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Chemical and Mechanical Properties of *Melia Azedarach* Mature Wood as Affected by Primary Treated Sewage-Effluent Irrigation

Ramadan Nasser, Hamad Al-Meffarrej, Mohamad Abdel-Aal and Said Hegazy

College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia

Abstract: To investigate the effect of primary treated sewage-effluent irrigation (TS) on the chemical and mechanical properties of chinaberry wood (*Melia azedarach* L), small clear specimens from mature wood of 9 year age were prepared and tested according to British Standard Specification. Static bending, compression parallel to grain and Janka hardness tests were done. Based on extractive-free and the oven-dry weight, cellulose, hemicellulose, lignin and ash contents were determined. The results indicated that using TS in irrigation of Chinaberry trees significantly increased all chemical components of wood except hemicellulose content. The hemicellulose content decreased non-significantly, compared with municipal water. With exception for ash content, the effects of TS irrigation on chemical constituents of wood were inconspicuous. TS significantly increased wood specific gravity and all mechanical properties of wood. The chemical components of the wood were clearly correlated with each of modulus of rupture (MOR), MOE and maximum crushing strength (C_{max}).

Key words: Sewage-effluent · Municipal water · Chinaberry · Mechanical properties · Chemical properties

INTRODUCTION

Many developing countries, including Saudi Arabia, do not possess adequate forest reserves to cover their needs for fuel wood, industrial wood, sawn wood and wood-based composition panels. The annual wood and wood products import in Saudi Arabia is estimated at 115 million dollars in 2004 and 305 million dollars in 2007. In order to meet the increasing demand of wood products, Saudi Arabia has planted fast growing tree species all over the country and used sewage effluent to irrigate forest trees. Water has become an increasingly scare resource in many arid and semi-arid regions, thus necessitating development of water resources through untraditional ways [1]. The domestic wastewater generated from Riyadh City has increased from 420 x 10^3 m^3.day^{-1} in 1993 to 538.5 x 10^3 m^3.day^{-1} in 2007 [2]. The treated domestic wastewater increased from 396.3 x 10^3 m^3.day^{-1} in 1993 to 536.33 x 10^3 m^3 .day^{+} in 2007 [3].

Many studies have shown that wastewater safe use after primary treatment for irrigation of tree plantations, forestlands, green belts around the cities and non-food crops. Changes in the physical and chemical properties of soil by use of sewage effluent [4] and effects of irrigation with sewage effluent on growth parameters of some forest trees, tree biomass potential and allocation of its components [5,6] have been studied.

Effects of irrigation with sewage effluent on wood specific gravity, fibre length and volumetric shrinkage of forest trees have also been worked out [7,8]. However, mechanical properties of wood in trees irrigated with sewage effluent are yet to be properly evaluated. Significant effect on the specific gravity and fibre length of wood from different wood species [8,9] was reported. In *Melia azedarach* L., however, sewage water had a slight effect on these properties but volumetric shrinkage increased significantly [7].

Melia azedarach (chinaberry), a fast-growing deciduous hardwood tree in the meliaceae family, is native to Himalayan region of Asia and grows up to 20 m high. Its wood is used for turnery, furniture, decorative veneers, novelty items, boxes and chests [10]. It is important to evaluate the chemical composition and mechanical properties of a wood in order to ascertain its proper utilization.

This study investigates the effect of treated sewage-effluent irrigation on the chemical and mechanical properties of the chinaberry wood and finds out mutual relationship among these properties.

Corresponding Author: Ramadan Nasser, College of Food and Agricultural Sciences,
King Saud University, Riyadh, Saudi Arabia

MATERIALS AND METHODS

Nine-year-old trees with a straight trunk were randomly chosen from a *Melia azedarach* L. (six trees of each of the municipal water and treated wastewater population) grown in Derab, 60 km south Riyadh city. The site has the following characters: 24° 6' N, latitude; 46° 5' E, longitude; temperature (as an average of season) ranged between 10° C in winter and 41° C in summer; and 50 mm rainfall annually. The trees were planted in 1999 at 2x2 m spacing and irrigated twice a week in summer and twice a month in winter seasons by either treated wastewater (TW) or municipal water (MW). TW used to irrigate the plantation was derived from industrial and municipal sources. It treated primary, then stored in lagoons temporarily before irrigation. The soil of the site is calcareous, low clay silt and its physical and chemical properties are shown in Table 1. Results of the analysis of MW and TW used in the current study are presented in Table 2.

After the trees were felled, one 60-cm long bolts were removed from them at about 140 cm from the ground level. The two ends of the bolts were coated with tar to prevent moisture losses. The bolts were then transported to the Wood Testing Laboratory, College of Food and Agricultural Sciences, King Saud University, piled and machined green resembling the ASTM [11]. From each bolt, two adjacent diametric strips (3*3 cm) were removed. Each strip removed from each bolt was re-sawn longitudinally into four sticks. Two sticks of them, near the bark (mature wood or outer zone) were taken following [12]. The specimens were stacked on pallets for air-drying in the laboratory until the equilibrium moisture content was reached.

Mechanical Testing Procedure: The small clear specimens were prepared and tested according to British Standard Specifications [13]. In this specification, the 2-cm system of testing was used, which is one of the principal schemes accepted internationally for the purpose mentioned. The performed tests are listed in Table 3. All mechanical tests were carried out using Instron Universal Testing Machine (Model 1195).

In static bending test, the load at proportional limit (P_{PL}), maximum load (P_{max}) and deflection (y) were obtained from load-deflection curves. The modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated using the equations presented in Table 3. In compression parallel to grain, increasing load was applied to the individual test specimens until a failure occurred and maximum crushing load value was recorded, then the maximum crushing strength (C_{max}) was calculated. On the other hand, Janka hardness test was conducted in radial and tangential directions with ball diameter of 11.28 mm (100 mm^2 projected area) and the hardness strength (Janka hardness number, JHN) calculated as the maximum load (kN). The dimensions of test specimens, loading rates and the calculated parameters from each test are shown in Table 3.

Table 1: Texture, physical and chemical characteristics of soil used

	Type of Soil	
Character	Municipal water	Treated wastewater
pH	7.8	7.8
EC (ds.m^{-1})	4.8	2.3
$CaCO_3$ (%)	32.5	30.4
Texture:		
Sand	53	51
Clay	26	27
Silt	21	22
Soluble cations (mg.l^{-1})		
Na^+	2.1	4.2
Ca^{2+}	1.11	2.68
Mg^{2+}	1.34	3.16
Soluble anions (mg.l^{-1})		
CO_3^{2-}	0.19	0.21
HCO^{2-}	1.21	1.43
Cl^-	2.2	8.56
SO_4^{2-}	4.6	5.1

Table 2: Analysis of primary treated wastewater and municipal water used

	Type of Water	
Parameter	Municipal water	Treated wastewater
pH	8.1	8.4
EC (ds.m^{-1})	5.6	1.4
TDS (mg.L^{-1})	3254	741
SAR (mg.L^{-1})	7.5	3.1
Soluble cations (mg.l^{-1})		
Na^+	15.87	215.05
Ca^{2+}	23	151
Mg^{2+}	6.72	44.16
K+	3.12	4.54
Soluble anions (mg.l^{-1})		
CO_3^{2-}	1.04	37.5
HCO^{2-}	30.5	144.9
Cl^-	26.66	301.75
SO_4^{2-}	17.28	369.6
Heavy metals (mg.l^{-1})		
Cd	0.003	0.004
Pb	0	0.002
Ni	0.005	0.006
Zn	0.022	0
Cu	0	0.07
Mn	0.02	0.130
Available N (ppm)	0.31	2.48
Available P (ppm)	0.12	0.69

Table 3: Dimensions of test specimens, loading rates and calculated parameters

	Dimensions (cm)		Loading	
Test	Cross Section	Length	Rate	Calculated parameters
Bending	2 x 2	30	6.6	MOR= (1.5 x Lx P_{max})\(b x h^2) MOE= (P_{PL} x L^3)\(4xDxbxh^3)
Compression parallel to grain	2 x 2	6	0.63	C_{max}=P_{max}\(b x h)
Janka Hardness	2 x 2	8	6.3	JHN in radial direction
JHN in tangential direction				

P_{max}=maximum load,
b and h=breadth and depth of specimen
MOE= Modulus of elasticity
Cmax= Maximum crushing strength
Loading rate is the rate of load applied in mm\min.
P_{PL}=load at proportional limit,
L= specimen span, 28 cm
MOR= Molulus of rupture
JHN= Janka hardness number

Specific Gravity and Moisture Content of Wood: Upon completion of bending test, the moisture content and specific gravity were determined by removing two pieces of 2x2x1.5 cm near the failure point. Specific gravity was calculated based on oven-dry weight and volume at test measured by dimensions using digital caliper to the nearest 0.01 mm. However, moisture content was determined based on oven-dry weight basis.

Chemical Analysis of Wood: After the mechanical tests were completed, each sample was divided into small pieces and milled in a laboratory Wiley mill to obtain a 40-60 mesh meals. Total extractives content was determined based on oven-dry weight of the wood meals according to ASTM [11]. Based on extractive-free and the oven-dry weight of wood meal, cellulose, hemicellulose, lignin and ash contents were determined by the methods of Nikitin [14], Rozmarin and Simionescu [15], ASTM D-111 [16] and NREL [17], respectively.

Statistical Analysis: The data was analyzed by student (*t-test*) to compare the actual difference between the two means in relation to the variation in the data using SAS program. Results are expressed as means and standard deviation (SD). In the second stage multiple regressions were used to reach the full model. The best reduced model representing the relationship studied was then extracted from the full model using a type of backward elimination procedure [18]. Coefficient of determination, R^2 and simple regression analysis were also undertaken.

RESULTS AND DISCUSSION

Growth and Biomass Characteristics: The growth characteristics and total biomass of the trees that the samples were taken are given in Table 4. Treated sewage-effluent irrigation (TW) had a significant effect for all the tested characters. These results indicate that TW enhanced the growth and biomass production of chinaberry trees.

Wood Chemical Compositions: The mean values for chemical constituents of chinaberry wood, as affected by irrigation treatments, are shown in Table 5. The primary treated sewage-effluent significantly increased the wood contents of cellulose ($t= -11.27$, $p=0.0001$), lignin ($t= -5.02$, $p=0.0001$), extractives ($t=-9.88$, $p=0.0001$) and ash ($t= -3.19$, $p=0.012$). However, the decrease in hemicellulose content of wood was not significant ($t= 0.32$, $p=0.756$). Table 5 shows that sewage-effluent irrigation resulted in higher mean values of cellulose (44.64%), lignin content (30.96%) and ash content (0.393%) compared with the municipal water. The increase in cellulose content at sewage effluent irrigation may be due to increase in latewood compared to early wood or to the thicker fibre walls especially in S_2 layer [19].

The increase in the cellulose, extractives and ash contents of wood, as caused by the sewage-effluent, is in agreement with the findings of Kherallah [20] on *Eucalyptus camaldulensis*. However, the significant increase in lignin content in the current study with sewage-effluent irrigation (29.93% vs. 30.96% for municipal water) is in contradiction with Abdel-Aal [21] who found a slight decrease in the lignin content (28.98%) as compared with the municipal water (29.18%) in *Casuarina cunninghamiana* trees irrigated with sewage sludge. Likewise, the insignificant decrease in hemicellulose content in the Chinaberry is in contrast with Kherallah [20] who reported a highly significant decrease of hemicellulose (28% vs. 31.0% for municipal water) in *Eucalyptus camaldulensis.*

The highest effect of primary treated sewage-effluent irrigation on the chemical constituents of wood was obtained with ash content which increased from 0.335%

Table 4: Means and standard deviation for growth and biomass production of the test trees irrigated by municipal water and primary treated sewage-effluent

	Irrigation Treatment		
Character	Municipal water	Primary treated sewage-effluent	*t-sign*
Total height (m)	6.56 (0.54)	11.43 (1.04)	**
Diameter at breast height (cm)	22.98 (1.39)	25.67 (0.99)	**
Volume of stem (m^3)	0.365(0.043)	0.501 (0.066)	**
Total fresh biomass (kg)	287.5 (24.5)	455.9 (32.9)	**
Total dry biomass (kg)	165.4 (31.8)	211.8 (54.1)	**

Each value is an average of 6 samples, ** $p < 0.01$.

Values between parentheses are standard deviations.

Table 5: Effects of primary treated sewage-effluent irrigation on wood chemical components

	Irrigation treatments		
Chemical Components (%)	Municipal water	Primary treated sewage-effluent	*t-sign*
Cellulose content	42.31(0.57)	44.64 (0.25)	**
Hemicellulose content	24.73(0.26)	24.68 (0.38)	ns
Lignin content	29.93(0.41)	30.96 (0.46)	**
Extractive content	12.43(0.23)	13.41 (0.19)	**
Ash content	0.335(0.008)	0.393 (0.053	*

Each value is an average of 9 specimens,

* and **: Significant at 0.05 and 0.01 level of probability, respectively ns: not significant

( ) Values between parentheses are standard deviations.

to 0.393%, showing a variation of 17.31%. These findings are in agreement with those of Kayad *et al.* [7] who reported that despite an enhanced growth of chinaberry trees wood properties were little affected by sewage water irrigation.

Physical Properties of Wood: The mean values for the physical properties of wood as affected by irrigation treatments are presented in Table 6. All test specimens had about the same moisture content which ranged between 11.99 to 12.15% without showing any significant difference (t= 0.603, *p*=0.563). This means that all the specimens were carefully conditioned and reached the equilibrium moisture content before the test (about 12%). Therefore, the values of mechanical properties ***i.e.*** MOR, MOE and C_{max} were not adjusted for differences in moisture content.

In the present study, application of primary treated sewage-effluent significantly (t=-6.97, *p*=0.0001) increased wood specific gravity of chinaberry (0.65 vs. 0.59 for municipal water) and the difference between the two values was higher (10.68%). These results are in harmony with those of Szopa ***et al.*** [8] on *Quercus alba* and Kayad ***et al.*** [7] on *Melia azedarach*, they showing a slight increase in specific gravity of wood due to sewage-effluent irrigation.

Mechanical Properties of Wood: The mean values and standard deviations for the physical properties of wood as affected by irrigation treatments are shown in Table 6. Primary treated sewage-effluent irrigation had a significant positive effect on all mechanical properties of wood ($p < 0.0121$). It can be noticed that trees irrigated with sewage-effluent gave higher mean values of MOR (131.99 MPa) and C_{max} (51.63 MPa), as compared with trees irrigated with municipal water (120.80 and 46.52 MPa, respectively). Modulus of elasticity (MOE) had the largest difference (15.98%) between the two mean values for the municipal water and sewage-effluent (11489.4 and 13305.9 MPa, respectively), while the least difference was obtained with Janka hardness number in the radial and tangential directions. It can be seen from Janka hardness number in the radial direction was lower (5.80 vs. 5.46 kN for municipal water) than in the tangential direction (6.34 vs. 5.93 kN for municipal water).

In general, although most mechanical properties of wood are closely correlated to density [22], the small change observed in the current study in specific gravity is not sufficient to account for the relatively large differences in the mechanical properties observed due to irrigation treatments. This finding are agreement of [23] on *Populus tremuloides* and [24] on *Ostrya carpinifolia*. The large change in mechanical properties with

Table 6: Means and standard deviations of physical and mechanical properties of wood as affected by primary treated sewage-effluent irrigation

	Irrigation treatments		
Property	Municipal water	Primary treatedsewage-effluent	*t-sign*
Specific gravity	0.590(0.02)	0.653 (0.02)	**
Moisture content (%)	12.15(0.80)	11.99 (0.11)	ns
Modulus of rupture, MOR (MPa)	120.80(8.58)	131.99 (6.53)	**
Modulus of elasticity, MOE (MPa)	11489.4(141.48)	13305.9 (264.88)	**
Maximum crushing strength, Cmax (MPa)	46.52(2.36)	51.63 (1.95)	**
Janka hardness number in radial (kN)	5.93(0.111)	6.34 (0.167)	***
Janka hardness number in tangintial (kN)	5.46(0.133)	5.80 (0.092)	**

Each value is an average of 9 specimens.

**: Significant at 0.01 level of probability, respectively. .ns: not significant.

+ SG is based upon volume at test and oven-dry weight.

( ) Values between parentheses are standard deviations.

Table 7: Correlation coefficients matrix among the parameters of mature wood

	SG	Cellulose	Hemicellulose	Lignin	Extractives	Ash
Modulus of rupture, MOR	0.91^{**}	0.55^{*}	-0.16^{NS}	0.56^{*}	0.50^{*}	0.36^{NS}
Modulus of elasticity, MOE	0.80^{**}	0.87^{**}	-0.26^{NS}	0.75^{**}	0.89^{**}	0.37^{NS}
Maximum crushing strength, C_{max}	0.68^{**}	0.78^{**}	-0.24^{NS}	0.95^{**}	0.88^{**}	0.28^{NS}
Janka hardness number in radial	0.67^{**}	0.81^{**}	-0.23^{NS}	0.82^{**}	0.86^{**}	0.23^{NS}
Janka hardness number in tangential	0.74^{**}	0.76^{**}	-0.21^{NS}	0.54^{*}	0.71^{**}	0.33^{NS}

*, ** Significant differences at 0.05 and 0.01 probability levels, respectively. NS: Not significant.

increasing age may reflect combined effects of increasing specific gravity, cell dimensions and increasing fibril angle in the secondary cell wall [23].

Based on the above results, it can be concluded that TW had a notable positive effect on all mechanical properties of chinaberry wood especially the modulus of elasticity (MOE) as compared with MW.

Correlation Between Chemical Components and Mechanical Properties: The correlation coefficients matrix among each of the physical, mechanical and chemical properties of the mature wood are summarized in Table 7. Good positive correlations (r= 0.50 to 0.95, $p<0.01$) occurred between all the mechanical properties and each of the extractives, cellulose and lignin contents of wood. These coefficients were significant or highly significant. This means that those wood chemical components were clearly correlated with each of MOR, MOE and C_{max}. There were insignificant negative correlations between each of hemicellulose and ash content of the wood and all the mechanical properties of wood (Table 7). These results are in agreement with those of El-Osta *et al.* [25] and El-Sayed *et al.* [26].

Extractives content showed a significant positive correlation with each of mechanical properties of mature wood (r= 0.50 to 0.89), as shown in Table 7. This means that the higher the extractives content of wood the greater the mechanical properties. These results are in harmony with the observations of many authors [24,27], which led them to suggest that the extractives have an important role in reinforcing the cell walls. Grabner *et al.* [28] reported that sapwood extraction had a minor effect on the mechanical properties, whereas the heartwood extractives had a great impact. This affirms that removal of high extractives contents of *Ceteris paribus* had a significant consequence on C_{max} and MOE. On the other hand, our findings contradict Badran and El-Osta [29] and Al-Mefarrej [30]. The former concluded that extractives content did not affect the maximum crushing strength significantly, whereas the later found no significant correlation between the extractives content and the bending strength parameters (MOR and MOE). This disagreement could be because exact location of extractives in wood tissues was not well defined. If the extractives were located on the lumen surface of cell wood, the major repository in wood structure, they would not be expected to influence the strength [29]. However, if these extraneous substances were to be located within the cell wall, i.e., the amorphous regions, their influence on strength properties would be considerably pronounced [25]. Hernandez [22] concluded that the differences of mechanical properties of wood should be explained both by the density and the presence of extractives.

Table 8: Regression equations$^+$ and coefficient of determination (R^2) of the mature wood

Property (Y)	Equation	R^2
Modulus of rupture, MOR	Y= 391 – 12.62 Hem* + 128.6Ash**	0.79
Modulus of elasticity, MOE	Y=17658+414Cell*–900Hem*–614Lig*+1366Ext*	0.94
Maximum crushing strength, C_{max}	Y= -94.3 + 4.71 Lig**	0.91
Janka hardness number in radial	Y = 2.59 + 0.18 Ext* + 2.10 Ash*	0.68
Janka hardness number in tangential	Y = -1.14 + 0.10 Cell* + 0.39 Ext* – 2.0Ash*	0.84

*, ** Significant differences at 0.05 and 0.01 probability levels, respectively.

+ Carried out using least square method a stepwise elimination technique [35].

Cell= Cellulose Hem= Hemicellulose Lig= Lignin Ext= Extractive.

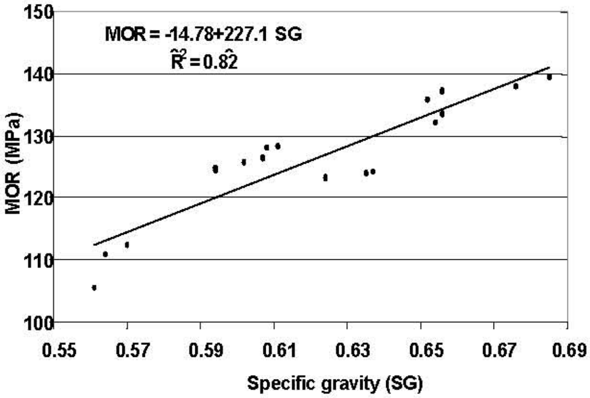

Fig. 1: Relationship between the modulus of rupture (MOR) and specific gravity (SG)

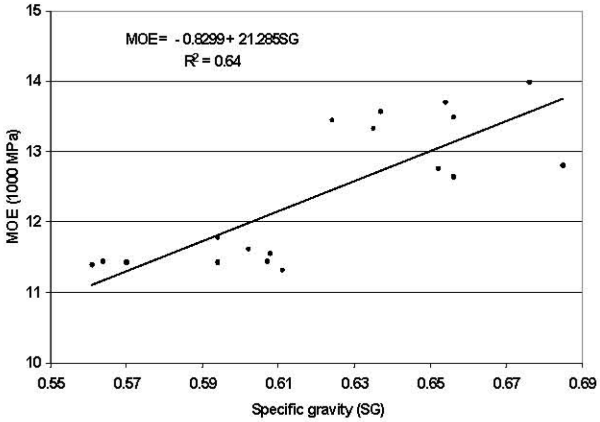

Fig. 2: Relationship between the modulus of elasticity (MOE) and specific gravity (SG)

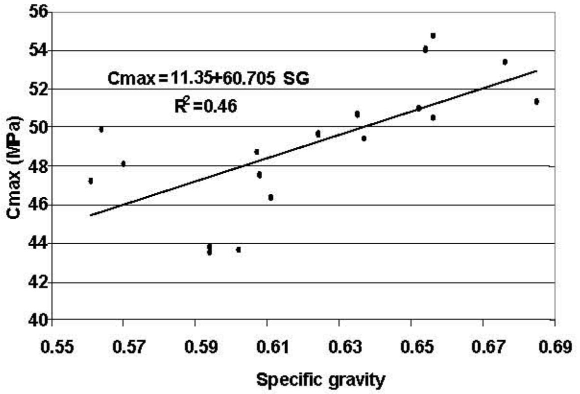

Fig. 3: Relationship between the maximum crushing strength (C_{max}) and specific gravity (SG)

There were significant positive correlations (0.67 to 0.91) between wood specific gravity (SG), for the mature wood and each of the mechanical properties of wood (Table 7). As a general rule, the relationship between wood SG and mechanical properties varies according to the considered properties and the different wood species, but in most cases it is linear. With increasing SG, strength also increases and this is because SG is a measure of the wood substance contained in a given volume [31]. These results support Schniewind and Gammon [32] and Pometti *et al.* [33], who concluded that strength properties of wood are closely correlated with specific gravity and that the higher the specific gravity the greater the strength.

The multiple regression equations in the reduced model for each of the mechanical properties versus each of the variables of the chemical components of the mature wood are presented in Table 8. The data suggest that after elimination of non-significant variables based on the test of each partial regression coefficient (R^2) from the full model, all regression equations in the table account 68.1% to 90.9% of the total variation on all the mechanical properties studied. It is clear that these equations were the best reduced models to describe the total variations of each of the mechanical test data *i.e.,* MOR, MOE,. etc in the current study.

Simple regression analysis revealed that the coefficients of determination (R^2) between SG and each mechanical property range from 0.45 to 0.83. This means that even for statistically significant regressions, 32% up to 83% of the total variation in mechanical properties can be explained by SG variation. Some of these relations which exhibit a relatively high degree of association between SG and some of the mechanical test parameters are plotted in Figs 1-3. It can be seen from these figures that SG is a good indicator to explain and detect the mechanical properties of the mature wood. These results ratify many earlier researches carried out to study the relationship between SG and mechanical properties [33,34].

CONCLUSIONS

Based on the results of the current study, the following conclusions are drawn:

- The effect of primary treated sewage-effluent on wood chemical constituents was highly significant with an exception of hemicellulose which was not significant.
- Primary treated sewage-effluent significantly increased the cellulose, lignin, ash and extractives contents of wood but decreased the hemicellulose content.
- The highest effect of sewage-effluent on chemical components was obtained with ash content which increased from 0.335% to 0.393%.
- Although trees irrigated by sewage-effluent had a significant effect on the wood chemical components, wood taken from trees irrigated by sewage-effluent did not differ much from the wood after irrigated with municipal water, with exception for ash content.
- Good correlations ($r = 0.50$ to 0.95, $p < 0.01$) were found between all mechanical properties and each of the wood chemical components.

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