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Synthesis of Eugenyl Acetate in Solvent-Free Acetylation: Process Optimization and Kinetic Evaluation

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Abstract

In this work, the synthesis of eugenyl acetate was evaluated in the presence of heterogeneous catalysts aiming developing an economical and environmentally friendly process. The catalysts used were molecular sieve 4Å and Amberlite XAD-16, and highest conversions were obtained in the investigated conditions by experimental design for both catalysts. In the kinetic study the effects of temperature, catalyst concentration and eugenol to acetic anhydride molar ratio in the conversion process were evaluated. The kinetics using molecular sieves 4Å were performed until 6 h of reaction, reaching conversions above 90% in 2 h and the activation energy was 2.40 kcal.mol^{-1}. With Amberlite XAD-16 up to 2 h reactions were conducted and in just 3 min high reaction conversions (97.8%) were achieved with lower activation energy (1.73 kcal mol^{-1}) than the molecular sieve, demonstrating that both catalysts are effective for producing the eugenyl acetate. Heterogeneous catalysts allowed reaching high conversions using less amounts of substrates, in a solvent-free system, and also making possible regeneration and reuse.

Keywords: Eugenyl acetate; Acetylation; Heterogeneous catalysis; Molecular sieve; Polymeric resin

Introduction

The growing demand for safe and natural products has increased the interest in the use of essential oils as natural additives in foods to replace the chemical ones, due to various properties presented by these oils [1]. Essential oils are aromatic oily liquids obtained from plant material (flowers, buds, seeds, leaves, twigs, bark, herbs, wood, fruits and roots). Among the essential oils, the clove oil was reported to have several activities, antimicrobial [2,3], antioxidant [4-7], antimutagenic [8], antinflammatory [9], antiulcerogenic [10], antithrombotic [11], anticarcinogenic [12] and antiparasitic [13]. Some authors attribute the beneficial activities to its major compound, eugenol, characterized by low solubility and stability [14-16].

Thus, to minimize the potent oxidative activity of eugenol, various esters of eugenol related compounds can be synthesized by esterification, for example, through group protection by acetylation with acetic anhydride, in this case, the product is eugenyl acetate, as reported by Chiaradia et al. [17] who studied the eugenyl acetate production in a solvent-free system using Novozym 435 as catalyst, with a conversion of 99%. Other authors also used acetylation with acetic anhydride, but used different substrate and enzymatic catalyst [17] or heterogeneous chemical catalyst [18,19].

The eugenyl acetate is classified as a flavoring substance belonging to benzenediol chemical group, and is considered safe for use in food by two reputable international committees related to food safety, Joint FAO/WHO Expert Committee on Food Additives (JECFA) and European Food Safety Authority (EFSA). The recommended limits vary depending on the type of food, the highest concentrations indicated 25 ppm for meat products and the lowest 2.83 ppm for non-alcoholic beverages. Besides, this compound exhibits several interesting properties such as antimicrobial [17], antioxidant [20], anticarcinogenic [21], antiacaricidal [22], heart protective agent heart, liver and lens of diabetic rats [23], inhibitors of tooth decalcification [24].

Though literature is somewhat vast regarding experimental conditions for ester synthesis, there has been on the other hand

a continuous effort to maximize ester yield and quality of the final product depending on the end use by changing the reaction conditions such as nature of catalyst (chemical/biochemical) and its concentration, reactants molar ratio, temperature, reactor type, operation mode, reaction time, reaction system, etc. Furthermore, discussion around environmental issues has been an unceasing concern in various segments of world society, whether by governmental and non-governmental organizations, researchers from different areas of science or even by the industrial sector, have been intensively charged in order to adapt their processes to systems environmentally friendly, in addition, economical. Thus, processes that fall within the concept of fine chemicals have been gaining prominence in the flavors and fragrances market, representing a challenging goal for academic research and industrial [18,25].

Heterogeneous catalysis is one of the most efficient way to achieve clean transformations that are both environmentally and economically acceptable, allowing operationally simple reactions to be performed without toxic, corrosive or expensive reagents [18,26].

Several new heterogeneous catalysts have been employed to improve the yield of esterification reactions. Yadav and Yadav [27] evaluated the synthesis of eugenol benzoate using super acid UDCaT-5; natural montmorillonite itself or exchanged with Na+ cations, a wide variety of primary, secondary, benzylic, allylic, homocyclic, and heterocyclic alcohols has been acetylated with acetic acid [28], acetylation of

α-methylene-β-hydroxy esters under zeolites and Amberlyst-15 [19], producing triacetylglycerol with Amberlyst-35 [29].

In this study, two heterogeneous catalysts were used: (i) the molecular sieve 4 Å shows high internal surface area and its pore prevent access of molecules whose dimensions are greater than 4 Å, to its interior, providing different types of shape selectivity. The acid characteristics are due to two types of sites, Brönsted and Lewis. Zeolites are used more commonly in the oil industry, however, research has focused on their ability to act as catalysts in a wide variety of reactions, many of them extremely specific, and they are now extensively used in the industry for this purpose. (ii) Amberlite XAD-16 is a non-ionic polymer resin and operates by forming physical bonds with the adsorbed substance. Its main applications are in sugar refining, gas adsorption, wastewater treatment, separation and enrichment of pharmacologically active natural products and purification of bioproducts.

In this context, this work aims at the synthesis of eugenyl acetate through esterification by acetylation of eugenol present in clove oil, testing the effectiveness of heterogeneous catalysts in solvent-free reaction.

Materials and Methods

Materials

Clove essential oil (*Eugenia caryophyllus* Leaf Oil), purchased from Ferquima Indústria e Comercio de Oleos Essenciais (Sao Paulo, Brazil), and acetic anhydride (Vetec, 97% purity) were used as substrates for the acetylation reactions. Molecular sieve 4 Å (Merck Milipore Brazil) and polymeric resin Amberlite XAD-16 (Sigma- Aldrich) were used as catalysts for the acetylation reactions. The standard of eugenyl acetate was obtained from Sigma-Aldrich (Fluka, 99% purity).

Heterogeneous acetylation

Eugenyl acetate was obtained by acetylation of acetic anhydride with clove essential oil in solvent-free system. The acetylation reaction was carried out in screw-capped flasks at various eugenol to acetic anhydride molar ratios (mol:mol), temperature (°C) and amount of catalyst (g.g⁻¹), according to the conditions defined in the experimental design. After complete dissolution of the substrates, the catalyst was added to the mixture. All experiments were carried out in a thermostatic bath. After the reaction time, the catalysts were filtered and samples were kept at 5°C until the determination of reaction conversion.

Sequential strategy of experimental designs

Molecular sieves 4Å: To determine the best reaction conditions in terms of eugenyl acetate production, a Central Composite Rotatable Design 2^3 (CCRD) with three independent variables: X_1, eugenol:acetic anhydride molar ratio, X_2, temperature (°C) and X_3, amount of catalyst (g.g⁻¹) (Table 1) was carried out. The reaction time was kept constant at 2 h (time fixed after a previous kinetic evaluation). The significant differences were tested at the 95% confidence interval based in the F-test. The statistical analysis was accomplished using software Statistica version 7.0 (Statsoft Inc, USA).

Amberlite XAD-16: Initially, a complete factorial design was used to verify the effects of eugenol:acetic anhydride molar ratio, reaction temperature and amount of catalyst, in terms of eugenyl acetate production (results not shown). To study the effect of the independent variables on the ester production a complete factorial design with two independent variables: Y_1, eugenol:acetic anhydride molar ratio and Y_2, temperature (°C) was concieved, as shown in Table 2. The reaction time was kept constant at 30 min (time fixed after a previous kinetic

evaluation). The significant differences were tested at 95% confidence interval based on the F-test. The statistical analysis was accomplished using software Statistica version 7.0 (Statsoft Inc, USA).

Kinetic study of heterogeneous acetylation

From the results obtained in the experimental designs, a kinetic study was carried out using both catalysts, varying the eugenol to acetic anhydride molar ratio, amount of catalyst and temperature, as shown in Table 3. Samples were taken from the bulk reaction system without agitation.

Activaction energy

The activation energy was determined using the Arrhenius equation plot made on basis of ln V vs 1/T and the value of activation energy was calculated from:

$$\ln k = \ln A - \left(\frac{E_a}{R}\right).\left(\frac{1}{T}\right) \tag{1}$$

where: k is constant reaction kinetics (h⁻¹); A is a pre-exponential factor; E_a the activation energy (cal mol⁻¹); R is the universal constant of perfect gases (1.987 cal mol⁻¹ K⁻¹) and T is temperature (K).

Reuse of catalyst

The reactions were conducted in thermostatic bath at the optimized experimental conditions for each catalyst, defined previously. At the end of each process, the reaction medium was filtered and the catalyst washed with hexane (to remove residues) and dried at a temperature of 100 ± 5°C for 4 h. The catalysts were stored at room temperature, and the process repeated for each reuse determination of the catalyst.

Eugenyl acetate quantification

The analyses of the reaction conversion in terms of eugenol esters were performed in a gas chromatography (Shimadzu GC-2010) equipped with data processor, using a capillary column of fused silica INOWAX (30 m × 250 μm × 0.25 μm), flame ionization detector (FID), with the following temperature program: 40°C (8 min), 40-180°C (10°C/min), 180-220°C (10°C/min), 220°C (5 min), injector temperature 250°C, detector at 275°C, injection in the mode split,

Levels					
Variables	-1.68	-1	0	1	1.68
Eugenol	1:0.48	1:1	1:3	1:5	1:5.52
Temperature (X_2)	38	45	55	65	72
Amount of Catalyst	0.03	0.1	0.2	0.3	0.37

Table 1: Experimental domain and level distribution of the variables used for optimization of esterification yield.

Levels			
Variables	-1	0	1
Eugenol: Acetic anhydride molar ratio (Y_1)	1:3	1:4.5	1:6
Amount of Catalyst (Y_2)	0.025	0.100	0.175

Table 2: Experimental domain and level distribution of the variables used for optimization of esterification yield with Amberlite XAD-16.

Variables	Molecular Sieves 4Å	Amberlite XAD-16
Eugenol: Acetic anhydride molar ratio (mol: mol)	1:1, 1:2, 1:3	1:1, 1:2, 1:3
Temperature (ºC)	40, 50, 60	45, 55, 65
Amount of Catalyst (g.g⁻¹)	0.1, 0.2, 0.3	0.1, 0.2, 0.3

Table 3: Variable Values for molecular sieves 4Å and Amberlite XAD-16 used in kinetic study.

ratio of split 1:100, N_2 as carrier gas, injected volume of 1 μL of sample diluted in dicloromethane (1:10). Reaction conversion was calculated based on the reduction of area of limitant reagent on the basis of reaction stoichiometry. This method was based on the that described by Chiaradia et al. [17].

Eugenyl acetate identification

The product (eugenyl acetate) was purified in a rotary evaporator under reduced pressure. After purification, the product was subjected to ^{1}H NMR analysis, in Nuclear Magnetic Ressonance equipment, model Varian Mercury Plus AS-400 MHz, in 100 MHz, using TMS as internal standard and chloroform-d_1 ($CDCl_3$) as solvent.

Results

Optimization of eugenyl acetate production by molecular sieve 4 Å as calalyst

In the evaluation of using molecular sieve 4 Å as catalyst for eugenyl acetate production, a 2^3 Central Composite Rotatable Design was executed. The variables studied were eugenol:acetic anhydride molar ratio (X_1), temperature (X_2) and amount of catalyst (X_3). Table 4 shows the matrix of experimental design with the coded and real values of the independent variables with the experimental (EC) and predicted (PC) conversion in eugenyl acetate. From this table it can be seen that higher conversions were obtained in the experimental conditions of trial 8 (96.9%) and 12 (97.7%).

From the matrix generated by the experimental data and assuming a polynomial model, a predictive equation (eq 2) for eugenyl acetate conversion, C_{ea}, was obtained by multiple regression analysis. In this equation X_1 is a molar ratio; X_2 is the temperature and X_3 is the amount of catalyst.

$$C_{ea}\ (\%) = 84.43 + 10.63\ X_1 - 12.71\ X_1^2 + 15.42\ X_2 - 6.09\ X_2^2 + 19.45\ X_3 - 10.09\ X_3^2 \quad (2)$$

In 2 h of reaction of eugenol with acetic anhydride, only the effects of the interactions were not significant ($p<0.05$) in the conversion. The three linear variables presented a positive effect, with the most representative being the catalyst amount followed by temperature and reactants molar ratio.

The analysis of variance (ANOVA) of the resulting empirical model showed the value of the correlation coefficient (R^2) of 0.99 and F calculated 21 times greater than the F tabulated for the regression, the model was then able to well represent the experimental data of eugenyl acetate conversion in the range of the values investigated, suggesting a satisfactory representation of the process by the empirical model, as shown by the predicted conversion (column 6 and Table 4) and standard error (column 7 and Table 4). With the validation of the model it was possible to build the response surfaces, shown in Figure 1.

Optimization of eugenyl acetate production by amberlite XAD -16 as calalyst

Analyzing the influence of each variable of the previous experimental design and aiming to maximize the production of eugenyl acetate, a 2^2 full factorial design was performed using Amberlite XAD-16 as catalyst. Since the temperature had no significant effect this variable was fixed at 55°C towards assessing the effect of eugenol to acetic anhydride molar ratio and amount of catalyst on the reaction conversion to eugenyl acetate. The amount of catalyst was not increased, and amounts above 0.2 g.g^{-1} showed a pasty appearance of the reaction system.

Table 5 shows the matrix of the design with the coded and real

values of the independent variables and the experimental (EC) and predicted (PC) conversion in eugenyl acetate. From this table it can be seen that higher conversions were obtained in the experimental conditions of trial 4 (97.8%) and 3 (92.0%).

From the matrix generated by the experimental data and assuming a polynomial model, a predictive equation (eq. 3) for eugenyl acetate conversion, C_{ea}, was obtained by multiple regression analysis. In this equation X_3 is the amount of catalyst.

$$C_{ea}\ (\%) = 74.171 + 24.625\ X_3 \quad (3)$$

The values obtained in the analysis of variance (ANOVA), correlation coefficient (0.945) and F test (F calculated 2 times greater than F tabulated), statistically validated the model with 95% confidence. The experimental conversion data of eugenyl acetate in the range of values studied were satisfactorily represented by the empirical model as shown by the predicted conversion (column 5 and Table 5) and standard deviation (column 6 and Table 5).
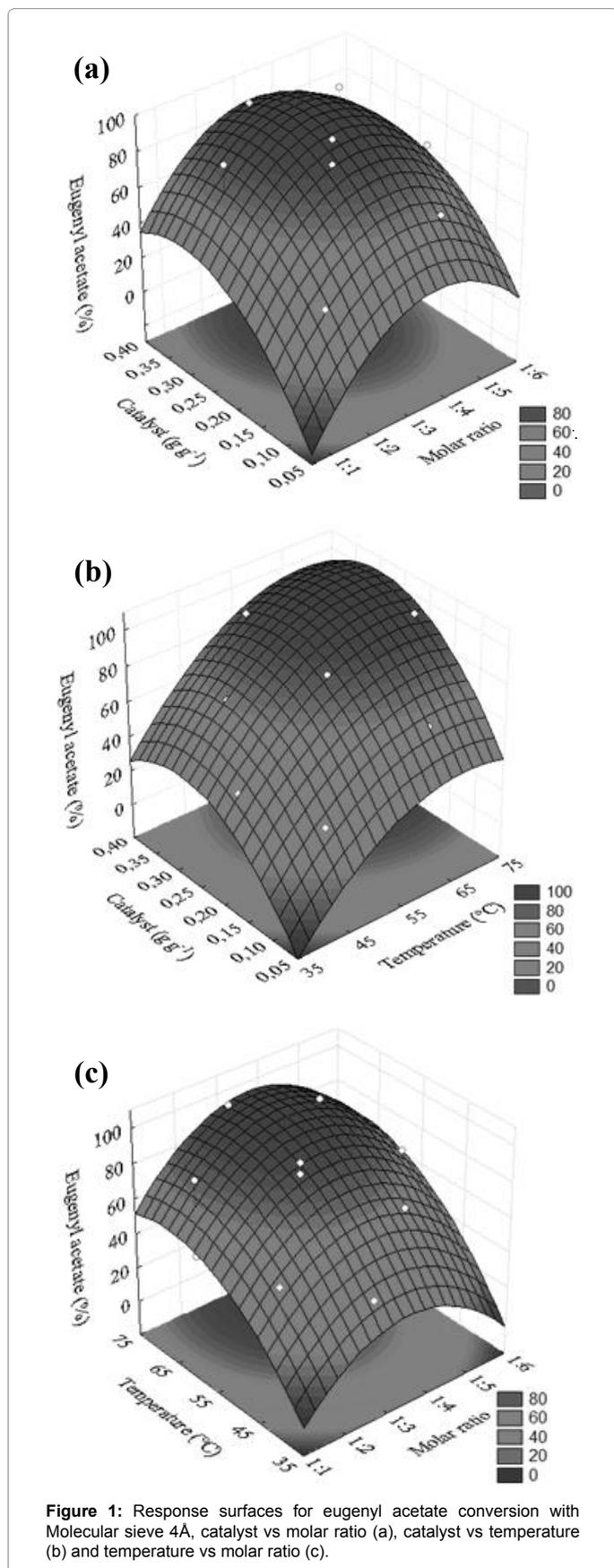
Kinetics of heterogeneous acetylation

The effects of eugenol to acetic anhydride molar ratio, temperature and amount of catalyst were investigated on the kinetics of eugenyl acetate production using molecular sieve 4 Å and Amberlite XAD-16 as catalysts. To evaluate the effect of eugenol to acetic anhydride molar ratio on eugenyl acetate production using molecular sieve 4 Å as catalyst, the temperature was fixed at 55°C and the amount of catalyst at 0.125 g.g^{-1} making possible the construction of experimental curves of conversion versus reaction time, for eugenol to acetic anhydride molar ratio of 1:1, 1:2 and 1:3, as presented in Figure 1a. From this figure, it can be verified that an enhancement in molar ratio led to higher conversions. Using molar ratio of 1:3, higher conversions were obtained (85% and 98.6%, for reaction time of 180 and 360 minutes, respectively). When the same eugenol to acetic anhydride molar ratios were evaluated, using Amberlite XAD-16 as catalyst, temperature was also fixed at 55°C and amount of catalyst was 0.2 g.g^{-1}. Through Figure 2 it is possible to notice that an increase in molar ratio led to higher conversions, as well as using molecular sieve 4 Å. Using molar ratio of 1:3, higher conversions (95.4%) were obtained in just 3 min. These results are in agreement with those obtained in the experimental design

Trial	X_1	X_2	X_3	EC (%)	PC (%)	RED (%)
1	1:15	45	0.1	12.4	10.0	19.0
2	1:4.5	45	0.1	30.3	31.3	3.3
3	1:1.5	65	0.1	37.0	40.9	10.5
4	1:4.5	65	0.1	60.0	62.	3.6
5	1:1.5	45	0.3	52.6	48.9	6.9
6	1:4.5	45	0.3	65.2	70.2	7.7
7	1:1.5	65	0.3	80.4	79.8	0.8
8	1:4.5	65	0.3	96.9	101.1	4.3
9	1:0.48	55	0.2	27.9	30.7	10.0
10	1:5.52	55	0.2	72.6	66.4	8.5
11	1:3	38	0.2	40.2	41.4	2.9
12	1:3	72	0.2	97.7	93.2	4.6
13	1:3	55	0.03	24.9	23.3	6.5
14	1:3	55	0.37	90.4	88.6	1.9
15	1:3	55	0.2	84.3	84.4	0.2
16	1:3	55	0.2	84.3	84.4	0.3
17	1:3	55	0.2	84.2	84.4	0.3

[a] Relative Error Deviation (RED)=|(EC-EP)/EC| × 100.

Table 4: Matrix of the Central Composite Rotatable Design 23 (CCRD) with responses in terms of eugenyl acetate conversion.

Figure 1: Response surfaces for eugenyl acetate conversion with Molecular sieve 4Å, catalyst vs molar ratio (a), catalyst vs temperature (b) and temperature vs molar ratio (c).

that pointed out the molar ratio of 1:3 as being the most appropriate for this reaction system.

The effect of amount of catalyst on eugenyl acetate conversion was evaluated at 55°C maintaining the eugenol to acetic anhydride molar ratio constant at 1:3, varying the amount of catalyst of 0.1, 0.2 and 0.3 g.g^{-1}. The conditions were the same for both catalysts. When molecular sieve 4 Å was used as catalyst, conversions for the highest amounts of catalyst (0.2 and 0.3 g.g^{-1}) were almost the same over the kinetics, reaching approximately 92% of eugenyl acetate in 120 min of reaction (Figure 2a) whereas for Amberlite XAD-16 as catalyst, the highest conversions (95.4%) were obtained using 0.2 g.g^{-1} at only 3 min of reaction (Figure 2b).

To evaluate the effect of temperature on eugenyl acetate conversion, using molecular sieve 4 Å as catalyst, eugenol to acetic anhydride was fixed at 1:3 and amount of catalyst at 0.125 g.g^{-1} varying the temperature from 40 to 60°C, as presented in Figure 2a. The conversion increased with increasing temperature and reached maximum conversion of 96.6 and 98.2% at 360 min of reaction at 50 and 60°C, respectively. When Amberlite XAD-16 was used as catalyst, the same eugenol to acetic anhydride molar ratio and amount of catalyst were used, while temperature ranged from 40 to 65°C, as presented in Figure 2b.

Activation energy for acetylation of eugenol

From the kinetics at different temperatures (40 to 65°C) and fixed amount of catalyst 0.125 (g.g^{-1}) and eugenol to acetic anhydride molar ratio 1:3, the activation energy (Ea) was estimated for molecular sieve 4 Å and Amberlite XAD-16. Figure 3 shows the Arrhenius plot made on the basis of ln K vs 1/T. The value of activation energy was calculated based on eq 1 and the Ea obtained was 2.40 kcal mol^{-1} (Figure 3a) for molecular sieve 4 Å and 1.73 kcal mol^{-1} (Figure 3b) for Amberlite XAD-16.

Reuse of the catalyst

The use of heterogeneous catalysts is motivated by several factors, among which it can be highlighted the possibility of reuse. Based on this argument, the cycles of reuse of the studied catalysts were evaluated. After 10 reuses no loss of catalytic activity of molecular sieve was observed, unlike the resin, in the second reuse, which decreased by around 50% conversion.

Confirmation of the formed ester

The ^{1}H NMR spectra of both catalysts presented the characteristic peaks for each coupling present in the structure of the eugenyl acetate.

Discussion

Optimization study for eugenyl acetate production

In Table 5 and Figure 1 it is observed that higher temperatures and amount of catalyst may lead to increased conversion of eugenyl acetate.

Trial	Y_1	Y_2	EC (%)	PC (%)	RED (%)[a]
1	1:3	0.025	42.1	46.3	-10.0
2	1:6	0.025	49.2	52.8	-7.3
3	1:6	0.175	92	95.6	-3.9
4	1:3	0.175	97.8	102.0	-4.3
5	1:4.5	0.1	78.6	74.2	5.6
6	1:4.5	0.1	79.5	74.2	6.7
7	1:4.5	0.1	80	74.2	7.3

[a] Relative Error Deviation (RED)=|(EC-EP)/EC| × 100.

Table 5: Matrix of Experimental design format 2$^-$ using Amberlite XAD-16 catalyst, response in terms of eugenyl acetate conversion.

Increasing the molar ratio (Figure 1b and Figure 1c) no increase in the conversion was observed. This fact can be relevant from an industrial viewpoint since the process does not need a large amount of acetic anhydride, facilitating the ester purification step. No significant effect was observed regarding possible interaction among variables (cross interactions). However, considering that conversion is lower at the lowest level of temperature, this fact must be compensated by an increase of the amount of catalyst in order to enhance the number of catalytic sites available and therefore to enhance the probability of effective collisions which, in turn, results in higher conversion. The same can be observed at lower amount of catalyst, which must be counteracted with increasing temperature. Increased molar ratio caused a decrease in conversion, probably due to a decrease in reactant concentrations as molar ratio increases causing a decrease of conversion. This fact was also observed by Ochoa-Gómez et al. [30] in the synthesis of glycerol carbonate optimization with CaO as catalyst.
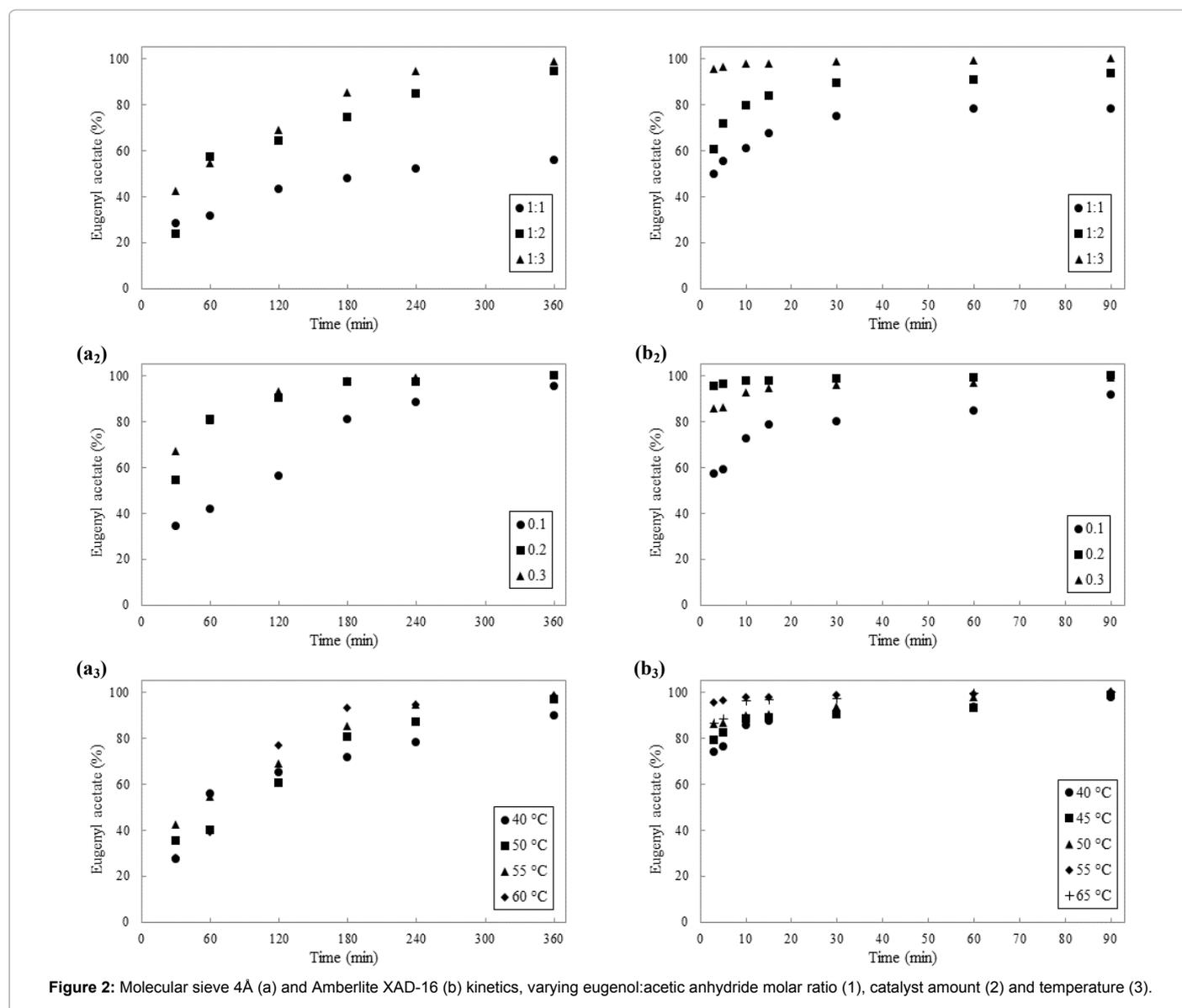
From Table 5 it can be observed that only the amount of catalyst was significant. As already mentioned the increase of molar ratio decreases the concentration of reagents and may result in a decrease in reaction conversion. Chiaradia et al. [17] studied the optimization of eugenyl acetate synthesis by enzyme-catalyzed process. As in this study, the optimized conditions were mild, however, approximately 100% conversion was reached at 6 h reaction time and when compared to this work, such reaction time is 3 and 12 times higher when using molecular sieve 4 Å and Amberlite XAD-16, respectively.

Kinetic of heterogeneous acetylation

The substrates molar ratio is usually one of the most important parameters in the esterification reactions. Since the reaction is reversible, a raise in the concentration of one substrate (particularly, acetic anhydride) can displace the chemical equilibrium, resulting in higher conversions. On the other hand, high acetic anhydride concentrations may reduce the reaction rate due to the inhibition effect [31-34].

For both catalysts, higher conversions were obtained using 1:3 molar ratio, however, in only 3 min high conversions were achieved for
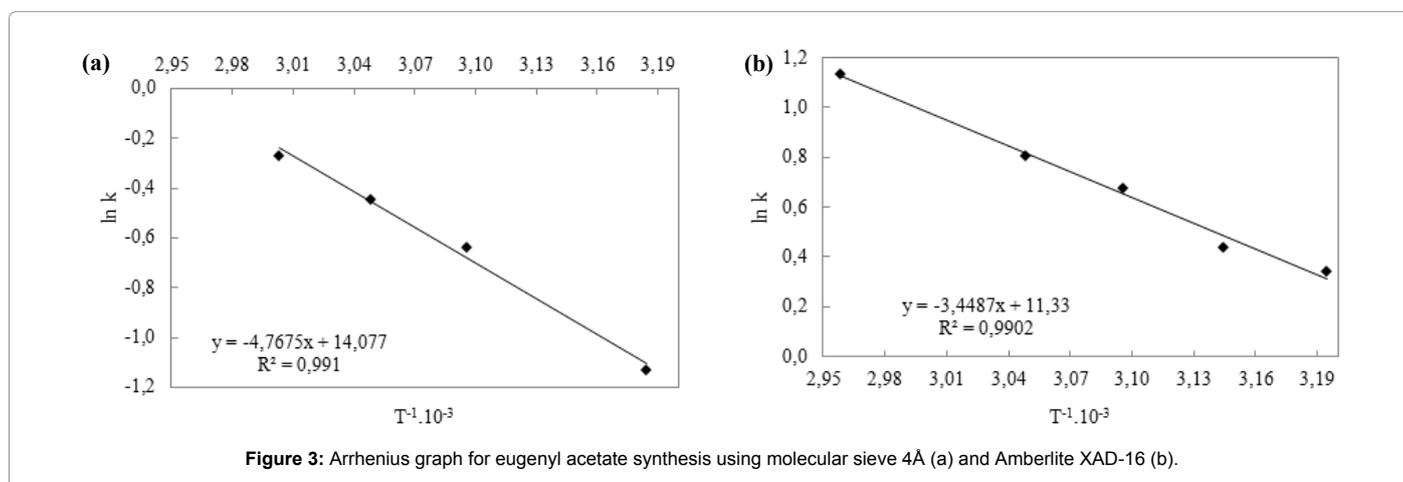

Figure 2: Molecular sieve 4Å (a) and Amberlite XAD-16 (b) kinetics, varying eugenol:acetic anhydride molar ratio (1), catalyst amount (2) and temperature (3).

Figure 3: Arrhenius graph for eugenyl acetate synthesis using molecular sieve 4Å (a) and Amberlite XAD-16 (b).

Amberlite XAD-16 catalyst, since the use of molecular sieve needed 240 min for obtaining the same conversion. Chiaradia et al. [17] showed a more pronounced effect for the first 4 h reaction, leading to 80% conversion to eugenyl acetate in a esterification catalyzed by Novozym 435. The maximum yield of eugenyl acetate (>90%) was reached after 6 h of reaction at molar ratios of 1:3 and 1:5. In the study developed by Palani and Pandurangan [35], the effect of amyl alcohol to acetic acid molar ratio in a esterification catalyzed by molecular sieves Al-MCM-41 was evaluated and 100% of conversion was obtained with molar ratio of 1:2 and using higher molar ratios, reduction in the production of esters was observed.

The higher catalysts amounts tested (0.2 and 0.3 g.g⁻¹) for molecular sieve 4 Å showed no difference in the conversions, this may be due to the fact that above a certain catalyst concentration the number of active sites was larger than actually required by the reactants. At the lowest catalyst concentration the conversion was 56.2% in 120 minutes. For Amberlite XAD-16 the best conversion was obtained with 0.2 g.g⁻¹ amount of catalyst and while the lowest conversion was obtained for 0.3 g.g⁻¹ of catalyst. This may be due to the paste appearance of the reaction medium, which probably hindered the mobility of substrates, hindering the progress of the reaction. Yadav and Yadav [27] studied the esterification of benzoic acid with eugenol using 5 UDCaT as heterogeneous catalyst and also observed that increasing the catalyst concentration did not increase the conversion, as observed in the present study, where no increase in esters conversion was observed when the catalyst concentration increased from 0.2 to 0.3 g.g⁻¹.

The increase in temperature can reduce the viscosity of the mixture increasing the solubility and enhancing the diffusion process of the reactants, thereby reducing mass transfer limitations and enhancing the interaction between catalyst particles and substrates.

In the kinects when we compare different temperatures using Amberlite XAD-16 (Figure 2b), increasing the temperature from 45 to 55°C causes an increase in conversion. This behavior was also observed in the kinect study using molecular sieve 4 Å as catalyst (Figure 2a). Higher temperatures usually promote and increase the number of collisions between catalyst and substrate, resulting in a faster reaction. Moreover, the increased temperature reduces the viscosity of the mixture and enhances the diffusion process, favoring the interaction between the catalyst and substrates. On the other hand, for Amberlite XAD-16, when increasing the temperature to 65°C, there was a decrease in conversion, which may be due to the relatively weak interaction between the solute and the resin, thus decreasing the attractive forces and accordingly the reaction rate.

Activacion energy

The activation energy is the minimum kinetic energy that reactants must have for that product formation occurs. Therefore, processes with low activation energy occur faster, while processes with high activation energy are slower. Therefore, molecular sieve 4 Å proved to be an interesting catalyst for the acetylation of essential clove oil and acetic anhydride, once the activation energy obtained in this study (2.27 kcal mol⁻¹) was lower than that found by several authors. Basri et al. [36] obtained an Ea of 4.02 kcal.mol⁻¹ for the production of ethyl esters using Lipozyme TL IM. Khor et al. [37] also used the Lipozyme TL IM as a catalyst in the production of ethyl esters and obtained an Ea of 5.3 kcal.mol⁻¹. Yadav and Yadav [27] evaluated the production of eugenyl benzoate catalyzed by UDCaT 5, a solid catalyst, and obtained an Ea of 9.36 kcal.mol⁻¹. Akyalçın and Altıokka [38] studied the esterification kinetics of acetic acid with octanol catalyzed by Amberlyst 36 and obtained the activation energy of the reaction of 5.95 kcal.mol⁻¹. Yu and Li [39] obtained an activation energy of 5.56 kcal.mol⁻¹ in the esterification of propyl gallate acid and propanol, catalyzed by tannase from *Aspergillus niger*. The Ea found for Amberlite XAD-16 was 1.73 kcal mol⁻¹, which is 31% lower when compared with the Ea of molecular sieve 4 Å.

Reuse of the catalyst

The molecular sieve 4 Å did not lose the activity after 10 reuse cycles, unlike what was found for Amberlite XAD-16 , in the latter, an adsorbent resin, the active sites were impregnated by substrates or by washing with hexane, this fact can be observed in weighing the catalyst after the reaction, with higher mass compared to the initial mass. However, most heterogeneous catalysts can have their active sites regenerated with simple methodologies, but more investigation on this catalyst is needed.

Pande and Samant et al. [40] studied the reusability of Amberlyst 15 in the synthesis of 4-bromo phenyl acetate and after 4 cycles no loss of catalytic activity was observed. Yadav and Thathagar [41] also observed no loss of activity for Indion-170 resin after 3 cycles during synthesis diethyl maleate. The loss of catalytic activity was also not observed during the esterification of benzoic acid and eugenol using heterogeneous catalyst UDCaT-5 [27].

Thus, Amberlite XAD-16 showed great potential for the synthesis of eugenyl acetate since in only 3 minutes of reaction it was obtained

95.4% conversion using 0.2 g.g^{-1} catalyst , eugenol to acetic anhydride molar ratio of 1:3 acetic and temperature of 55°C. The experimental conditions tested for achieving a 100% conversion, along with simple methodology and mild reaction conditions, showed the feasibility of this processing industrial synthesis. Furthermore, there is the possibility of recycling and/or regeneration the catalysts tested, and the purification step can be simplified, because the reaction does not require large amounts of excess substrate, being possible to achieve high conversions in reduced time, in a solvent-free system, using a reduced amount of catalyst and reactant, the reaction system does not require shaking. The advantages presented by these catalysts are of great importance from the industrial standpoint, because they are environmentally acceptable and economical.

Conclusions

The analytical methodology for the synthesis of eugenyl acetate was effective in quantifying the ester produced by the esterification reaction using the molecular sieve catalyst 4 Å and Amberlite XAD-16. Through the results of the experimental designs it was possible to establish the variables with major effect on the reaction conversion. The highest conversions obtained within the range of experimental conditions investigated were about 100% for both catalysts. The mathematical models obtained satisfactorily represented the experimental data. In kinetic studies it was possible to evaluate the behavior of the variables temperature, molar ratio (eugenol:acetic anhydride) and catalyst concentration, relative to the conversion of eugenyl acetate, and the initial specific rate of the reactions. In the reuse of catalysts, the molecular sieve, after 10 cycles, showed no loss of catalytic activity, as Amberlite led to a drastic decrease in the conversion of eugenyl acetate after only three cycles. Results showed that both catalysts are effective for producing ester eugenyl acetate. The heterogeneous catalysis has the advantage of simplicity in the separation and purification of the reaction products step. It is possible to use smaller amounts of reactants in solvent-free reactions, and the possibility of reuse and regeneration. Hence, these catalysts fall within the concept of green chemistry, with great potential for application in industrial processes.

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