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

Youssef Elrhayam*, Ahmed Elharfi

Laboratory of Agro Resources Polymers and Process Engineering (LAPPE), Team of Macromolecular & Organic Chemistry, Faculty of Sciences, Ibn Tofail University, Kenitra, 14000, Morocco

A R T I C L E   I N F O

Keywords:
Natural product chemistry
Organic chemistry
Biomass
Chemical modification
QSAR
Descriptors

A B S T R A C T

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 (μ) 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 R² = 0.987, R² adjusted = 0.981 and RMSE = 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
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 (EHOMO), the lowest unoccupied molecular orbital energy (ELUMO), Electronic Chemical Potential (μ), the absolute hardness (η), and the Reactivity Index (ω). The indices η, μ and ω [22, 23] were determined through the use of the following Eqs. (1), (2), (3), and (4):  

$$
\Delta E = \left( \frac{E_{HOMO} - E_{LUMO}}{C_0} \right)
$$  

(1)

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

(2)

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

(3)

$$
\omega = \frac{\mu^2}{2\eta}
$$  

(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 (R²), 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 R². 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 – R²), 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.](image-url)
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 (%))

\[ N = 8; R^2 = 0.987; R^2 \text{adj} = 0.981; ECM = 0.0000, \text{RMCE} = 0.012, F = 170.287, p < 0.0001. \]

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 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 \( R^2 \) are greater than 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 \( \text{E HOMO} \) and \( \mu \) are highly correlated positively along the F1 axis. The descriptors were highly correlated positively along the F1 axis.

The confusion matrix summarizes the information about the reclas-

| Table 1 | Computational results compounds. |
|---------|---------------------------------|
| Compounds | \( \text{E}_{\text{HOMO}} \) (ev) | \( \text{E}_{\text{LUMO}} \) (ev) | \( \mu(u.a) \) | \( \omega(u.a) \) | \( \eta(u.a) \) | WPG (%) |
| Lignin | -0.349 | -0.198 | -0.273 | 0.075 | 0.495 |
| Coniferlyque | -0.341 | -0.202 | -0.271 | 0.069 | 0.530 |
| Sinaplyque | -0.338 | -0.201 | -0.269 | 0.068 | 0.530 |
| 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 |
| Mannose | -0.351 | -0.097 | -0.224 | 0.127 | 0.197 |
| Mannose | 0.990 | 0.996 | 0.222 | 0.126 | 0.195 |

| Table 2 | Correlation matrix for the descriptors obtained. |
|---------|---------------------------------|
| \( \text{E}_{\text{HOMO}} \) | \( \text{E}_{\text{LUMO}} \) | \( \mu \) | \( \omega \) | \( \eta \) | WPG (%) |
| \( \text{E}_{\text{HOMO}} \) | 1 | | | | |
| \( \text{E}_{\text{LUMO}} \) | -0.245 | 1 | | | |
| \( \mu \) | 0.988 | -0.205 | 1 | | |
| \( \omega \) | -0.937 | 0.205 | -0.934 | 1 | |
| \( \eta \) | -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. |
|---------|---------------------------------|
| Tolerance | \( \text{E}_{\text{HOMO}} \) | \( \text{E}_{\text{LUMO}} \) | \( \mu \) | \( \omega \) | \( \eta \) |
| Tolerance | 0.000 | 0.291 | 0.002 | 0.109 | 0.001 |
| VIF | 2186.618 | 3.431 | 448.335 | 19.82 | 1615.384 |

| 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 | \( \text{E}_{\text{HOMO}} \) | \( \text{E}_{\text{LUMO}} \) | \( \mu \) | \( \omega \) | \( \eta \) | WPG (%) |
| \( \text{E}_{\text{HOMO}} \) | 1.000 |
| \( \text{E}_{\text{LUMO}} \) | -0.245 | 1.000 |
| \( \mu \) | 0.998 | -0.205 | 1.000 |
| \( \omega \) | -0.937 | 0.205 | -0.934 | 1.000 |
| \( \eta \) | -0.999 | 0.275 | -0.996 | 0.932 | 1.000 |
| WPG (%) | 0.990 | -0.237 | 0.987 | -0.945 | -0.990 | 1.000 |
3.7. Prediction of electrophilic/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 (\(\mu\)) of the wood components is greater than that of the wood reagents. This implies that the transfer of electrons will take place from the wood to the reagent. The electrophile index (\(\omega\)) of the chemical reagents which are used in the chemical modification of wood is higher than that of the wood components. As a result, the reagents will behave as electrophiles while the wood components will behave like nucleophiles. The small difference in electrophilic/nucleophilic character of 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. \(\mu\) According to Tables 6 and 7, we notice that the lower value of the difference \(E_{HOMO} - E_{LUMO}\) 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 \(\eta\) 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).

| Compounds       | \(E_{HOMO}\) | \(E_{LUMO}\) | \(\mu\) | \(\omega\) | \(\eta\) |
|-----------------|--------------|--------------|--------|---------|--------|
| 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-methyguaiacol | -9.033       | 0.265        | -4.384 | 0.215   | 4.649  |
| 4-vinylguaiacol | -9.021       | 0.065        | -4.478 | 0.228   | 4.543  |
| Vanilline       | -9.9       | 0.316        | -4.858 | 0.22     | 4.542  |
| E-isoeugenol    | -9.855       | 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-methylsyringol| -9.123       | 0.175        | -4.474 | 0.215   | 4.649  |
| 4-vinylsyringol | -9.127       | -0.054       | -4.59  | 0.22     | 4.536  |
| Syringaldehyde  | -9.506       | -0.429       | -4.967 | 0.22     | 4.538  |
| E-4-propensyringol | -9.033   | -0.006       | -4.519 | 0.221   | 4.513  |
| E-Synapylalcool | -9.086       | -0.061       | -4.573 | 0.221   | 4.512  |

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

4. Conclusion

The relationship between 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
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 ob-
tained, 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 \(\varepsilon_{\text{HOMO}}\), \(\varepsilon_{\text{LUMO}}\), \(\eta\) and \(\omega\) 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 sen-
sitive to the modification of their surface.

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

| Compounds           | \(\varepsilon_{\text{HOMO}}\) | \(\varepsilon_{\text{LUMO}}\) | \(\Delta\varepsilon\) | \(\mu\)  | \(\eta\)  | \(\omega\) | \(\sigma\) |
|---------------------|--------------|--------------|----------------|--------|--------|--------|--------|
| 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      | 0.027        | 11.033         | -4.889 | 5.516  | 2.166  | 0.181  |
• 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.

*Funding statement*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2019.e02173.

References

[1] R.M. Rowell, Acetylation of wood - a review, Int. J. Lignocellulosic Prod. 1 (1) (2014) 1–27.
[2] R.M. Rowell, Dimensional stability and fungal durability of acetylated wood, Drewno 59 (197) (2016) 139–150.
[3] P. Gérardin, New alternatives for wood preservation based on thermal and chemical modification of wood - a review, Ann. For. Sci. 73 (2016) 559–570.
[4] C.A.S. Hill, Wood Modification – Chemical, Thermal and Other Processes, Wiley Series in Renewable Resources, J. Wiley and Sons, Chichester, United Kingdom, 2006, p. 260.
[5] R.M. Rowell, Handbook of Wood Chemistry and Wood Composites, second ed., CRC Press, Taylor and Francis Group, Boca Raton, Florida, USA, 2012, p. 703.
[6] H. Chang, S. Chang, Moisture excluding efficiency and dimensional stability of wood improved by acylation, Bioresour. Technol. 85 (2002) 201–204.
[7] Nilgu Özen, Nihat S. Çetin, The effect of chemical modification on the strength of wood and bonded wood joints, Eur. Polym. J. 38 (7) (2002) 1483–1486.
[8] M.C. Khoathane, E.R. Sadiku, C.S. Agwuncha, Surface modification of natural fiber composites and their potential applications. Surface Modification of Biopolymers, John Wiley & Sons, Inc., 2015, p. 370e400.
[9] M. El Boustani, G. Lebrun, F. Brouillette, A. Belkhira, Effect of a solvent-free acetylation treatment on reinforcements permeability and tensile behaviour of epoxy/wood fibre/wood fibre composites, Can. J. Chem. Eng. 95 (2017) 1082e92.
[10] F. Ahmad, H.S. Choi, M.K. Park, A review: natural fiber composites selection in view of mechanical, light weight, and economic properties, Macromol. Mater. Eng. 300 (2015) 10e24.
[11] F.V. Ferreira, M. Mariano, S.C. Rabelo, R.F. Gouveia, L.M.F. Lona, Isolation and surface modification of cellulose nanocrystals from sugarcane bagasse waste: from a micro- to a nano-scale view, Appl. Surf. Sci. 436 (2018) 11125–1122.
[12] D.J. Gardner, G.S. Oporto, R. Mills, M.A.S.A. Samir, Adhesion and surface issues in cellulose and nanocellulose, J. Adhes. Sci. Technol. 22 (2008) 545–567.
[13] R. Scaffaro, L. Botti, F. Lopresti, A. Maio, F. Sutera, Polysaccharide nanocrystals as fillers for PLA based nanocomposites, Cellulose 24 (2017) 447–478.
[14] F.V. Ferreira, L.D.S. Cividanes, F.S. Brito, B.R.C. de Menezes, W. Franceschi, E.A.N. Simonetti, G.P. Thim, Functionalization of carbon nanotube and applications. Funct. Graphene Carbon Nanotub., Springer International Publishing, 2016, pp. 31–61.
[15] F.V. Ferreira, L.D.S. Cividanes, F.S. Brito, B.R.C. de Menezes, W. Franceschi, E.A.N. Simonetti, G.P. Thim, Functionalization of graphene and applications. Funct. Graphene Carbon Nanotub., Springer International Publishing, 2016, pp. 1–29.
[16] F.V. Ferreira, M. Mariano, L.S.S. Lepesqueur, I.F. Pinheiro, I.S. Santos, J. Burga-Sánchez, D.H.S. Souza, C.Y. Koga-Ito, A.A. Teixeira-Neto, L.H.I. Mei, R.F. Gouveia, L.M.F. Lona, Silver nanoparticles coated with dodecanethiol used as fillers in non-cytotoxic and anti-fungal PBS/PA composite based on nanocomposites, Mater. Sci. Eng. C 98 (2019) 800–807.
[17] R.J. Moon, A. Martini, J. Nairn, J. Simonsen, J. Youngblood, Cellulose nanomaterials review: structure, properties and nanocomposites, Chem. Soc. Rev. 40 (2011) 3941.
[18] F.V. Ferreira, I.F. Pinheiro, R.F. Gouveia, G.P. Thim, L.M.F. Lona, Functionalized cellulose nanocrystals as reinforcement in biodegradable polymer nanocomposites, Polym. Compos. 39 (2018) E9–E29.
[19] Y. Habibi, L.A. Lucia, O.J. Rojas, Cellulose nanocrystals: chemistry, self-assembly, and applications, Chem. Rev. 110 (2010) 3479–3500.
[20] J. Yang, J. Sidler, N. Grishkewich, K.C. Tam, Functionalization of cellulose nanocrystals for advanced applications, J. Colloid Interface Sci. 494 (2017) 397–409.
[21] H. Waterbeemd, S. Rose, Quantitative approaches to structure-activity relationships. Book “Quantitative Approaches to Structure-Activity Relationships, Elsevier, 2003, pp. 351–367.
[22] R.G. Parr, W. Wang, Density Theory for Atoms and Molecules, Oxford University Press, Oxford, 1989.
[23] R.G. Pearson, Absolute hardness: companion parameter to absolute electronegativity, J. Am. Chem. Soc. 105 (1983) 7512.