



Ethyl hexanoate rich stream from grape pomace: A viable route to obtain fine chemicals from agro by-products

Valeria D'Ambrosio^a, Gonzalo Martinez^b, Emma Jones^b, Lorenzo Bertin^b, Carlo Pastore^{a,*}

^a Water Research Institute (IRSA), National Research Council (CNR), via F. de Blasio 5, 70132 Bari, Italy

^b Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, via Terracini, 28, I-40131 Bologna, Italy

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ABSTRACT

A novel viable route for obtaining ethyl hexanoate-rich streams from grape pomace, an agro by-product generated from the winery industry, was investigated. Highly concentrated hexanoic acid (87 wt%) was efficiently produced through the chain elongation fermentation of red and white grape pomace, easily separated, recovered and reacted with ethanol by using AlCl₃·6H₂O as a catalyst. Under the optimised mild reactive conditions (molar ratio acid:ethanol:catalyst of 1:2:0.1, 5 h, 348 K), a high conversion equal to 93.5 % was achieved in a single step. AlCl₃·6H₂O was very effective in catalysis, playing an additional key role in the separation of products, shifting the equilibrium of the reaction and making products' recovery easier. After the reaction cycle, the catalyst was easily recoverable and reusable without losing effectiveness. According to this simple layout of processes, including the anaerobic digestion of the residual part of grape pomace, a specific production cost of 0.935 €·kg⁻¹ was calculated related to the final products. This proposed approach could represent a promising green and sustainable route to produce ethyl esters of volatile fatty acids from agro by-products.

1. Introduction

Ethyl esters of short and medium-chain fatty acids are non-hazardous naturally occurring organic compounds found in fruits and flowers, contributing to their distinctive, enjoyable aroma [1,2]. For this pleasant characteristic, they find applications in the food and beverage, cosmetic, pharmaceutical and personal care sectors [3–5]. Furthermore, they can also be used as bio-solvents [6,7] and as fuel additives [8,9]. When these compounds are used in blends with gasoline, it is expected to obtain positive effects such as a reduction of unburnt hydrocarbons, NO_x and particulate emissions [10]. The global market for flavour esters is estimated to rise at a Compound annual growth rate (CAGR) of 4.90 % through the prediction period 2019–2025 [11]. The extraction of natural flavour agents from plants, fruits and flowers is a costly, time-consuming and low-yielding process to be used at an industrial scale; furthermore, these raw materials are not enough to meet the market demands [12,13]. Therefore, other strategies for the synthesis of these flavour compounds are needed. An indirect route, based on the fermentation of sugars to produce short and medium-chain fatty acids and their subsequent conversion into the relevant esters, could be a viable alternative strategy to obtain bioderived flavour esters [14]. In

this perspective, two aspects must be addressed and improved to achieve a sustainable production. The first is related to producing and recovering alcohols and fatty acids from biomasses. Among the alcohols, ethanol is the most representative, and its production and purification are the most mature option [15–17]. As for short-chain fatty acids, besides the production through fermentation of different substrates, which has been largely investigated [18–20], the relevant purification often represents the bottleneck for their prompt exploitation [21–23]. Instead, medium-chain fatty acids, in addition to the advantage of being obtainable from the anaerobic fermentation of organic leftovers (through a carboxylic acid chain elongation process) [24–26], they can be easily recovered due to their lower water solubility. In this regard, very recently, hexanoic acid was effectively produced from grape pomace, recovering by physical separation a good amount (54 %) of the produced hexanoic acid (87 wt% purity) [26]. The second aspect is related to converting fatty acids into their esters. Industrially, ethyl esters of short and medium-chain fatty acids are obtained by Fisher esterification, with the relative fatty acids reacting with ethanol in the presence of an acidic catalyst, commonly mineral acids [12]. Nevertheless, despite their effectiveness, mineral acids are hardly recoverable or reusable, and their separation from the final mixture results in the co-production of waste (e.g. sodium

* Corresponding author.

E-mail address: carlo.pastore@ba.irsa.cnr.it (C. Pastore).

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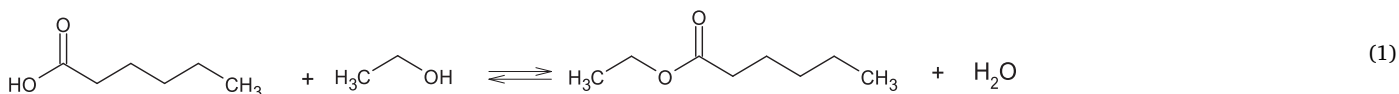
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or calcium sulphates) that needs to be disposed of at the end of the process [1,27]. The use of heterogeneous catalysts is preferred due to their greater sustainability in recyclability and low toxicity. Several materials have been tested as heterogeneous catalysts for Fisher esterification, such as zeolites [28], acid ion exchange resins [29,30] and solid acids [31]. Nevertheless, depending on the case, moderate conversions were obtained (51–63.9 %) under mild conditions [29]; higher conversions (>90 %) were obtained only under harsh conditions, in terms of temperature, amount of catalyst or acid:alcohol molar ratio [28,31] or removing water from the reactive system [32]. An alternative route for the synthesis of ethyl esters is based on the use of enzymes as catalysts, mostly lipases, which allows an environmentally friendly synthesis under low temperatures (30–50 °C) and the obtainment of a product that can be labelled as *natural*, increasing its market value [3]. Nevertheless, very long reaction times (>72 h) are usually required for obtaining high yields (>95 %) [33,34]. Recently, aluminium chloride hexahydrate ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$) has been reported to combine the benefits of homogeneous and heterogeneous catalysis for Fisher esterification [35], being very effective in the catalysis of such a reaction and also useful for simplifying the product purification, inducing a favourable separation of the resulting esters from the co-formed water, in two distinguished phases [27,35].

In this work, the use of $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ was tested for the esterification reaction of hexanoic acid with ethanol for obtaining ethyl hexanoate, an apple-pineapple flavour ester (Eq. (1)).



After kinetic and thermodynamic studies related to such a reaction, reactive conditions were optimised by investigating the effect of the temperature, the amounts of ethanol and $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$. Then, the catalyst's recoverability and reusability were assessed, and the feasibility of such a reaction on samples of highly concentrated hexanoic acid (HCHA) produced through the fermentation of grape pomace was evaluated. For the first time, a sustainable production route of highly concentrated ethyl hexanoate starting from an agro by-product was realised.

2. Experimental

2.1. Materials

2.1.1. Commercial reactants

All reagents used were of analytical grade. Aluminium chloride hexahydrate ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$, 99 %) was purchased from Baker; Ethyl hexanoate ($\text{CH}_3\text{CH}_2\text{COO}(\text{CH}_2)_4\text{CH}_3$, >98 %) and Hexanoic acid ($\text{CH}_3(\text{CH}_2)_4\text{COOH}$, >98 %) were purchased from Acros Organics; Anhydrous Ethanol ($\text{CH}_3\text{CH}_2\text{OH}$, >99 %) was purchased from Carlo Erba; Phenolphthalein (99 %), Eriochrome Black T (99 %), EDTA disodium salt (99 %), Potassium chromate (K_2CrO_4 , 99 %), Potassium hydroxide (KOH, >98 %) and 0.1 N Argentum nitrate (AgNO_3) solution were Sigma-Aldrich products.

2.1.2. Hexanoic acid obtained from red and white grape pomace

Highly concentrated hexanoic acid (HCHA) was obtained from red and white grape pomace (RGP and WGP, respectively) by using the procedure previously described elsewhere slightly modified [26]. Briefly, RGP or WGP were fed into a leaching process with water which allowed to obtain: A) the ethanol solution (30–40 g/L) to be fermented for hexanoic acid production; and B) the grape pomace that could be

further valorised through a conventional process (tartaric acid, seed oil extraction; out of the focus of this work). Thereafter, the procedure was as previously reported: *i*) the corresponding ethanol solutions (from RGP and WGP) were fermented in batch mode at 30 L scale (310 K and pH 7) to obtain 22–25 g/L of hexanoic acid; *ii*) the biomass was separated from the broth by centrifugation (Beckman J2-HS; 8000 rpm, 279 K, 15 min); *iii*) commercial H_2SO_4 96 % was added until pH level was 2; and *iv*) the hexanoic acid rich phase (upper phase) was separated from water phase with a separation funnel and stock at room temperature until used.

2.2. Esterification reactions of hexanoic acid with ethanol catalysed by $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$

For the kinetic and thermodynamic study, esterification reactions were carried out at four different temperatures, namely 318, 328, 338 and 348 K, using an acid:alcohol:catalyst 1:1:0.01 M ratio. At the highest temperature (348 K) also other reaction conditions were investigated, namely the use of different amounts of catalyst (1–10 % molar with respect to the acid) and ethanol (1–2 alcohol: acid molar ratio), in order to study the effect of their amounts on the reaction yield and find the best reaction conditions, which were then used for the esterification of HCHA samples derived from RGP and WGP. All reactions were carried out in a 30 mL glass reactors equipped with a silicone cap, which allowed sampling throughout the reaction. 11.6 g hexanoic acid was

introduced into the reactor, placed into a thermostatic oil bath and magnetically stirred. Then, a previously prepared solution of $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ in ethanol, heated to the appropriate temperature, was introduced into the reactor to obtain the final acid:alcohol:catalyst molar ratio required for the specific experiment. When needed, aliquots of 0.3 mL were collected at different times, and the composition was determined by acid-base titration, GC-TCD and GC-FID analysis. At the end of the esterification reaction, when a biphasic system was observed, the two distinguishable phases were recovered, weighed and chemically characterised. All the experiments were performed in triplicate: results were reported as mean value together with the relevant standard deviation.

2.3. Analytical techniques

2.3.1. Gas chromatographic determinations

Ethyl hexanoate and hexanoic acid were quantitatively analysed on an Agilent 8890 GC-FID equipped with a DB-FATWAX UI (30 m, 0.25 mm, 0.25 μm , Agilent Technologies). In detail, an aliquot of 1 μL was injected in splitless mode; helium was used as a carrier gas, with a flow of 2.8 $\text{mL} \cdot \text{min}^{-1}$ and the injector temperature was set at 523 K. Initial oven temperature was set to 333 K, held for 4 min; the temperature was then increased to 473 K (rate of increase 10 $\text{K} \cdot \text{min}^{-1}$), held for 1 min, and the final temperature of 513 K (rate of increase 20 $\text{K} \cdot \text{min}^{-1}$), held for 3 min; the temperature of the detector (FID) was set to 613 K. Water and ethanol were quantified on an Agilent 8890 GC-TCD equipped with an HP-5MS capillary column (30 m; \varnothing 0.32 mm; 0.25 μm , Agilent Technologies). An aliquot of 1 μL was injected in split mode (25:1 split ratio); helium was used as a carrier gas, with a flow of 2.8 $\text{mL} \cdot \text{min}^{-1}$ and the injector temperature was set at 523 K. Initial oven temperature was set to 313 K, held for 2 min; then, the temperature was increased to 523 K

(rate of increase 35 K·min⁻¹), held for 5 min.

2.3.2. Acid-base titration

Hexanoic acid content was also determined by acid-base titrations. Aliquots of 0.3 mL were sampled, weighed and dissolved in a hydroalcoholic solution (EtOH: water 1:1). The acid content was evaluated by titrating with a 0.1 N KOH aqueous solution using phenolphthalein as an indicator.

2.3.3. Determination of chlorides (Cl⁻) and aluminium (Al³⁺)

AlCl₃·6H₂O content was evaluated by titrations of chlorides (Cl⁻) and aluminium (Al³⁺). For Cl⁻ determination, argentometric titrations were performed. Aliquots of 0.2 mL of the lower phases were sampled, weighed and the pH was adjusted to 8 by adding a KOH 0.1 N solution. Then, samples were titrated with a 0.1 N AgNO₃ aqueous solution, using potassium chromate as an indicator.

Al³⁺ content was evaluated by performing a complexometric back-titration. Aliquots of 0.7 mL of the lower phases were sampled, and the indicator black Eriochrome T and 2 mL of an NH₄Cl/NH₃ pH 10 buffer solution were added. An excess amount of 0.02 N EDTA aqueous solution was then added, stirring and heating the system for 5 min. The excess was then back-titrated with a 0.02 N Mg²⁺ solution.

2.4. Parameters calculation

The acid conversion was determined as follows (Eq. (2)):

$$X_{eq} = \left(\frac{n_0 - n_t}{n_0} \right) * 100 \quad (2)$$

where n_0 are the starting moles of the acid and n_t the moles of the acid at the time t .

Rate constants of the forward reactions (k_f) at four different temperatures (318, 328, 338, 348 K) were determined by plotting the equation specified in Banchero's study [36], which can be used when an alcohol:acid molar ratio equal to 1 is considered, namely (Eq. (3)):

$$\frac{\ln Y}{a_2} = \frac{1}{a_2} \ln \left[\left(\frac{2a_1 X_A - 1 - m - a_2}{2a_1 X_A - 1 - m + a_2} \right) \left(\frac{-1 - m + a_2}{-1 - m - a_2} \right) \right] = k_f t \quad (3)$$

where $a_1 = (1 - 1/K_{eq})$; $a_2 = [(m + 1)^2 - 4 a_1 \bullet m]^{1/2}$; $m = \text{alcohol/acid molar ratio}$.

The equilibrium constant (K_{eq}) was determined by evaluating the acid conversion after 72 h (Eq. (4)). Rate constants of the reverse reactions (k_r) were calculated by using Eq. (5) [36]. E_a , E_a^{-1} , ΔH^0 and ΔS^0 were obtained by using Arrhenius and Van't Hoff equation (Eq. (6) and Eq. (7)) [27].

$$K_{eq} = \frac{X_{eq}^2}{(1 - X_{eq})^2} \quad (4)$$

$$k_r = \frac{k_f}{K_{eq}} \quad (5)$$

$$\ln(k) = \ln(A) - \frac{E_a}{R^*T} \quad (6)$$

$$\ln(K_{eq}) = -\frac{\Delta H^0}{R^*T} + \frac{\Delta S^0}{R} \quad (7)$$

3. Results and discussion

3.1. Kinetic and thermodynamic study and optimisation of the reactive conditions on hexanoic acid

Kinetic, thermodynamic and optimisation of the reactive conditions studies were performed on standard-grade hexanoic acid; the optimised conditions were then used for the esterification of HCHA produced and

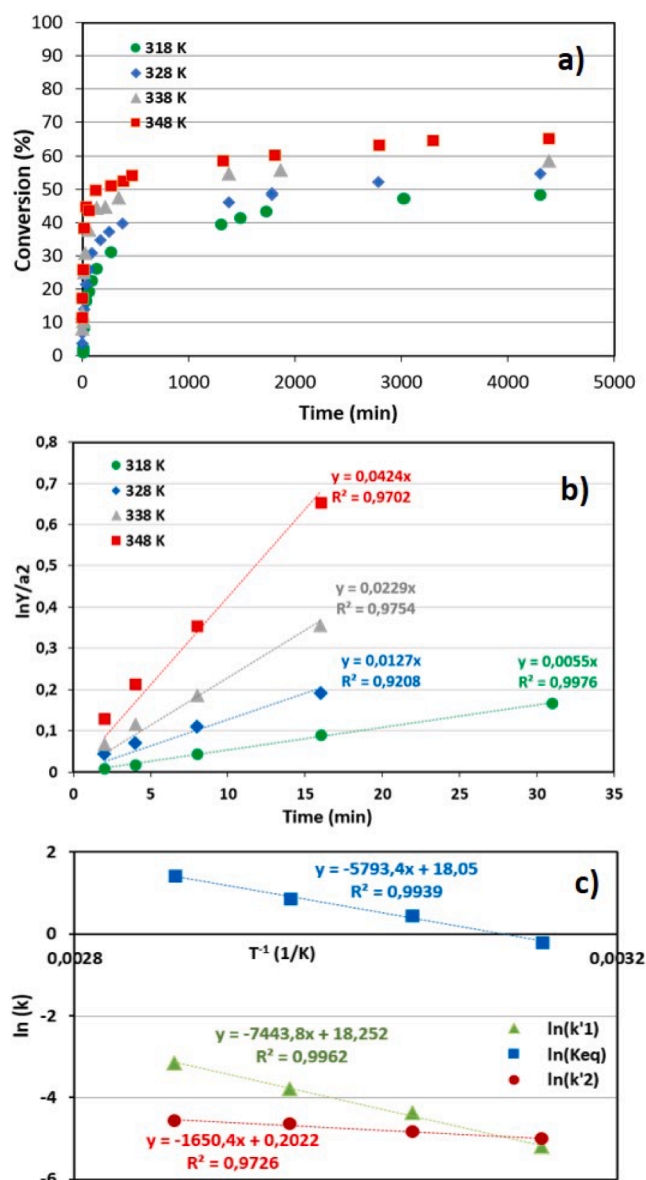


Fig. 1. (a) conversion of hexanoic acid along time at different temperatures (acid: ethanol: catalyst 1: 1: 0.01 M ratio); (b) rate constants evaluation at different temperatures (318–348 K); (c) Arrhenius and Vant' Hoff plots for the determination of E_a , E_a^{-1} , ΔH^0 , ΔS^0 values.

recovered from the fermentation of RGP and WGP.

3.1.1. Kinetic and thermodynamic study

The esterification reactions were carried out at four different temperatures, namely 318, 328, 338 and 348 K, using an acid:alcohol: catalyst 1:1:0.01 M ratio. The conversion of hexanoic acid into ethyl hexanoate at the four different temperatures was monitored over time: an increase in the conversion with the increase of time and temperature

Table 1

Rate constants (k_f , k_r) and equilibrium constants (K_{eq}) values for the esterification reaction of hexanoic acid with ethanol catalysed by AlCl₃·6H₂O (acid: ethanol: AlCl₃·6H₂O 1:1:0.01 M ratio) at different temperatures (318–348 K).

	318 K	328 K	338 K	348 K
K_{eq}	0.8	1.6	2.4	4.1
k_f	0.0055	0.0127	0.0229	0.0424
k_r	0.0068	0.0080	0.0097	0.0103

was observed, determining after 72 h, in the best case, a conversion of $66.9 \pm 0.6\%$ (Fig. 1 a). From the sampling of the reaction systems in the early times of the reaction (1–30 min), it was possible to evaluate the rate constant of the forward reaction k_f , according to Eq. (3) (Fig. 1 b); the activation energies of the forward and reverse reactions (E_a , E_a^{-1}), and thermodynamic parameters (K_{eq} , ΔH^0 , ΔS^0) were evaluated according to Vant'Hoff and Arrhenius equations (Eq. (6); Eq. (7)) (Fig. 1 c).

Kinetic constants of the forward and reverse reaction (k_f and k_r) and equilibrium constants (K_{eq}) values increased with the increase of temperature from 318 to 348 K, with K_{eq} values ranging from 0.8 to 4.1 (Table 1).

Table 1 shows a comparison between kinetic (E_a) and thermodynamic parameters (ΔH^0 , ΔS^0) determined for such a reaction with those reported in the literature for the same reaction with shorter chain fatty acids, from acetic to butyric acids [1]. All the esterification reactions were endothermic, with the highest value of ΔH^0 determined for the esterification of hexanoic acid. Even the ΔS^0 value was higher for such a reaction, as well as the energy of activation (E_a). For the latter, in particular, an increase was observed as the length of the carboxylic acid chain increased (Table 2), attributable to the lower stabilisation of the transition state due to the more significant steric hindrance for longer chains.

At the end of each reaction, a biphasic system was observed. The two phases were separated, gravimetrically determined, and their compositions characterised. Table 3 shows, for each system analysed, the conversion at the equilibrium, phases distribution and composition. The upper phases were constituted mostly by the ester, the unreacted acids and alcohols, and a small amount of water; the lower phases were constituted by the catalyst, which was entirely solubilised in with most of the water produced from the reaction. The increase in the amount of the lower phase was related to the increase of the conversion, being the upper phase more hydrophobic with the increase of the ester content, and being the water produced in more significant amounts.

3.1.2. Effect of ethanol and $AlCl_3 \cdot 6H_2O$ amounts: Optimisation of the reactive conditions

On the basis of this preliminary study, a final conversion of hexanoic acid never higher than 66.9 % was achieved. With the aim of obtaining better conversions, the use of higher amounts of ethanol and $AlCl_3 \cdot 6H_2O$ was investigated.

Different ethanol and $AlCl_3 \cdot 6H_2O$ amounts were tested (ethanol: hexanoic acid = 1–4 M ratio; $AlCl_3 \cdot 6H_2O$:hexanoic acid = 1–10 % molar), performing the reaction at 348 K for 72 h (Table 4).

For the same reaction conditions, an increase in the conversion with the ethanol amount was observed as the reaction shifted towards products. For most tests, a biphasic system was obtained; only for cases corresponding to the use of higher amounts of ethanol ($R = 3$ and 4, Entries 8 and 12 in Table 4) a homogeneous system was revealed. A reaction with azeotropic ethanol (ethanol 95 wt%; H_2O 5 wt%) was also performed (Entry 7, Table 4), observing a conversion not significantly different from that obtained with absolute ethanol (Entry 6, Table 4). For the same ethanol amount, the increase in $AlCl_3 \cdot 6H_2O$ amount had a very positive effect on the conversion: by considering an ethanol:hexanoic acid molar ratio equal to 2 ($R = 2$), an increase in the conversion from 84.5 % to 93.5 % was evaluated with the rise in the

Table 2

Kinetics (E_a , E_a^{-1}) and thermodynamic parameters (ΔH^0 , ΔS^0) evaluated for the esterification reaction of hexanoic, butyric, propionic and acetic acids with ethanol, catalysed by $AlCl_3 \cdot 6H_2O$ (acid:ethanol: $AlCl_3 \cdot 6H_2O$ 1:1:0.01 M ratio).

	E_a (KJ/mol)	ΔH^0 (KJ/(mol))	ΔS^0 (J/(mol*K))
Hexanoic acid	61.9	48.2	150.1
Butyric acid	35.8	34.7	104.3
Propionic acid	23.0	25.9	82.3
Acetic acid	22.3	28.5	97.1

$AlCl_3 \cdot 6H_2O$ amount from 1 to 10 % molar with respect to the acid (Entries 2 and 12, Table 4). For the same R value, an increase in the lower phase amount and a decrease in the water content in the upper phase were observed with the rise of the catalyst amount. This behaviour can be attributed to the higher conversions and the consequent higher amounts of ethyl hexanoate and water, which are poorly miscible, and to the catalyst ability to draw out water from the upper phase to the lower layer, where it was completely solubilised. The highest conversion, equal to 95.8 %, was obtained using an acid: alcohol: catalyst 1: 3: 0.1 M ratio (Entry 11, Table 4). In those conditions, a not negligible amount of ethyl hexanoate was distributed in the lower phase, losing the advantage of recovering the entire reaction product separately from the catalyst. The use of an acid:alcohol:catalyst 1:2:0.1 M ratio was preferred at the cost of a slightly lower conversion, equal to 93.5 %. All conversion values reported in Table 3 were evaluated by carrying out the reactions for 72 h. In order to assess a good compromise between reaction time and yield, the kinetic of the reaction in the best reaction conditions (acid:alcohol:catalyst 1:2:0.1 M ratio) was evaluated, observing the achievement of high conversions (80 %) in 40 min, 90 % in 3 h and the maximum conversion equal to 93.5 % was instead reached in 5 h (Fig. S1).

3.1.3. Role of the catalyst in the increase of the hexanoic acid conversion

Lastly, the role of the catalyst amount on the hexanoic acid conversion was assessed in detail. As described in Section 3.1.2, the increase in the amount of $AlCl_3 \cdot 6H_2O$ allowed an increase in the final conversion and, therefore, in the equilibrium constant. For each of the tests reported in Table 4, the equilibrium constant was also calculated (Table S1), and the relevant relationship with the amount of catalyst (expressed as a mole fraction, X_{cat}) was investigated (Fig. 2).

A direct proportionality between X_{cat} and K_{eq} was observed, with a different equation depending on the alcohol:acid ratio used and on the homogeneity of the system. The increasing amount of $AlCl_3 \cdot 6H_2O$, proportionally removes water from the upper organic phase, reducing the amount of water that can hydrolyse the ester group, consequently shifting the equilibrium towards products. As for the different equations for different amounts of ethanol used ($R = 1$ and $R = 2$), this could be attributed to the amount of water in the upper phase, which is more significant for the same amount of catalyst, when a higher amount of ethanol is used. For homogeneous systems, on the other hand, lower values of K_{eq} were evaluated, attributable to a greater quantity of water capable of hydrolysing the ester (as there is no phase separation), as well as constants, indicating that the increase in the amount of catalyst does not significantly affect the K_{eq} when the system is homogeneous.

In order to validate these hypotheses and to fully assess the capability of $AlCl_3 \cdot 6H_2O$ to reduce the water content in the upper phase, different tests were performed by considering mixtures with identical amounts of water, hexanoic acid and ethyl hexanoate (corresponding to a hexanoic acid conversion equal to 80 %), and variable ethanol and $AlCl_3 \cdot 6H_2O$ amounts (Table 5).

The mixture obtained by using a hexanoic acid:ethanol 1:1 M ratio ($R = 1$), without the addition of $AlCl_3 \cdot 6H_2O$, has a not pronounced phase separation (Entry 1, Table 5). By increasing the catalyst amount up to 10 % molar with respect to the acid, an increase in the lower phase amount was observed, while the water content in the upper organic phase decreased from 1.94 wt% (Entry 1, Table 5) to 0.68 wt% (Entry 4, Table 5). When a hexanoic acid:ethanol 1:2 M ratio ($R = 2$) was tested, without the addition of $AlCl_3 \cdot 6H_2O$ no phase separation occurred. When $AlCl_3 \cdot 6H_2O$ was added, the separation of phases was induced, and with increasing the $AlCl_3 \cdot 6H_2O$ an increase in the lower phase amount and a decrease of the water content in the upper phase were observed. However, for the same X_{cat} used, the amount of water in the upper layer was higher for higher ethanol amounts (Entries 2 and 6, Table 5), which could justify the lower slope of the K_{eq} vs X_{cat} line observed when $R = 2$ was considered.

Table 3

Reaction systems with specified reaction conditions, phases distribution and their composition (determined after 72 h) for the esterification of hexanoic acid with ethanol catalysed by $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ (acid:ethanol: $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ 1:1:0.01 M ratio).

Temperature (K)	Catalyst (% mol)	Conversion %	Phases distribution (wt %)		Phases composition									
			Upper	Lower	Upper phase (wt %)					Lower phase (wt %)				
					A	E	C	W	H	A	E	C	W	H
318	1	47.5 ± 0.4	96.2	3.8	38.5	14.9	–	3.4	43.2	–	–	38.8	61.0	–
328	1	55.7 ± 0.6	95.7	4.3	32.7	12.4	–	3.4	51.0	–	–	34.0	65.7	–
338	1	60.6 ± 0.7	95.1	4.9	29.2	11.2	–	3.3	55.3	–	–	29.9	71.0	–
348	1	66.9 ± 0.5	94.0	6.0	24.8	9.7	–	3.0	62.4	–	–	24.4	75.1	–

A: Hexanoic acid; E: Ethanol; C: Catalyst; W: Water; H: Ethyl hexanoate.

Table 4

Reaction systems with specified reaction conditions, phases distribution and their composition determined at 72 h for the esterification of hexanoic acid with ethanol catalysed by $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ (hexanoic acid: ethanol = 1–4 M ratio; hexanoic acid: $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ = 1–10 % molar), performed at 348 K.

Entry	R	Catalyst (% mol)	Conversion (%)	Phases composition (%)		Phases distribution (wt %)									
				Upper	Lower	Upper phase (wt %)				Lower phase (wt %)					
						A	E	W	H	A	E	W	C	H	
1	1	1	66.9 ± 0.6	94.0	6.0	24.8	9.7	3.0	62.4	–	–	24.4	75.1	–	
2	2	1	84.5 ± 0.6	95.8	4.2	8.9	25.3	4.3	60.8	–	24.0	48.5	27.3	–	
3	1	3	76.3 ± 0.4	87.5	12.5	18.0	7.2	1.8	72.2	–	–	33.3	66.7	–	
4	2	3	87.9 ± 0.5	90.0	10.0	7.3	23.7	2.9	65.4	–	24.0	42.0	33.6	–	
5	1	5	81.1 ± 0.5	85.7	14.3	14.7	5.8	1.0	78.3	–	–	48.4	51.6	–	
6	2	5	90.3 ± 0.3	84.9	15.1	6.0	21.9	2.3	70.0	–	29.3	32.0	36.5	–	
7*	2	5	88.9 ± 0.6	84.1	15.9	6.3	22.0	2.4	68.5	–	29.7	35.6	34.5	–	
8	3	5	89.8 ± 0.4	Homogeneous					4.4	36.3	6.1	4.5	48.6	–	
9	1	10	86.2 ± 0.3	78.2	21.8	11.1	3.7	0.5	85.3	–	4.3	36.3	59.4	–	
10	2	10	93.5 ± 0.3	72.5	27.5	4.4	16.3	1.4	77.9	–	34.0	22.5	37.8	6.7	
11	3	10	95.8 ± 0.6	59.1	40.9	1.4	26.7	2.3	68.8	1.9	40.4	14.6	21.2	22.8	
12	4	10	92.2 ± 0.6	Homogeneous					2.8	53.2	6.2	9.1	49.9	–	

R: Alcohol-acid molar ratio; A: Hexanoic acid; E: Ethanol; C: Catalyst; W: Water; H: Ethyl hexanoate;

*Reaction carried out using not absolute ethanol (95 wt%).

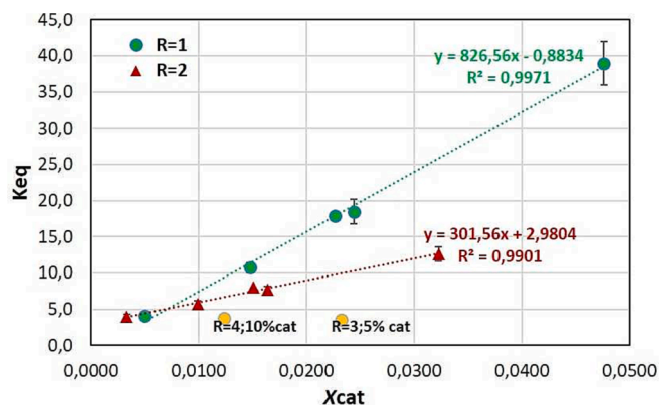


Fig. 2. Relationship between K_{eq} vs X_{cat} for the esterification reaction of hexanoic acid with different amounts of ethanol ($R = 1$ and $R = 2$).

3.1.4. Recoverability and reusability of the catalyst

The lower phase obtained after 5 h reaction (hexanoic acid:ethanol: $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ 1:2:0.1 M ratio) was recovered by physical separation and subjected to under vacuum evaporation (bath oil: 70 °C, 35 mbar). A solid residue corresponding to the weight of the catalyst initially added for the reaction was obtained (about 40 wt%).

The recovered catalyst was then reused, and the same procedure was repeated for four reaction cycles, each performed under the same reaction conditions. Conversions not significantly different from 93.5 ± 0.5 % were determined, showing that the catalyst does not lose its catalytic activity and its ability to increase K_{eq} even after four reaction cycles. In addition, no variations in the chemical composition of the catalyst were also confirmed by the Cl^- and Al^{3+} titrations of the catalyst

Table 5

Simulated systems consisting into a mixture of water, hexanoic acid and ethyl hexanoate (corresponding to an hexanoic acid conversion equal to 80 %) and variable amounts of ethanol (ethanol:hexanoic acid = 1–2 M ratio) and $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$:hexanoic acid = 0–10 % molar ratio).

Entry	R	Cat (% mol)	X cat (mol cat/mol tot)	Upper phase (wt %)	Lower phase (wt %)	Water in the upper phase (wt %)
1	1	0	0	93.7	6.3	1.94
2	1	5	0.02439	86.5	13.5	0.93
3	1	10	0.04338	78.9	21.1	0.68
4	2	0	0	Homogeneous		6.3
5	2	5	0.01639	84.9	15.1	2.54
6	2	7.5	0.02439	73.8	26.2	1.83

Table 6

Composition of real sample of highly concentrated hexanoic acid (HCHA) produced from red (RGP) and white (WGP) grape pomace.

	HCHA from RGP	HCHA from WGP
	wt %	wt %
Hexanoic acid	87 ± 2	87 ± 3
Butyric acid	8.0 ± 0.5	4.9 ± 0.4
Valeric acid	0.9 ± 0.4	1.2 ± 0.2
Water	4.8 ± 0.4	5.1 ± 0.4
Polyphenols	0.09 ± 0.01	0.08 ± 0.01
Other fatty acids	<2	<3

recovered at the 5th reaction cycle, evaluating Cl^- and Al^{3+} amounts not significantly different from the theoretic value (Cl^- : 45 ± 2 % vs 44.05 %; Al^{3+} : 10.4 ± 0.8 % vs 11.18 %).

3.2. Production of ethyl hexanoate from grape pomace-derived hexanoic acid

The reaction conditions previously optimised on standard-grade hexanoic acid (acid:ethanol:AlCl₃·6H₂O 1:2:0.1 M ratio, 5 h, 348 K) were then used for the esterification with ethanol of the two samples of highly concentrated hexanoic acid (HCHA) obtained from red and white grape pomace (RGP and WGP) through the chain elongation fermentation (Table 6).

The two samples were characterised, evaluating a hexanoic acid purity of 87 wt% and the presence of other fatty acids (almost 11 and 9 wt% from RGP and WGP, respectively), and then were reacted with ethanol, adding AlCl₃·6H₂O. Acid conversions equal to 93.5 ± 0.6 % and 93.4 ± 0.5 % were observed for HCHA samples derived from RGP and WGP, respectively. In both cases, a biphasic system was observed (Fig. S2), with the same phase repartition: the upper layer was equal to 71.5 wt%; the lower 28.5 wt%. The composition of the two layers is reported in Table 7.

The upper phases were dominated by ethyl hexanoate (68.9 and 68.7 wt% for HCHA from WGP and RGP, respectively), followed by residual ethanol (18.7 and 18.4, respectively). Ethyl butyrate, hexanoic acid and water represented minor components, followed by ethyl valerate and residual butyric and valeric acids, present in minimal amounts (<0.4 wt%), being converted for >93 %.

Catalyst recoverability and reusability were also checked after the esterification reactions of HCHA from RGP and WGP for further four reaction cycles, observing conversion values not significantly different from 93.5 ± 0.5 %. Therefore, the esterification reaction performed on HCHA samples gave the same results observed for the esterification reaction run on standards, without differences in the conversion values and loss in the AlCl₃·6H₂O effectiveness even after four subsequent reactions cycles.

3.3. Purification of ethyl esters

The upper phases obtained after 5 h reactions under the optimised conditions were recovered by simple separation of phases and subjected to evaporation. Upon the removal of most of the azeotropic ethanol, a residue consisting of ethyl hexanoate (80 wt%), other ethyl esters (8 wt%), mainly ethyl butyrate, residual ethanol (5.3 wt%), hexanoic acid (4.8 wt%), other fatty acids (<2 wt%), and residual water (0.5 wt%) was obtained. This residue was then washed with a 0.3 M KOH aqueous solution (considering KOH moles equal to that of residual acids), achieving an effective purification. Free fatty acids were neutralised and promptly transferred as potassium carboxylates from the upper organic phase to the aqueous phase, together with residual ethanol. A final

Table 7

Composition of the upper and lower phases obtained after the esterification reaction of the two highly concentrated hexanoic acid (HCHA) samples derived from red and white grape pomae (RGP and WGP) with ethanol (acids:ethanol: AlCl₃·6H₂O 1:2:0.1 M ratio; 348 K; 5 h).

	Upper phases		Lower phases	
	HCHA from WGP	HCHA from RGP	HCHA from WGP	HCHA from RGP
	wt%		wt%	
Hexanoic acid	3.9	4.0	–	–
Butyric acid	0.3	0.4	–	–
Valeric acid	0.2	0.2	–	–
Water	2.0	1.9	27.9	28.1
Ethyl hexanoate	68.9	68.7	4.1	4.0
Ethyl butyrate	3.1	5.3	–	0.4
Ethyl valerate	0.9	0.9	–	–
Ethanol	18.7	18.4	32.3	32.5
Catalyst	–	–	36.6	36.7

organic blend of flavour ethyl esters (99 wt%) was eventually obtained, with an ethyl hexanoate purity of almost 90 wt% and a remaining part consisting of other ethyl esters (9 wt%) and a minimal amount of water and ethanol (about 1 wt% in total), which could be eventually used without further purification. A final yield of 87 % with respect to the initial acid content in HCHA samples was evaluated.

3.4. Preliminary assessment of the process's economic feasibility

The cost of the reactants, the energetic need for the ethanol distillation from the upper phase after direct esterification and catalyst recovery (water and ethanol evaporation from the lower phase) were considered as the main items affecting the operative costs of the process.

The price of the reactants used for the reaction, namely highly concentrated hexanoic acid (HCHA), ethanol [26], AlCl₃·6H₂O and KOH [37], was considered. Particularly, HCHA cost was adapted [26] including only expenses related to the production process from grape pomace, avoiding the contribution related to the grape pomace transport. The energy demand E_i for ethanol and water evaporation was determined by the sum (Eq. (10)) of sensible heat Q_{i Sens} (Eq. (8)) and latent heat of evaporation Q_{i Lat} (Eq. (9)). The cost of that energy consumption C_E was calculated according to Eq. (11), considering the production of energy through the combustion of methane [6],

$$Q_{iSens} = m_i \cdot c_i \cdot \Delta t \quad (8)$$

$$Q_{iLat} = m_i \cdot \Delta H_i \quad (9)$$

$$E_i = Q_{iSens} + Q_{iLat} \quad (10)$$

$$C_E = E_i \cdot PCH_4 \quad (11)$$

where m_i, c_i, Δt and ΔH_i were the amounts (g) to be heated, specific heat capacities and enthalpies of vaporisation, respectively (c_{H₂O} = 4.18 J/°C g; ΔH_{H₂O} = 2257 kJ/kg; c_{EtOH} = 2.46 J/°C g; ΔH_{EtOH} = 846 kJ/kg) and PCH₄ the current cost of methane per MJ produced, equal to 6.86 * 10⁻³ €/MJ (US Energy Information Administration, EIA [38]). Table 8 shows the cost items of the process and their relative value. AlCl₃·6H₂O was considered in the sum of the costs, supposing its reuse for five cycles only, despite being wholly recoverable and reusable. As for ethanol, only the part chemically bound to acids to produce ethyl esters was considered, not including the amount of ethanol that can be recovered by distillation and recycled.

1043.7 kg of product (ethyl hexanoate purity of 90 wt%) can be obtained from an initial HCHA amount of 1000 kg, with a process cost equal to 1301.20 €. However, this value does not consider other benefits related to this process, namely the possible valorisation of residual biomasses. In detail, per each ton of HCHA recovered, about 65 tons of residual grape pomace having a biomethane potential of almost 200 NmL·g_{VS}⁻¹ and 100 tons of exhausted aqueous phase containing >800 kg of hexanoic acid were generated. The anaerobic digestion of residual grape pomace would produce a further benefit of 325 € [26], for a total

Table 8

Cost evaluation for the production process of ethyl hexanoate starting from highly concentrated hexanoic acid produced through the fermentation of grape pomace.

	Starting amounts (kg)	Price (€/kg)	Real amounts (kg)	Total price (€)
Highly Concentrated Hexanoic acid	1000	0.966	1000	966.0
Ethanol	790	0.852	351.1	299.1
AlCl ₃ ·6H ₂ O	205.1	0.54	41.02	22.15
KOH	35	0.25	–	8.75
Catalyst recovery	–	–	–	2.8
Ethanol recovery	–	–	–	2.4
				TOT 1301.20 €

cost of 976.30 €, corresponding to a specific production cost of 0.935 €·kg⁻¹. In addition, the possible recovery of hexanoic acid from the residual aqueous phase would significantly increase the overall feasibility of the process. Using more efficient techniques for VFA recovery [39–41] would increase the productivity of hexanoic acid from the aqueous residual stream by considerably reducing the specific production cost and resulting in a feasible alternative way to process RGP and WGP [42].

Alongside the economic aspect, the proposed process also has a shallow environmental impact, and it is in complete agreement with the principles of the circular economy. From the grape pomace chain elongation fermentation, a good amount of hexanoic acid was produced and recovered from the fermentation broth with elementary and low-impact processes (acidification and phase separation). The samples obtained showed a reasonable degree of purity (87 wt% of hexanoic acid), and above all, they were free of interferents, guaranteeing a subsequent conversion into ethyl hexanoate comparable to that evaluated on standard compounds. AlCl₃·6H₂O resulted to be a very robust and effective catalyst for such reaction, having not only a catalytic activity but also playing a key role in the equilibrium of the reaction, leading to an high reaction yield obtained under mild reaction conditions, and on the purification of the final product. Furthermore, it was found to be very easily recoverable and reusable for five subsequent reaction cycles without losing effectiveness and eventually, after the use in catalysis, it could also find application in wastewater treatment as an alternative coagulant to poly aluminium chlorides [43].

Ethyl hexanoate rich-stream was obtained, valorizing an agro by-products with an energy-effective and cleaner process with no resource consumption and practically zero-waste compared to the more common synthesis performed by using mineral acids as catalysts for the esterification of fossil-derived hexanoic acid.

4. Conclusion

The use of AlCl₃·6H₂O as a catalyst for the esterification reaction of hexanoic acid with ethanol has proven to be very effective, with the advantage to be easily and completely recoverable and reusable, without loss in its effectiveness. Also the phase separation induced by using AlCl₃·6H₂O is beneficial for the product purification, which, after the reaction, is already separated from the catalyst and most of the water produced from the reaction. AlCl₃·6H₂O was very effective even when used on real samples of hexanoic acid produced through the chain elongation anaerobic fermentation. Such kind of samples, with a high titre of hexanoic acid, obtained after very simple operations of acidification of the fermentation broth and phase separation, could represent a viable alternative to fossil-derived hexanoic acid. Thus, by using AlCl₃·6H₂O as a catalyst for their esterification with ethanol, an ethyl hexanoate rich-stream can be obtained, with a practically zero-waste green process, leading to a viable valorization of an agro by-products.

CRedit authorship contribution statement

Valeria D'Ambrosio: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Gonzalo Martinez:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Emma Jones:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Lorenzo Bertin:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft. **Carlo Pastore:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seppur.2023.123100>.

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