, and PRC) were evaluated. In regression analyses, the stepwise variable selection method was employed to simultaneously evaluate the effects of multiple explanatory variables and enhance the model's explanatory power. This method combines forward selection and backward elimination algorithms, ensuring that variables that provide statistically significant contributions remain in the model [51]. This type of analysis is frequently preferred in understanding complex cause-effect relationships, especially in environmental and biological studies [52].

Table 1. Assigned codes and definitions of variables included in the statistical analysis process

Parametrs	Variable	Variable description	Codes
Dependent Variable	Physical and mechanical variables	Oven-dry wood density	OWD
		Modulus of rupture	MOR
		Modulus of elasticity	MOE
		Dynamic bending	DB
		Compressive strength parallel to the grain	CPG
Independent Variables	Soil variables	Ca^{2+}	Ca
		Mg^{2+}	Mg
		K^{+}	K
		Na^{+}	Na
		Fe^{2+}	Fe
		Mn^{2+}	Mn
		Sand	SAND
		Silt	SILT
		Clay	CLAY
		Field capacity	FC
		Available water capacity	AWC
		Organic matter	OM
		Soil reaction	pH
	Environmental factors	Altitute	ALT
		Slope	SLP
		Aspect	ASP
		Precipitation	PRC
		Tempeature	TEMP

CCA was applied to explore the comprehensive pattern of associations in the multivariate structure. CCA is an ordination analysis used to reveal multidimensional linear relationships between dependent and independent variable sets and is frequently preferred in the evaluation of environmental data [53]. This analysis produces canonical axes that maximize correlation between the explanatory and response variable sets, enabling directional and contextual interpretations. CCA reveals mutual relationship structures between variable sets that extend beyond classical multiple regression models and is especially effective in visualizing meaningful patterns in ecological datasets [54].

2.6. Model Validation

R^2 (coefficient of determination) and RMSE (Root Mean Square Error) are widely used metrics to evaluate model performance in regression analysis. R^2 indicates how well the independent variables explain the variability in the dependent variable, while RMSE measures the average magnitude of the prediction errors [55].

$$R^2 = 1 - [\sum(y_i - \hat{y}_i)^2] / [\sum(y_i - \bar{y})^2]$$
$$RMSE = \sqrt{[\sum(y_i - \hat{y}_i)^2 / n]}$$

Where: y_i: Observed value, $\hat{y}_i$: Predicted value, $\bar{y}$: Mean of observed values, n: Number of observations, $\sum(y_i-\hat{y}_i)^2$: Residual Sum of squares (RSS), $\sum(y_i-\bar{y})^2$: Total sum of squares (TSS), $\sum(y_i-\hat{y}_i)^2$: Sum of squared errors.

3. Results and Discussion

3.1. Descriptive Statistics

Basic statistics for soil, wood, and environmental variables in the study area are given in Table 2. Soil Ca, K, and Fe values exhibited a wide range of variation. The pH value of the soil was acidic in both KCl and H_2O solutions, averaging 4.1 and 4.6, respectively. The average OM content of the soil was 5.3%. The physical properties of the soil were dominated by sand (54.6%); clay and silt contents were 28% and 17.4%, respectively. The average AWC was determined to be 16.4%. MOR and MOE values of wood properties averaged 59.8 N/mm^2 and 4570.2 kgf/cm^2, respectively. OWD averaged 0.5 g/cm^3, DB 0.2 kpm/cm^2, and CPG 374.3 kp/cm^2. Regarding environmental variables, the average annual precipitation is 1380 mm, the altitude is 660 m, the slope is 41.9% and the aspect is 219.4°. According to the findings, the study area's soil pH and organic matter levels are generally compatible with humid climate forest ecosystems [1, 56].

Table 2. Basic descriptive statistics of soil, wood, and environmental variables of the study area

Variables	Unit	Minimum	Maximum	Mean	Standard Deviation
Ca	ppm	2.7	109.8	51.5	46.9
Mg	ppm	3.7	8.0	6.2	1.5
K	ppm	61.0	260.0	121.4	46.9
Na	ppm	17.2	46.9	26.0	7.6
Fe	ppm	8.2	71.8	39.3	16.7
Mn	ppm	9.9	47.1	29.0	10.4
pH_{KCl}	-	3.4	5.4	4.1	0.6
pH_{H2O}	-	3.5	5.7	4.6	0.7
OM	%	0.3	11.9	5.3	2.9
SAND	%	21.3	77.7	54.6	18.2
CLAY	%	8.0	55.3	28.0	14.0
SILT	%	6.0	29.3	17.4	6.0
AWC	%	9.7	22.0	16.4	3.8
OWD	g/cm^3	0.4	0.8	0.5	0.1
MOR	N/mm^2	8.1	86.8	59.8	11.9
MOE	kgf/cm^2	1626.5	6409.1	4570.2	692.7
DB	kpm/cm^2	0.2	0.8	0.2	0.1
CPG	kp/cm^2	225.9	523.9	374.3	54.5
PRC	mm	1275.0	1492.5	1380.0	79.3
ALT	m	160.0	1070.0	660.0	274.4
SLP	Degre	15.0	65.0	41.9	17.2
ASP	Degre	45.0	360.0	219.4	117.0

3.2. Results and Discussion of CCA Analysis

The CCA analysis in the study revealed that soil chemical variables such as pH, Mg, and K play a dominant role in determining the mechanical properties of bearded alder wood. The first canonical component (CC1) exhibited a high and significant correlation (r = 0.89) between soil chemical properties, including pH, Mg, and K, and wood mechanical properties, such as MOR, MOE, and OWD. This component explained 79.4% of the relationship between the two groups of variables, indicating that soil chemistry is a significant determinant of wood quality. The strong association of soil pH with MOR, MOE, and OWD, and its positive effect in the models, suggests that pH should be considered not only in terms of element solubility but also in combination with the buffering capacity and ion binding ability of organic matter. The second canonical component (CC2) revealed a moderate relationship (r = 0.52) between soil moisture (FC, WP) and altitude (ALT), as well as growth indicators such as CPG and DB. High-altitude and moist soil conditions can positively impact MOE by favoring lignin production and cell wall development [57]. This indicates that MOE is shaped by individual variables and environmental interactions (Table 3, Figure 1). Soil properties such as SAND, CLAY, and OM were not significant in the canonical components, indicating that the influence of these variables on wood quality is indirect.

Table 3. Canonical correlation between wood properties and soil factors

Component	Canonical Correlation (r)	Explained Variance (%)	Main Interpretation
CC1	0.89	79.4	Wood mechanical properties (MOR, MOE, OWD) are highly influenced by soil chemical variables (pH, Mg, K).
CC2	0.52	26.8	CPG and DB show a moderate association with AWC and ALT.

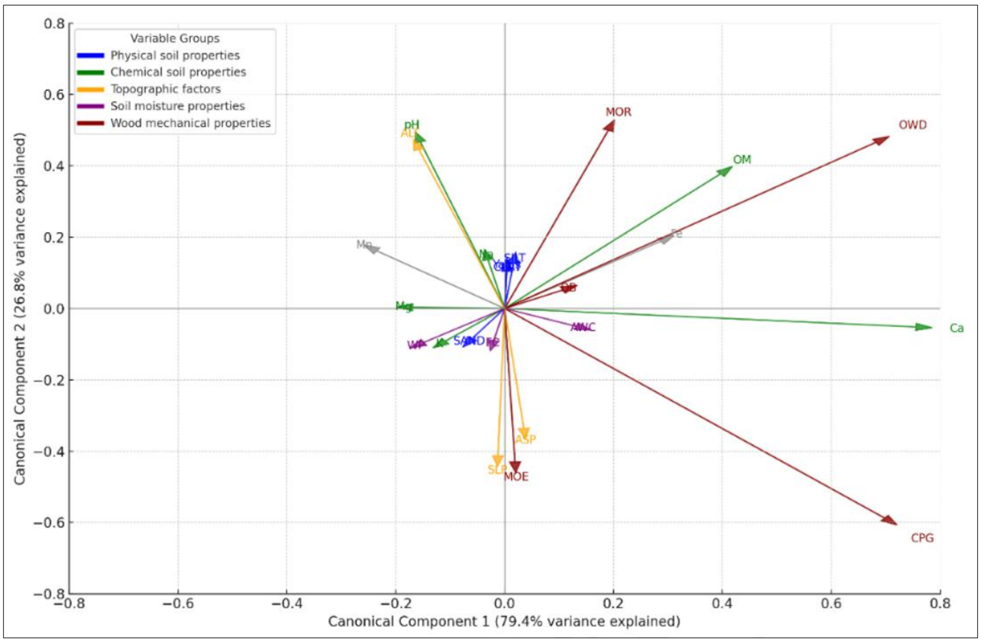

Figure 1. Canonical relationship plot between wood and soil variables

3.3. Prediction and Interpretation of Wood Properties with MLR

The interaction of various environmental factors shapes tree growth. Environmental factors such as soil chemistry (C/N ratio, K content, pH), PRC, moisture status, and ALT significantly affect tree growth [58-61]. Changes in wood properties are caused by the joint influence of genetic makeup and environmental factors [62]. Some studies have argued that soil properties do not affect wood [63], while others have reported significant relationships between these factors [64].

As the plants' lignin-to-cellulose ratio increases, MOE and CPG also increase. Structural changes in the cell wall affect mechanical properties such as MOR, MOE, DB, and CPG [57, 65]. Lignin significantly contributes to compressive resistance, particularly in the direction perpendicular to the fibers, and influences the plant's response to stress factors [66]. The influence of different nutrients shapes the structure and function of the plant cell wall. Ca increases cell wall stability by forming cross-links between pectin chains. Ca deficiency can impair cell wall stability, leading to tissue softening. Mg is involved in cell wall metabolism in biochemical processes linked to ATP. Mn functions as a cofactor of enzymes involved in lignin and pectin modification. Mn deficiency reduces cell wall stiffness by decreasing lignin deposition. Similarly, Iron (Fe^{2+}/Fe^{3+}) ions are required for the functioning of peroxidase enzymes involved in lignin synthesis. Fe deficiency can cause disruptions in the lignification process. K, conversely, maintains the intracellular osmotic balance and affects cell expansion and the length of wood fibers through turgor pressure [57, 67, 68].

The MLR model based on OWG revealed the effect of soil chemical properties. The explanatory power of the model was high (R^2 = 0.541; adjusted R^2 = 0.534), and the error rate was low (RMSE = 0.0352) (Table 4, Figure 2). The positive effects of Fe and K in the model indicate the role of these elements in increasing wood density. Fe acting as a cofactor in lignin synthesis may have contributed positively to OWG by increasing structural stiffness. Antagonistic relationships may explain the negative effect of Mg; high Mg may indirectly suppress lignification by limiting Fe uptake. Furthermore, the inability of Mg to compete with Ca in permeable sandy soils may have reduced structural density [57]. Bellote et al. (2007) reported a negative effect of Mg on wood density [69]. The limited contribution of K is likely due to the soil's low K retention capacity, attributed to its low clay content [1]. This may have led to less accumulation of K in the wood. The positive effect of PRC is in line with the common trend of increasing wood density with increasing altitude [70, 71]. This result aligns with studies conducted in various geographical areas. Indeed, it has been reported in the literature that wood density tends to increase with increasing altitude [70-74].

Similar studies have focused more on physical, morphological, and environmental variables in determining the occurrence of OWG. For example, in a study by Watt et al. (2006) on Pinus radiata, stem tapering, fall temperature, and leaf area index explained 76% of the OWG [30]. Elrhayam et al. (2024) explained 98% of OWG in Eucalyptus camaldulensis with an ANN-based model using water absorption, volumetric mass, and mass loss variables [75]. Using the same data, the multiple linear models yielded an R^2 value of 80%. This study reveals that soil chemical properties are more influential on OWG, accounting for 54% of the variance. This suggests that the indirect effects of soil are more systematically revealed compared to previous models that focused on structural variables. Thus, this study is one of the few studies that clearly emphasize the effect of soil components on wood density.

Table 4. MLR model results for OWG prediction

Model	Predicted	Predictors	β	t	*p*	VIF	R^2	*adj.*	F	RMSE
Model 1	OWG	Constant	0.530	6.899	0.001	-	0.541	0.534	78.78	0.0352
		Fe	0.002	17.776	0.001	2.214				
		PRC	0.001	9.387	0.001	1.437				
		K	0.001	8.478	0.001	1.646				
		Mg	-0.094	-6.890	0.001	2.830				
		pH	0.032	6.653	0.001	2.950				

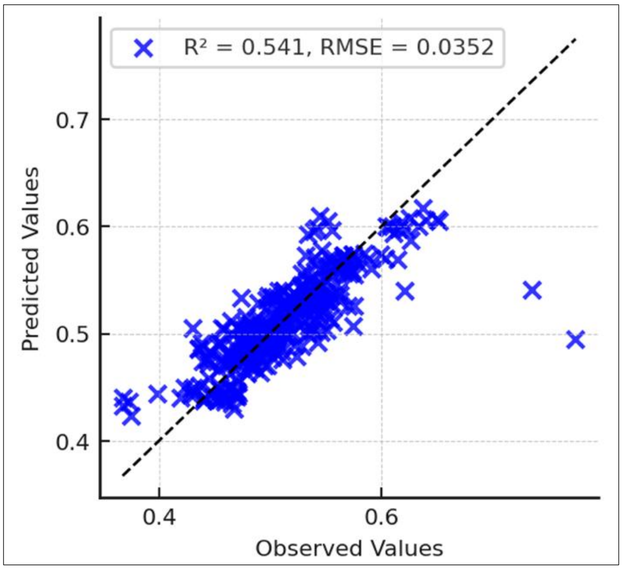

Figure 2. Relationship between observed and predicted OWG values

The MOE model shows the effects of soil properties on the modulus of elasticity of wood. The explanatory power of the model is moderate (R^2 = 0.386; adjusted R^2 = 0.374), and the error rate is relatively high (RMSE = 530.99) (Table 5, Figure 3). This suggests that about 39% of the variation in MOE is related to soil. K and Fe contents had a positive effect, consistent with the function of these elements in cell wall formation. However, this limited explanatory power suggests that MOE is affected not only by soil factors but also by genetic structure, age, and individual tree characteristics. In this study, these variables were not included in the model. Zhu et al. (2015) reported that only air-dry density and tangential shrinkage coefficient explained 61% of the variance in MOE. This result indicates that woody physical properties are more determinant of MOE [76]. Similarly, Watt et al. (2008) reported that stem thinness and total phosphorus explained 90% of the variation in MOE in P. radiata and C. lusitanica species. It was observed that elasticity decreased in the case of excess phosphorus. This supports the limited effect of some soil nutrients, such as Mg, on MOE [32]. Elrhayam et al. (2024) found that MOE can be predicted with 98% accuracy using an ANN model with physical variables such as water absorption, density, and mass loss. These findings suggest that structural features dominate the prediction of MOE, while soil variables have a limited contribution [75].

Table 5. MLR model results for MOE prediction

Model	Predicted	Predictors	β	t	*p*	VIF	R^2	*adj.*	F	RMSE
Model 2	MOE	Constant	-567.160	-0.651	0.516	-	0.386	0.374	30.97	530.99
		PRC	2.407	3.793	0.001	2.065				
		Fe	12.208	6.876	0.001	1.767				
		K	1360.453	6.027	0.001	1.136				
		Mn	-20.821	-5.172	0.001	1.878				
		pH	382.120	4.366	0.001	2.495				

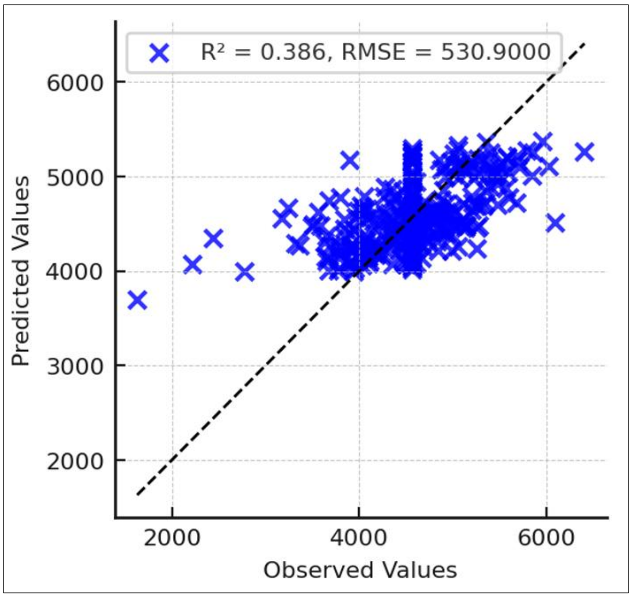

Figure 3. Relationship between observed and predicted MOE values

The CPG model analyzed how soil properties influence this mechanical resistance. The model exhibits high explanatory power (R^2 = 0.552, adjusted R^2 = 0.544), and the error rate is acceptable (RMSE = 35.66) (Table 6, Figure 4). This finding suggests that soil factors account for 55% of CPG variability. The positive effects of OM and K indicate that soil fertility contributes to CPG. Soil organic matter, especially humus content, influences wood structure not directly but through strong indirect pathways. Soils high in humic and fulvic acids stimulate root growth and increase cambium activities involved in wood tissue formation [77]. Furthermore, humic compounds support lignification enzymes by chelating microelements such as Fe and Mn, thus increasing the production of polymers that determine the hardness and flexibility of wood [78]. Low levels of organic matter can limit the retention of nutrients in the topsoil, especially cations such as exchangeable Mg. The retention of Mg in this form is highly dependent on the organic matter fraction in soils with low clay content [79]. This can reduce magnesium availability in the root zone, affecting cell wall processes such as lignin and cellulose synthesis, resulting in localized differences in structural properties, including wood density and flexibility. In contrast, the negative effects of FC and Mn on CPG are noteworthy. The strong performance of the model reveals that soil factors are more effective on CPG than OWG and MOE. The high R^2 value may be due to considering multiple soil variables (Fe, pH, K, Mn, OM, FC) in the model. Lower retention of Fe in soils with low clay content may reduce its accumulation in sapwood tissue [1]. On the other hand, Mn can accumulate excessively at low pH and high clay content, resulting in high solubility and loss of flexibility [57, 65].

Table 6. MLR model results for CPG prediction

Model	Predicted	Predictors	β	t	*p*	VIF	R^2	*adj.*	F	RMSE
Model 3	CPG	Constant	67.518	2.887	0.004	-	0.552	0.544	68.47	35.6643
		Fe	1.838	16.451	0.001	2.082				
		pH_{KCl}	66.226	12.765	0.001	2.609				
		K	75.644	5.501	0.001	1.254				
		Mn	-1.286	-6.900	0.001	1.215				
		OM	5.611	6.922	0.001	3.229				
		FC	-1.462	-5.229	0.001	2.134				

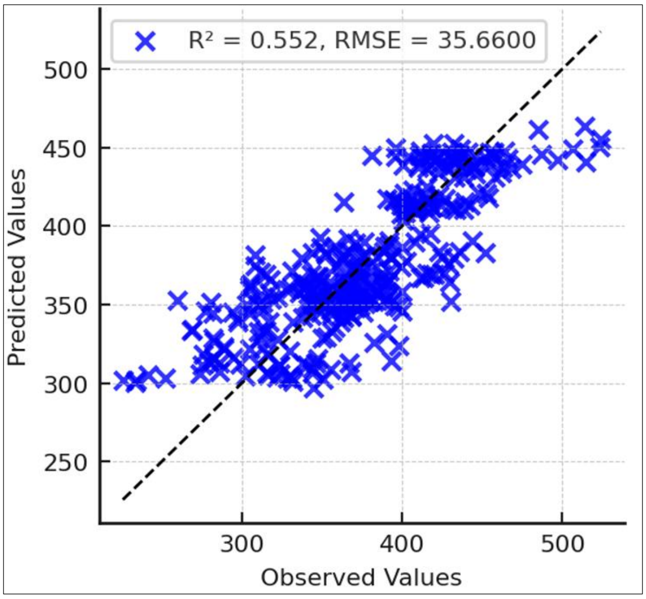

Figure 4. Relationship between observed and predicted CPG values

When CCA and MLR analyses are considered together, it is seen that these two methods provide complementary information. While CCA showed the general relationship structures between soil and wood properties, MLR provided the opportunity to examine the effect of each variable in detail. Strong relationships between soil chemistry, OWG, and MOE were generally consistent in CCA (79.4% variance) and MLR ($R^2 = 0.541$ for OWG; $R^2 = 0.386$ for MOE). However, the positive effect of Mg in CCA and the negative effect in MLR indicate that MLR more clearly reveals the complex relationships between variables. This differential effect of Mg may be because MLR reflects the independent variable effects, while CCA reflects interactions within the environmental context. Therefore, while CCA can reveal the indirect effects of Mg, MLR shows more clearly suppressive effects [1, 80].

Conclusion

This study demonstrates that soil chemical properties play a fundamental role in shaping the mechanical properties of Alnus glutinosa wood. Both CCA and MLR models revealed that pH, Fe, K, Mg, Mn, and organic matter significantly influence wood traits, including MOE, MOR, OWG, and CPG. The CCA results underscored a strong relationship between soil chemistry (notably pH, Mg, and K) and wood mechanical traits, explaining up to 79.4% of the variance in the first canonical axis. In parallel, MLR models confirmed these effects with substantial predictive power, particularly for OWG (R^2 = 0.541, RMSE = 0.0352) and CPG (R^2 = 0.552, RMSE = 35.66). The relatively lower explanatory power of MOE (R^2 = 0.386) suggests that this trait may be more influenced by structural or genetic factors not accounted for in the current models. Notably, the contrasting roles of Mg in CCA (positive) and MLR (negative) underscore the complex and sometimes antagonistic interactions among soil nutrients, which are more effectively captured when using both multivariate and regression-based approaches in tandem. Integrating these methods provided a nuanced understanding of how environmental conditions, particularly soil fertility and mineral availability, affect wood quality. Overall, the findings provide valuable insights into how edaphic factors influence timber characteristics in temperate forest ecosystems and may inform future silvicultural practices and site-species matching strategies in sustainable forest management.

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