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3D-QSAR studies of the chemical modification of hydroxyl groups of biomass (cellulose, hemicelluloses and lignin) using quantum chemical descriptors

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ABSTRACT

The models of Quantitative Structure-Activity Relationship (QSAR) are indeed useful for understanding the mechanism of chemical modification of wood by the method of acetylation. This study shows that the electrophile index ω in combination with other descriptors, namely LUMO energy, HOMO, hardness (η) and chemical potential (μ), prove their utility in predicting the chemical modification of wood (gain in mass). The QSAR models are developed through use of Multiple Linear Regression (MLR) and Principal Component Analysis (PCA) methods. The statistical results indicate that the multiple correlation coefficient $R^2 = 0.987$, R^2 adjusted $= 0.981$ and RMCE $= 0.012$. This shows both the favorable estimation stability and the appropriate predictive power. The results also indicate that there are significant correlations between the weight gain and the highest occupied molecular orbital HOMO. They also show that the chemical potential μ which are useful for modeling the wood modification are characterized by large hydrophobic properties and high electrophilic powers and therefore could be applied effectively in estimating the acetylation of wood. Finally, the developed model shows that cellulose and hemicellulose are mostly affected by the chemical modification of hydroxyl groups.

1. Introduction

For many centuries, wood has been used by humans mainly for fuel, shelter, weapons, tools and furniture. As a material, it was considered as an easily renewable, easily available and sustainable element to work with since it has been used without any modifications [1, 2]. In addition, the regulatory progress in Europe, North America and elsewhere in the use of biocidal products has led to new developments in the field of wood modification [3]. This, in its turn, has led to increasing the attention of scientists in non-biocidal treatments involving chemical modifications, thermal modifications or impregnation modifications so as to cope with the forthcoming ban on biocidal products [4, 5]. Through the chemical modification of wood, low-durability species could be transformed into new modified wood products with advanced properties and without deleterious effects on the environment or humans [1, 4]. Acylation transforms highly polar wood hydroxyl groups into weakly polar ester groups which makes wood more hydrophobic, dimensionally stable and therefore more resistant to fungal attack [6, 7].

Alternatively to the physical methods, natural fibers can also be treated with several chemical methods such as alkali treatment (mercerization), silane treatment, maleated coupling, acetylation, permanganate and peroxide treatment, benzoylation, graft polymerization, etherification, isocyanate treatment, etc. These chemical processes for modification of natural fibers are used in order to improve their surface and mechanical characteristics. These chemical modifications consist of chemical reactions between the reactive constituents of the natural fibers (hydroxyl groups, for example) and a chemical reagent forming a covalent bond between the two [8]. This chemical modification promotes the substitution of polar hydroxyl groups found on fiber cell wall by the less polar acetyl groups [9]. As a result, the hydrophilic nature of the fiber decreases leading to a better compatibility with the nonpolar matrix. The acetylation treatments are effective in reducing the moisture absorption of natural fibers and also in improving the mechanical properties of composites, such as the interfacial shear and tensile and flexural strength [10].

However, the cellulose is highly hydrophilic because of its surface abundance of hydroxyl groups (OH) [21,22] [11, 12]. This inherent hydrophilicity causes poor dispersion and weak interaction with most

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polymers, which are mostly hydrophobic. The surface modification is one of the most commonly used strategies to improve dispersion and the interaction of fillers with the surrounding hydrophobic polymer, and therefore, potentiates the reinforcing effect [23–26] [13, 14, 15, 16]. The functionalisation consists of adding functional groups onto the 4 cellulose surface, especially by replacement of OH groups of native cellulose by the functional group molecule [27–29] [17, 18, 19]. Depending on the choice of the functional groups involved to the cellulose surface, the hydrophilicity can be tailored, and consequently, the disadvantages related to the interaction and dispersion are surmounted [20].

Therefore, in order to study the chemical reactivity of wood, we used the QSAR method which includes all the statistical methods by which activities are related with structural elements (Free Wilson analysis), physicochemical properties (Hansch analysis) or various related parameters to the notion of field assisting in the description of the structure (3D-QSAR). The information which is extracted from the QSAR study results can be used to attain a better knowledge of the molecular structures and probably the mode of action at the molecular level (Fig. 1) [21].

The purpose of this study is to study the impact of quantum chemistry parameters on the chemical modification of the cell wall of wood. It also predicts the wood constituents which are mostly affected by the modification. Therefore, wood has been modified with six different chemical agents which are frequently used.

2. Theory/calculation

2.1. Understanding the chemical modification of wood by the QSAR

There are currently a large number of molecular descriptors which can be used in QSAR studies. The results can be used to predict the activity of untested compounds and the calculation of the electronic descriptors is carried out by using the ChemBio Office 2015 software. The geometries of the structures are optimized with the DFT method. Then, several related structural parameters are selected from the results of quantum computing as follows: the highest occupied molecular orbital energy (E_{HOMO}), the lowest unoccupied molecular orbital energy (E_{LUMO}), Electronic Chemical Potential (μ), the absolute hardness (η), and the Reactivity Index (ω). The indices η, μ, andω [22, 23] were determined through the use of the following Eqs. (1), (2), (3), and (4):

$$\Delta E = (E_{HOMO} - E_{LUMO}) \quad (1)$$

$$\eta = \frac{(E_{LUMO} - E_{HOMO})}{2} \quad (2)$$

$$\mu = \frac{(E_{HOMO} + E_{LUMO})}{2} \quad (3)$$

$$\omega = \frac{\mu^2}{2\eta} \quad (4)$$

2.2. Statistical analyzes

In the QSAR study, the quantitative descriptors are used to explain the chemical reactivity of wood components during chemical modification and analysis results in a mathematical model which describes the relationship between chemical structure and activity. In order to explain the structure-activity relationship, these descriptors are calculated for the molecules by using the software which is mentioned above. The Quantitative descriptors were studied by using the statistical methods which are based on Principal Component Analysis (PCA) and Multiple Linear Regression (MLR) analysis with XLSTAT software version 2016. The MLR and PCA were generated by the XLSTAT software version 2016. In order to predict responsiveness, the quality of the model was justified by means of coefficient of determination (R^2), squared error (MSE), Fisher criterion (F) and the level of significance (P).

2.3. Computational calculation of the electronic properties of wood substances

The computational computations of the substances were carried out by studying the different electronic descriptors while using the method of electronic density DFT. The results are given in Table 1.

3. Results & discussion

3.1. The mathematical model of mass gains in the descriptor functions

In order to establish the mathematical models which connect the experimental results extracted from the mass gains and the values obtained by the quantum method, we calculated the correlation factors R^2. Table 2 shows the correlation matrix to quickly detect certain links between the studied variables.

In Table 2, the resulting matrix provides the information on high or low correlation between variables. In general, good co-linearity ($r > 0.5$) was observed between most variables. We also observe a very strong correlation between E_{HOMO} and μ ($r = 0.998$), E_{HOMO} and ω ($r = -0.937$), E_{HOMO} and η ($r = -0.999$). The elaborated QSAR model reveals that the chemical reactivity of the wood components with the reagent is explained by a number of electronic, steric and thermodynamic factors.

3.2. Statistics of multi-collinearity

Table 3 summarizes the inflation factors for stability and QSAR model validation.

The correlation coefficients between the model variables were calculated by the Variance Inflation Factor (VIF) as it is shown in Table 3. The VIF was defined as $1/(1-R^2)$, in which R was the multiple correlation coefficients for an independent variable against all other descriptors in the model. The Models with VIF greater than 5 were unstable and were eliminated while the models with VIF values between 1 and 4 mean that models can be accepted. We also observed the VIF values of descriptors

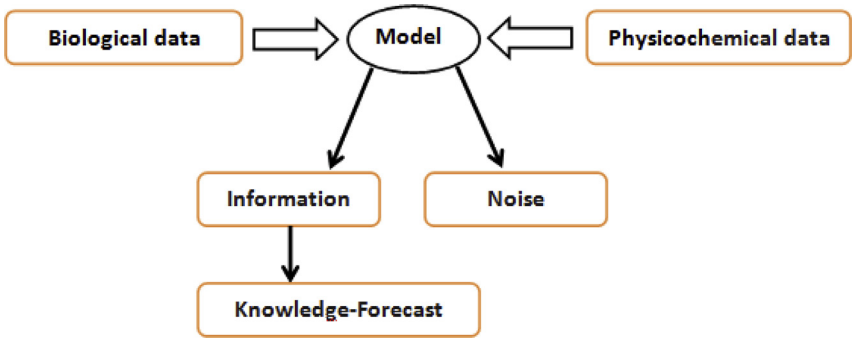


Fig. 1. The QSAR study and its application.

Table 1
Computational results compounds.

Compounds		E_{HOMO} (ev)	E_{LUMO} (ev)	μ(u.a)	η(u.a)	ω(u.a)
Lignin	Paracoumarylique	−0.349	−0.198	−0.273	0.075	0.495
	Coniferylique	−0.341	−0.202	−0.271	0.069	0.530
	Sinapylique	−0.338	−0.201	−0.269	0.068	0.530
Cellulose and hemicellulose	Galactose	−0.349	−0.088	−0.218	0.130	0.182
	Xylose	−0.350	−0.093	−0.221	0.128	0.190
	Glucose	−0.353	−0.100	−0.226	0.126	0.202
	Arabinose	−0.351	−0.097	−0.224	0.127	0.197
	Mannose	−0.349	−0.096	0.222	0.126	0.195

Table 2
Correlation matrix for the descriptors obtained.

	E_{HOMO}	E_{LUMO}	μ	ω	η	WPG (%)
E_{HOMO}	1					
E_{LUMO}	−0.245	1				
μ	*0.998*	−0.205	1			
ω	*−0.937*	0.205	*−0.934*	1		
η	*−0.999*	0.275	*−0.996*	*0.932*	1	
WPG (%)	0.990	−0.237	0.987	−0.945	−0.990	1

Italic values indicates a very good correlation between molecular descriptors.

Table 3
Variance inflation factors (VIF) of Descriptors in the QSAR model.

	E_{HOMO}	E_{LUMO}	μ	ω	η
Tolerance	0.000	0.291	0.002	0.109	0.001
VIF	2186.618	3.431	448.335	9.182	1615.384

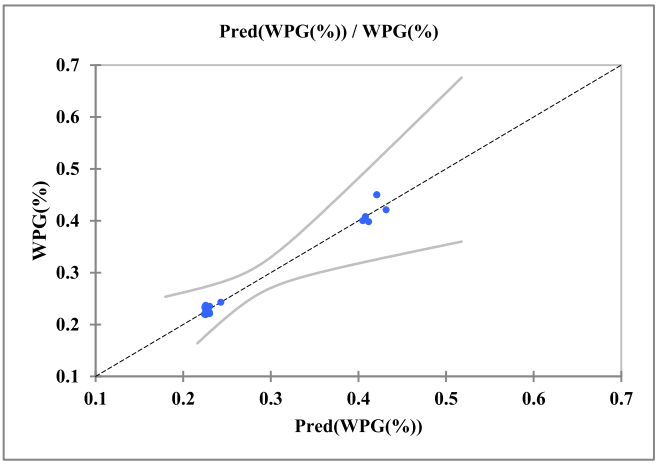


Fig. 2. Graphic representation of mass gain calculated and observed by MLR.

less than 5, therefore we accepted the model.

3.3. Regression of the variable WPG (%)

In order to establish the mathematical model which links the experimental results and the values obtained by the Multiple Linear Regression method, we calculated the correlation coefficient R^2 which gives an idea of the percentage (%) of variability of the variable to be modeled and explained by the explanatory variables.

According to Table 4, we notice that all the descriptors have a satisfactory descriptive quality because the correlation coefficient R^2 and R^2 adjusted are also very strong ($R^2 = 0.987$ and R^2 adju $= 0.981$).

3.4. Model equation (WPG (%))

$N = 8$; $R^2 = 0.987$; $R^2adj = 0.981$; ECM $= 0.0000$, RMCE $= 0.012$, $F = 170.287$, $p < 0.0001$. In this equation, N is the number of compounds, R^2 is the coefficient of determination, MSE is the mean squared error, F is the Fischer criterion and P is the significance level. A higher correlation coefficient and a lower mean squared error indicate that the model is more reliable, P which is less than 0.05 shows that the regression equation is statistically significant. The predicted and observed Correlation of WPG (%) is shown in Fig. 2.

According to this Fig. 2, we find that there is a strong correlation between the experimental and calculated values by using the proposed model with a correlation coefficient $R^2 = 0, 966$, which shows that the equation of regression obtained is interesting in this study. The prediction of the reactivity of wood components by the PLS method Principal component analysis (PCA) is a multivariate technique which is known as interdependence as long as there is no dependent or independent variable identified in advance. Another important feature of the PCA is that there is no null hypothesis to test or verify.

3.5. Correlation matrix

According to Table 5, we notice that the majority of the descriptors are very well correlated since their correlation coefficients are $r > 0.9$.

3.6. Analyzes of the correlation circle map

The descriptors were subjected to the Principal Component Analysis (PCA) (Fig. 3). The first two main axes are sufficient to describe the information provided by the data matrix. Indeed, the percentages of the variance are respectively 79.43% and 18.61% for the F1 and F2 axis.

From the correlation circle, we can notice that the descriptors E_{HOMO} and μ are very correlated following the axis F1 in the negative sense while the descriptors η and ω are highly correlated positively along the F1 axis.

The confusion matrix summarizes the information about the reclassifications of observations in which we can deduce the rates of good and bad ranking. According to Fig. 4, we observe that the hemicellulose and the cellulose have a very important reactivity compared to the lignin

Table 4
Estimates and statistics of coefficients observations.

Observations	17.000
Sum of weights	17.000
DDL	11.000
R^2	0.987
R^2 adjusted	0.981
MCE	0.000
RMCE	0.012

Table 5
Descriptor correlation matrix variables.

Variables	E_{HOMO}	E_{LUMO}	μ	ω	η	WPG (%)
E_{HOMO}	1.000					
E_{LUMO}	−0.245	1.000				
μ	0.998	−0.205	1.000			
ω	−0.937	0.205	−0.934	1.000		
η	−0.999	0.275	−0.996	0.932	1.000	
WPG (%)	0.990	−0.237	0.987	−0.945	−0.990	1.000

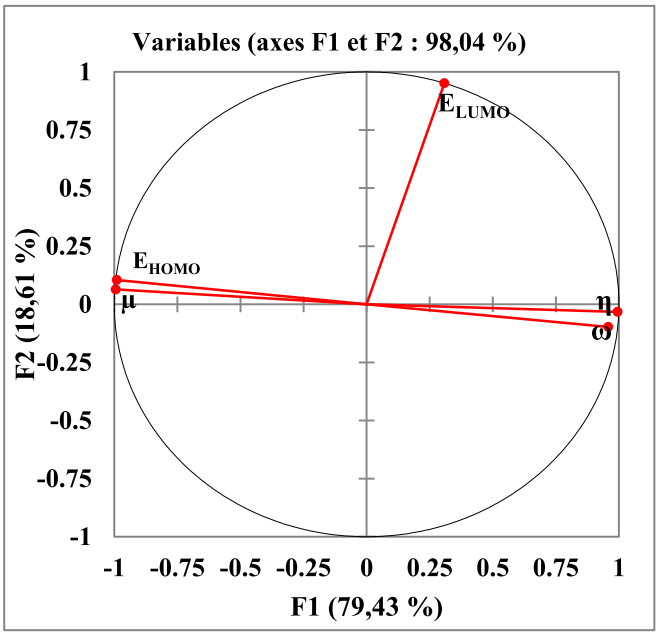


Fig. 3. Correlation circle between X and Y (Produced by EL RHAYAM. Y and al).

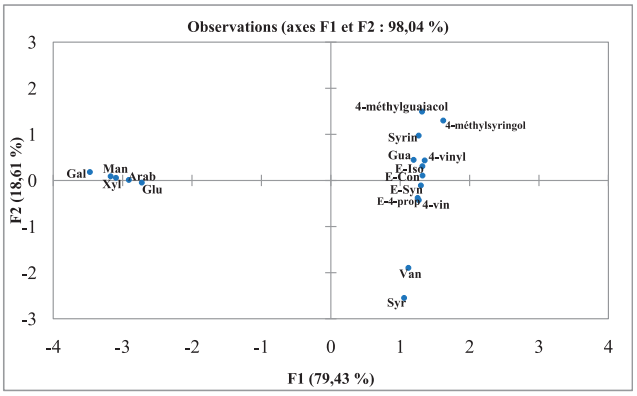
compound due to the fact that these molecules are well correlated with the axis F1 which represent 79% of the information.

3.7. Prediction of electrophile/nucleophilic character of reagents

In order to highlight the electrophilic/nucleophilic nature of the reagents which are used in the modification of wood and wood components (Cellulose, Hemicellulose and Lignin), we have calculated the electronic chemical potentials, the electrophile indices, the nucleophilicity. The results are shown in Table 6.

Table 7 shows that:

-The electronic chemical potential (μ) of the wood components is greater than that-the chemical reagents. This implies that the transfer of electrons will take place from the wood to the reagent. The electrophile index (ω) of the chemical reagents which are used in the chemical modification of wood is higher than that of the wood components. As a



Man: Mannose
Ara: Arabinose
Glu: Glucose
Gal: Galactose
Xyl: Xylose
Syr: Syringaldehyde
Van: Vaniline
4-Vin: 4-vinylsyringol
E-4-prop: E-4-propenylsyringol
E-Syn: E-Synapyllalcool
E-Con: E-Coniferylalcool
E-Iso: E-Isoeugenol
Gua: Guaiacol
4-Vinyl:4-Vinylguaiacol
Syrin: Syringol

Fig. 4. Map of Confusion (Produced by EL RHAYAM. Y and al).

Table 6
Electronic properties of wood components calculated by DFT/B3LYP 6-31G (EL RHAYAM. Y and al).

Compounds	E_{HOMO}	E_{LUMO}	μ	ω	η
Galactose	−0.349	−0.088	−0.218	0.182	0.13
Xylose	−0.35	−0.093	−0.221	0.19	0.128
Glucose	−0.353	−0.1	−0.226	0.202	0.126
Arabinose	−0.351	−0.097	−0.224	0.197	0.127
Mannose	−0.349	−0.096	0.222	0.195	0.126
Guaiacol	−9.153	0.244	−4.454	0.224	4.454
4-méthylguaiacol	−9.033	0.265	−4.384	0.215	4.649
4-vinylguaiacol	−9.021	0.065	−4.478	0.22	4.543
Vanilline	−9.4	−0.316	−4.858	0.22	4.542
E-Isoeugenol	−8.955	0.088	−4.433	0.221	4.521
E-Coniferylalcool	−9.008	0.031	−4.488	0.221	4.519
Syringol	−9.252	0.083	−4.584	0.214	4.667
4-méthylsyringol	−9.123	0.175	−4.474	0.215	4.649
4-vinylsyringol	−9.127	−0.054	−4.59	0.22	4.536
Syringaldéhyde	−9.506	−0.429	−4.967	0.22	4.538
E-4-propenylsyringol	−9.033	−0.006	−4.519	0.221	4.513
E-Synapyllalcool	−9.086	−0.061	−4.573	0.221	4.512

result, the reagents will behave as electrophiles while the wood components will behave like nucleophiles. The small difference in electrophilies between chemical reagents and wood components indicates a low polar character also a characteristic parameter of the reactivity plus this high value indicates that the compound is more reactive and less stable. Vinyl acetate = 4.889) is found to be more reactive than the other compounds. μ According to Tables 6 and 7, we notice that the lower value of the difference E_{HOMO} and E_{LUMO} explains the possible charge transfer interaction that takes place in the molecules. The greater the difference between the energy $E_{HOMO} - E_{LUMO}$, the more the molecule is hard and stable. Therefore, the less reactive molecule, maleic anhydride more reactive than the other compounds, the electronic chemical potential ($\mu = 2.166$) is more electrophilic. Therefore, in order to examine among accessible compounds to enhance the chemical react ω) is a characteristic parameter of chemical reactivity, the larger this value, the more the compound will be more electrophilic (the lower this value, the more the more nucleophilic compound). It is quite obvious that maleic anhydride ($\omega = 5,516$) more reagent. The Electrophilic index (η) of the molecule indicates the chemical reactivity, the higher the value, the harder and harder the molecule, according to this table we see that the vinyl acetate less hard ((η)In addition, the hardness (reactivity with the hydroxyl groups of wood, we correlated these electronic parameters with the degree of grafting (Figs. 5, 6, 7, and 8). This weight gain is thus an indication for the degree of grafting at the fiber surface during the chemical modification.

According to Figs. 5, 6, 7, and 8, it is clearly shown that the method of electron density is more precise, therefore, we will allow the prediction of the chemical reactivity of the macromolecular substances which were studied in wood and the acylation reaction or modification. The chemical composition of the hydroxyl group of wood strongly depends on the electronic chemical parameters and this makes the mass gain important.

The results in Fig. 9 show that the distribution of the electron density influences the chemical reactivity of the woods studied. The more the electron densities are distributed equivalently on the different atoms constituting the molecule, the more the chemical modification is of great interest. Therefore, the Vinyl Acetate reagent better represents the reactivity with the components of the wood.

4. Conclusion

The relationship between the mass gain of wood constituents and the electronic parameters of various reagents used in the chemical modification of wood by the acetylation method were carried out by the theoretical QSAR approach were used for this purpose. The results also

Table 7
Electronic properties of the chemical reagent calculated by DFT/B3LYP 6-31 G (EL RHAYAM. Y and al).

Compounds	E_{HOMO}	E_{LUMO}	ΔE	μ	η	ω	σ
Acetic acid	−11.544	1.055	12.599	−5.244	6.299	2.182	0.158
Acetic anhydride	−10.476	0.745	11.221	−4.865	5.610	2.109	0.178
Maleic anhydride	−10.883	−3.104	7.779	−6.993	3.889	6.287	0.257
Succinic anhydride	−11.838	−0.301	11.537	−6.069	5.768	3.192	0.173
Phthalic anhydride	−10.683	−1.467	9.216	−6.075	4.608	4.004	0.217
Vinyl acetate	−10.406	0.627	11.033	−4.889	5.516	2.166	0.181

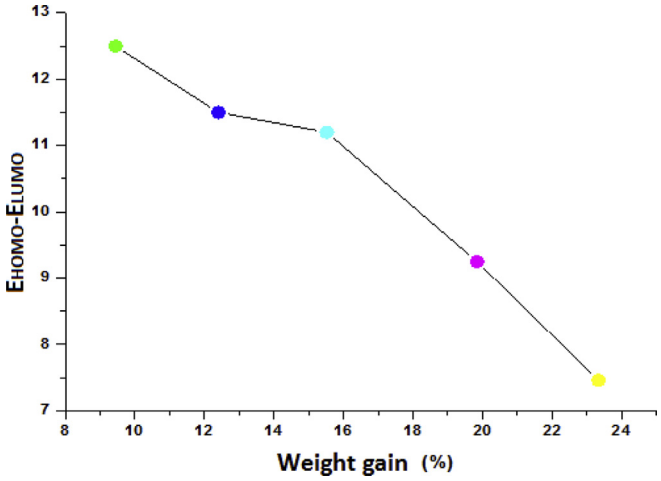


Fig. 5. $E_{HOMO}-E_{LUMO}$ variation as a function of mass gain (Produced by EL RHAYAM. Y and al).

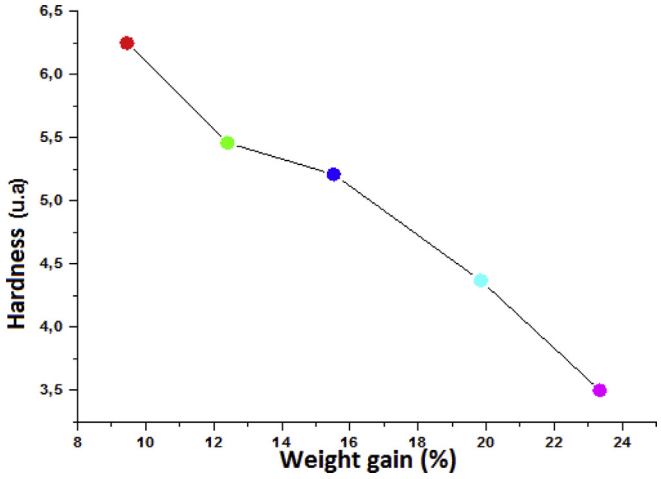


Fig. 6. Variation in hardness as a function of wood grafting rate gain (Produced by EL RHAYAM. Y and al).

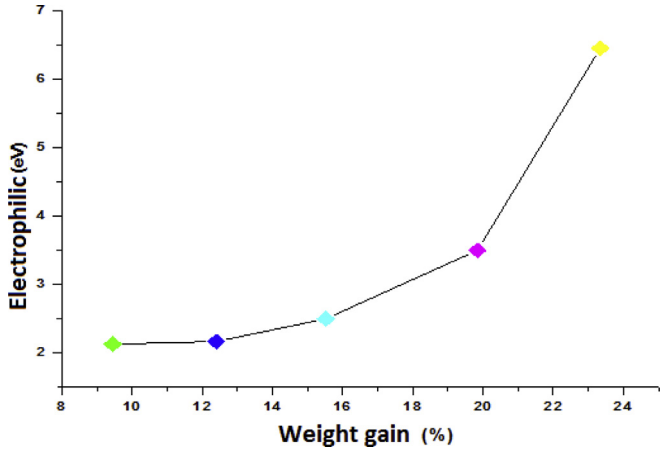


Fig. 7. Variation of the electrophilic index according to grafting rate (Produced by EL RHAYAM. Y and al).

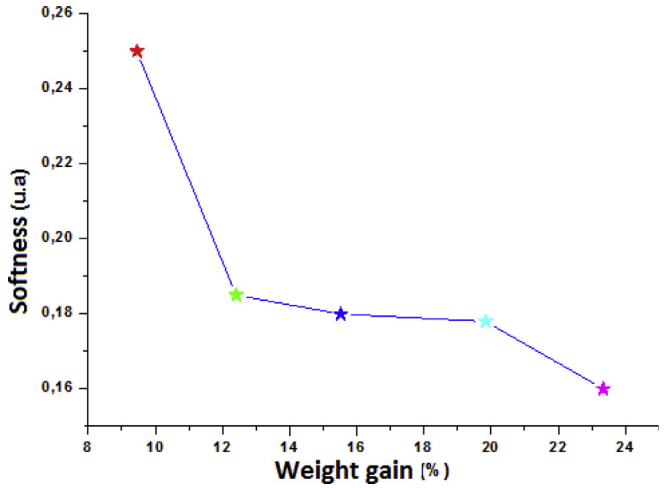


Fig. 8. Variation in softness according to grafting rate (Produced by EL RHAYAM. Y and al).

show that a model obtained from the MLR and the PCR methods can be used appropriately to calculate the degree of substituent that provided a high regression coefficient. According to the statistical analysis, the hemicellulose component is affected first by the modification whereas the lignin is less sensitive by the modification. Then, the results show that the calculated values provide a very acceptable curve with respect to the curve obtained from the experiment. It is expected that this work will provide useful information for estimating biomass mass gain and for designing appropriate operating conditions. Following the results obtained, we will study the chemical modification of wood flour by the vinyl acetate reagent in order to improve some intrinsic properties of wood, this work being processed.

This approach allowed us to draw the following information:

- The electronic descriptors (E_{HOMO}, E_{LUMO}, η, μandω) of the reagents influencing the modification of the biomass surface (cellulose, hemicellulose and lignin).
- The 3D-QSAR model allowed us to indicate the appropriate reagent for chemical modification of natural fiber.
- The results obtained show that cellulose and hemicellulose are sensitive to the modification of their surface.

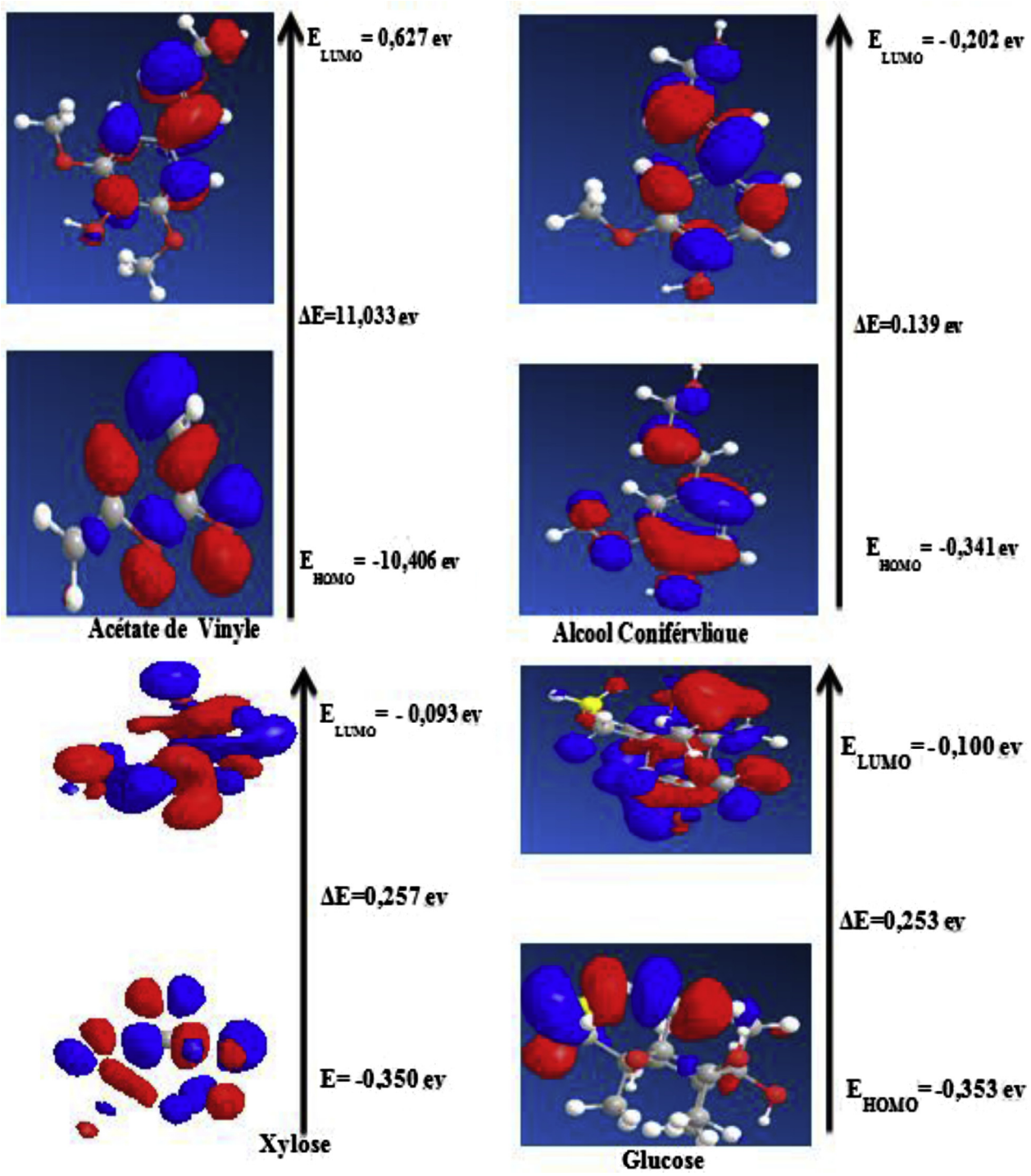


Fig. 9. Molecular orbitals of the studied wood components and the used reagent by showing the E_{HOMO} and E_{LUMO} energies (Produced by EL RHAYAM. Y and al).

- This work paves the way for the exploration of this powerful technique to better understand the effect of chemical modification of biomass on the overall properties of polymer composites.

Declaration

Author contribution statement

Youssef El Rhayam: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ahmed Elharfi: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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