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Transesterification of vegetable oils by AlPO_xN_y heterogeneous catalysts.

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Keywords

Transesterification, nitridation, aluminophosphates, heterogeneous catalysis, vegetable oils

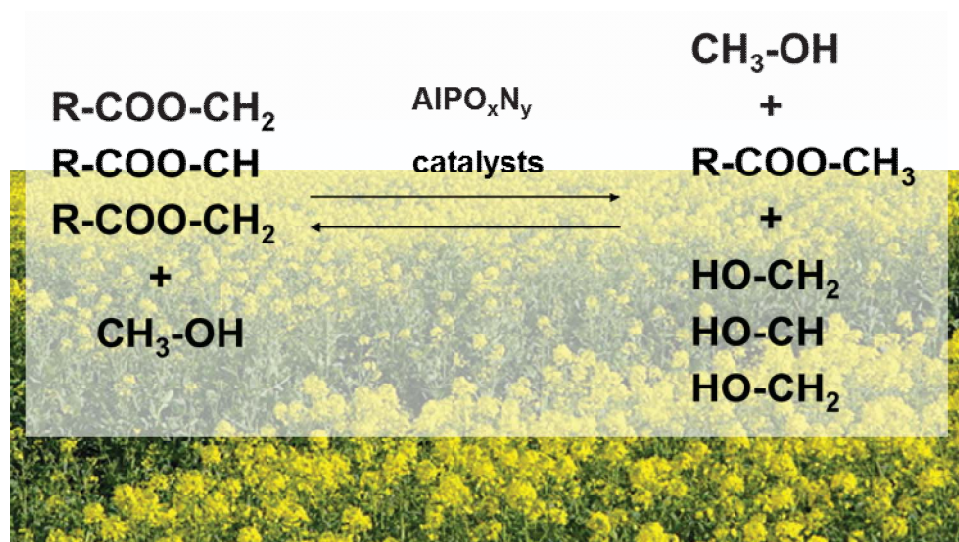
Abstract

AlPO_xN_y are the most studied materials among nitrided phosphates in heterogeneous catalysis. Such catalysts were tested in this work for the transesterification reaction of canola oil. High specific surface areas AlPO_4 precursors have been prepared using hydrogel or citrate routes. Nitrided powders obtained after thermal reaction under ammonia flow keep high surface areas and nitrogen contents can be modulated depending on the experimental conditions. Both precursor and oxynitrides have been characterized by BET, oxygen and nitrogen analyses, infrared and NMR spectroscopies. The influence of the metal, the alcohol and the nitrogen content on the catalytic performances was also studied. AlPO_4 and corresponding nitrided phases (with N wt.% < 10) produce higher catalytic activities for the transesterification of vegetable oils compared to that of the reference catalyst ZnAl_2O_4 .

Highlights

- High specific surface areas AlPO_4 precursors prepared by hydrogel or citrate routes
- Reactive AlPO_xN_y catalysts are prepared and characterized
- Nitridophosphates catalyze the transesterification reaction of vegetable oils
- higher catalytic performances compared to the reference catalyst ZnAl_2O_4

Graphical abstract



Introduction

Metallic phosphates of the $M^{III}PO_4$ type with $M = B, Al, Fe, Ga, Mn$ form an interesting class of materials [1,2]. Both cations -phosphorus and the metal- are in tetrahedral sites and tetrahedrons are linked to build 3D-networks analogous to those existing in various cristallized polymorphs of silica. Bondings in these MPO_4 phosphates are mainly covalent, with a stronger covalent behavior of phosphate ions compared to that of silicate ones [2]. This family of phosphates has excellent properties, for example in catalysis, as bifunctional acid and basic catalysts. They present a significant reactivity for several reactions such as alcohol dehydration, alkenes isomerisation, cracking of aromatic molecules as well as the Knoevenagel condensation [3-9].

The introduction of nitrogen N^{3-} within an oxide catalyst modifies the acid-base properties of the surface and allows to perform catalytic reactions leading to the synthesis of pure chemical substances (aldehydes or sulfones) [10-20]. Steins claimed that the nitrogen/oxygen substitution within a high specific surface area oxide should involve an increase of the Lewis basicity in relation to the lower electronegativity of nitrogen [21]. By tuning the nitrogen content of these materials, the acid-base character can be adjusted to give rise to a large panel of catalytic applications.

"AlPON"-type materials, developed in the early 90's are representative of the most studied nitridophosphates for catalysis [22]. $AlPO_4$ precursors are often prepared using the hydrogel route to form X-rays amorphous and high specific surface area powders ($350-400 \text{ m}^2.\text{g}^{-1}$). SEM analysis shows an homogeneous texture with aggregates made of particles with size around tens of nanometers. The oxide precursor is then modified by the progressive nitrogen insertion. "AlPON" results from the reaction of $AlPO_4$ under flowing ammonia between

650°C and 800°C and remains X-ray amorphous. A large domain of AlPO_xN_y compositions ($1.5 < x < 4$; $0 < y < 1.65$) exists according to the chosen temperature and nitridation step. Using ammonia temperature programmed desorption (TPD), Conanec has shown a decrease in the acidity of "ALPON" samples with increasing nitrogen content [19,22]. Moreover, under specific experimental conditions, CO_2 TPD enabled to evidence a stronger basic behavior for "ALPON", as observed in the Knoevenagel reaction test [19]. This reaction between a methylenic compound and an aldehyde or a ketone is largely studied as a standard basicity test [23,24]. ALPONS have shown during the condensation reaction of malonitrile or ethylcyanoacetate and benzaldehyde a higher activity compared to that of MgO , a well-known basic catalyst reference. ALPONS present both basic sites originating from amino groups at the surface ($-\text{NH}-$, $-\text{NH}_2$) and also acid sites linked to the metal.

Considering the interest of this aluminophosphate family, we have studied the behavior of such heterogeneous catalysts - both AlPO_4 and "ALPON" - in the transesterification reaction of vegetable oils. The final products are fatty acid esters (FAME) entering the composition of biodiesel and glycerine, a by-product (generally 10 to 15 wt.%) that can be further recycled and valued in industry if highly pure. In this work are presented the catalytic performances along with the characterizations of the powders including NMR and infrared spectroscopy.

Experimental section

Precursors syntheses.

Hydrogel route. This synthesis method was described by Kearby [25] and used in our laboratory by Conanec and Peltier to prepare AlPO_4 and GaPO_4 [22,26]. Considering the case of AlPO_4 (Figure 1): phosphoric acid H_3PO_4 (1 M) is added in a stoichiometric quantity to an aluminum chloride AlCl_3 , $6\text{H}_2\text{O}$ solution. The mixture is then cooled in an ice bath and

propylene oxide is poured dropwise in a large excess (3 to 30 times) under vigorous stirring. The very acidic pH of the solution ($\text{pH} < 1$) increases progressively. Starting from $\text{pH} \sim 2.5$ a thick and translucent gel forms after few hours rest at ambient conditions. The gel is then washed with isopropanol in order to dissolve chlorinated alcohols resulting from the reaction. After several washing steps, the remaining product is dried in an oven during 15 hours at 120°C . After grinding and calcination between 550 and 650°C the ensuing powder is X-rays amorphous.

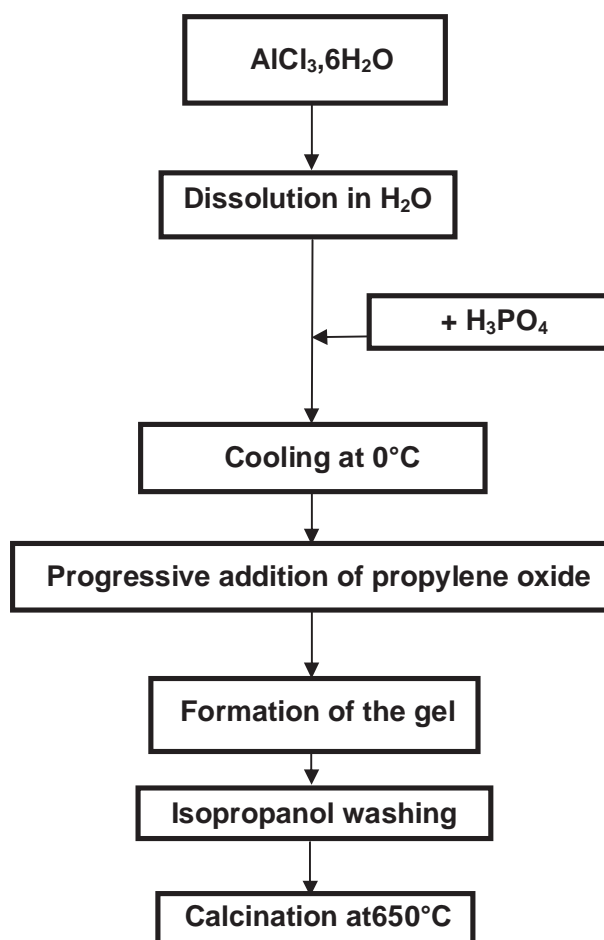


Figure 1 : Synthesis of AlPO_4 .

Amorphous citrate route. The citrate route is also a method of interest to prepare high specific surface area phosphate precursors [27]. Aqueous solutions of aluminum chloride and ammonium dihydrogen phosphate corresponding to an Al/P ratio = 1 were mixed under stirring. Then, citric acid ($\text{C}_6\text{H}_8\text{O}_7$, Merck, >99%) dissolved in a minimum amount of water was added to each solution, the addition being followed by a 30 min stirring step at 120°C. Since the complexation of cations by citric acid is improved at $\text{pH} \geq 7$, the acidic solutions were neutralized using an ammonia solution (25%, Merck) [28]. The solutions were then mixed together and stirred at 150°C for 20 min to promote chelate formation. The liquid was progressively heated up to 250°C to eliminate solvents and start the organics combustion, leading after 5 h to an expanded black solid residue. The solid was finally ground and calcined at 550°C in air in an alumina crucible for elimination of residual carbon. A heating step at 1000°C during few hours enables to confirm the presence of crystalline AlPO_4 with the ratio Al/P=1.

Thermal ammonolysis. Nitridation reactions were carried out in alumina boats placed inside an electric tubular furnace through which ammonia gas flowed with a flow rate of 20 L.h^{-1} . The temperature was raised to 800 °C range at a heating rate of $10 \text{ }^\circ\text{C.min}^{-1}$. After 15 to 50 h reaction time, the furnace was switched off and the nitrided powders were allowed to cool to room temperature under nitrogen atmosphere [29].

X-ray diffraction. XRD powder patterns were recorded using a Philips PW3710 diffractometer operating with Cu K_α radiation ($\lambda = 1.5418 \text{ \AA}$). X'PERT softwares – Data Collector and Graphics, and Identify – were used, respectively, for pattern recording, analysis and phase matching.

Elemental analysis. Nitrogen and oxygen contents were determined with a LECO[®] TC-600 analyzer using the inert gas fusion method. Nitrogen was measured as N_2 by thermal

conductivity and oxygen as CO₂ by infrared detection. The apparatus was calibrated using Leco[®] standard oxides, Si₂N₂O and ϵ -TaN as a nitrogen standard[30]. Nitrogen contents from 6 to 15 wt.% were measured depending on the nitridation temperature. Corresponding chemical formulas were calculated as AlPO_xN_y.

Energy-dispersive X-ray analysis (EDX) has been used for identifying the elemental Al:P contents of the products. The EDX analysis system works as an integrated feature of a scanning electron microscope (JEOL JSM 6400).

Specific surface area. A flowsorb II 2300 Micromeritics apparatus was used to determine the specific surface area of the powders by the single point method. Before measurement, the samples were outgassed under He/N₂ flow between 100 and 200 °C for 30 min. Analyses performed with the ASAP 2010 (Micromeritics) give access to the porosimetry, adsorption isotherm and also to the specific surface area by the multipoint method.

TGA analysis. The thermogravimetric diagram is obtained from a TA Instruments SDT 2960 analyzer. The temperature is raised at 10 °C/min rate from room temperature to 1000°C under air.

Scanning Electron Microscopy. Powder morphology and average particles size were checked by field-emission scanning electron microscopy (JEOL JSM 6301F).

Nuclear Magnetic Resonance. Experiments are performed on a Bruker Avance 400 spectrometer (161.904 MHz for ³¹P and 104.215 MHz for ²⁷Al). Quantitative ³¹P 1D spectra are recorded using a $\pi/2$ pulse and a 60 sec delay between two pulses. The spinning speed is set to 8 or 12 KHz depending on the sample (12 KHz for the 15.3 wt% N sample). ³¹P chemical shifts were referenced relative to a H₃PO₄ solution. The spinning speed for ²⁷Al NMR was set to 12 KHz with a $\pi/16$ pulse and a 0.5 sec delay between two pulses. An aluminum nitrate solution was used as

a reference for the chemical shifts. The separation between the contributions of the sites occupied by aluminum is often complex due to the quadrupolar feature of this atom.

DRIFT analysis. DRIFT spectra were collected with a FT spectrometer (Nicolet™ 380) using a deuterated triglycine sulphate (DTGS) detector working at 4 cm^{-1} resolution. The sample is placed inside a controlled environment chamber (Spectra-Tech 0030-103). Undiluted samples are heated from room temperature to 500°C at $10^{\circ}\text{C}\cdot\text{min}^{-1}$ under nitrogen flow. Data are presented in absorbance mode rather than on Kubelka-Munk units because of the undiluted feature of the samples.

Transesterification reaction. The transesterification reaction between triglycerides and alcohols can be catalyzed by both acids and bases to prepare methyl esters of vegetable oils and a by-product glycerol [31,32]. Experiments were performed in a 100 mL stainless steel batch reactor. The reaction medium was stirred with a magnetic stirring bar and heated with a heating magnetic stirrer. Reactants (commercial alcohols and edible-grade rapeseed oil) and catalyst (0.5 g) were first introduced in the reactor. The molar alcohol/oil ratio was set at 27.5, as the nature of the alcohol could change for the study. The total mass of liquid was set at 50 g. The reaction medium was then stirred at 200 rpm and heated at 453 K. The time $t = 0$ was assigned when the temperature reached 453 K, which explains nonzero conversion at $t = 0$.

The initial reaction medium and the reaction effluents form a biphasic mixture at ambient temperature (however, it is monophasic at 453 K), the polar phase containing mainly glycerol and unreacted alcohol, and the apolar phase containing mainly FAME (or other esters when alcohols other than methanol are used) and glycerides. Sample of 2 mL were collected manually from the reaction medium, at different reaction times, for analysis. The samples were washed with brine in order to remove glycerine and the alcohol. Eight drops of the apolar phase

(containing glycerides and FAME) were then diluted in 3 mL of analytical-grade THF, and the sample was analyzed by gel permeation chromatography on a Waters HPLC apparatus equipped with three Waters Styragel columns (THF) with a molar mass range of 0–1000 g·mol⁻¹. These columns were placed in a thermostated oven at 313 K. Detection was made using a Waters 2414 refractive index detector. The results gave the relative composition of the apolar phase in triglycerides, diglycerides, monoglycerides, and FAME. At the end of the reaction, the reaction medium was collected and filtered on a 0.1 µm Teflon filter, and extra alcohol was evaporated. The apolar phase (containing ester and nonconverted glycerides) and the polar phase (containing glycerine and ethers) were separated and analyzed by ICP-OES, to analyze eventual catalyst leaching products. The apparatus used was a Thermo Jarrell Ash Iris Advantage inductively coupled plasma optical emission spectrometer. The apolar-phase samples were diluted in xylene and directly injected, whereas the polar-phase samples were diluted in ethanol and injected via a cold (–10 °C) nebulization chamber.

Zinc aluminate (ZnAl₂O₄) was chosen as a reference catalyst, as the use of this mixed oxide has been described in a heterogeneous industrial transesterification process[33].

Results and discussion

Preparation of nitridoaluminophosphates

AlPO₄ was prepared either via the hydrogel or the amorphous citrate routes. The first method usually contributed to the synthesis of AlPO₄, GaPO₄ or AlGaPO₄ [22,34,26]. Both synthetic approaches are efficient to prepare reactive, X-rays amorphous and high specific surface area powders. After thermal reaction under ammonia, the corresponding surface area of the oxynitride is smaller, but in a minor extent, compared to that of the precursor. Conane

showed that the evolution of the specific surface does not depend on the nitrogen enrichment, nor the reaction step under NH_3 but is rather driven by the heating kinetics of the nitridation furnace [35]. Indeed, when considering a fast heating rate, the presence of adsorbed water at the surface of the phosphate precursor will not be eliminated at low temperature and at high temperature it will follow a sintering of the powder along with a decrease in the specific surface area. Our samples were all subjected to a heating rate of $10^\circ\text{C}/\text{min}$. The nitrogen content is essentially dependent on the nitridation step varying from 10 to 50 h. The temperature of the reaction was raised to 800°C . Above this maximum, a release of phosphorus is observed and lead to defective compositions with ratios $\text{Al/P} > 1$. EDX analyses confirmed a lower phosphorus content for sample nitrided over 800°C . Indeed, during the calcination under air at 1100°C of oxynitride samples prepared between 800 and 1000°C from AlPO_4 , mixtures of $\text{AlPO}_4 + \text{Al}_2\text{O}_3$ were identified by X-rays analysis, proving the release of phosphorus throughout the nitridation treatment. The main features of these white samples prepared and tested for the transesterification reaction are gathered in Table 1.

Table 1: Characterization of the samples tested for the transesterification reaction.

Sample	Synthesis route	Temperature and nitridation step	Specific surface ($\text{m}^2\cdot\text{g}^{-1}$)	% O (wt.%)	% N (wt.%)
AlPO_4	hydrogel	-	342	50.9	-
$\text{AlPO}_{3.16}\text{N}_{0.56}$	hydrogel	800°C - 10h	244	40.2	6.7
$\text{AlPO}_{2.93}\text{N}_{0.71}$	hydrogel	800°C - 15h	232	39.1	8.7
$\text{AlPO}_{2.20}\text{N}_{1.20}$	citrate	800°C - 50h	165	37.5	15.3

We have selected one aluminophosphate (hydrogel route) and three nitridophosphate compositions with increasing nitrogen contents. The sample prepared with the highest nitrogen content results from a "citrate route" precursor. The purpose of this work was to study the impact of nitrogen contents and specific surface areas on the structure and the surface of the catalysts, as well as on the transesterification catalytic activity.

NMR characterizations

Due to the amorphous feature of the samples, NMR ^{31}P and ^{27}Al analyses were undertaken to characterize any modification of the aluminum and phosphorus environments with nitridation in samples listed in Table 1.

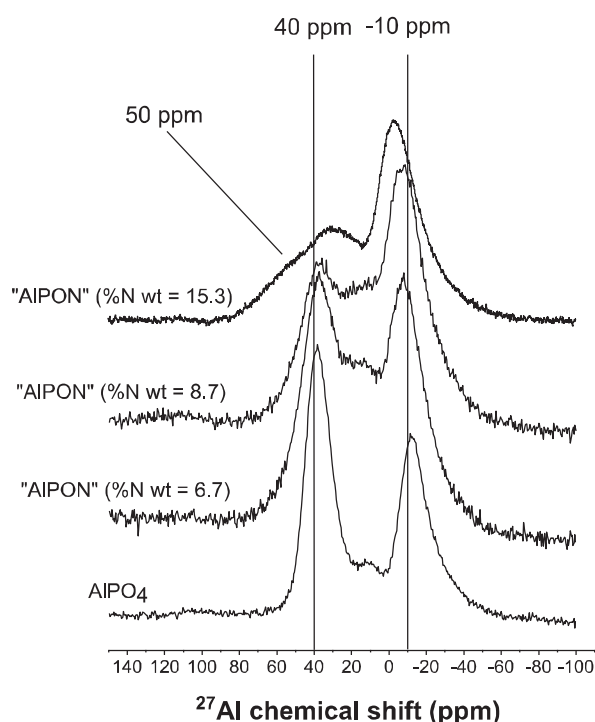


Figure 2 : NMR ^{27}Al spectra of AlPO_4 and corresponding oxynitrides.

NMR ^{27}Al spectrum of AlPO_4 displays a major peak at 40 ppm and a second one less intensive at -10 ppm, as well as a shoulder at 10 ppm (Figure 2). According to different authors, the main

peak is attributed to aluminum in tetrahedral environment [36-40]. Taking into account the amorphous and hygroscopic behaviors of the powders, peaks at -10 and 10 ppm are linked to aluminum in octahedral site and 5-fold coordinated sites respectively. Indeed, structural disorder [36,40] and/or the presence of OH groups [37,38] may involve the formation of supplementary peaks. Figure 3 represents NMR ^{31}P spectrum of AlPO_4 where a single peak centered at -25 ppm corresponds to tetrahedral phosphorus $\text{P}(\text{OAl})_4$. Peaks at 20 ppm and, in a less extent, at -70 ppm are related to the rotation bands of the rotor.

Regarding the nitrated samples, we observe on Figure 2, with increasing nitrogen content, a progressive decrease in the intensity of the peak at 40 ppm, while no change characterizes the component at -10 ppm. The composition of the tetrahedral environment evolves continuously while the octahedral sites remain unchanged (-10 ppm). Nitrogen affects significantly only the tetrahedral environment of aluminum. For sample $\text{AlPO}_{2.20}\text{N}_{1.20}$, the tetrahedral component (40 ppm) splits clearly into two contributions one close to 30 ppm and the other at 52 ppm. This second peak was also observed by Conanec et al. for nitrated aluminophosphates containing more than 15wt. % nitrogen [22] and assigned to a nitrated aluminum tetrahedral environment. An attempt to deconvolute the signal of this sample gives the following quantitative distribution: 10-15% (52 ppm), 25-30% (30 ppm) and 60% (-10 ppm). But it is not obvious to do a simple determination with such a quadrupolar ^{27}Al nuclei and the presence of asymmetric peaks. This result needs therefore to be taken with precaution.

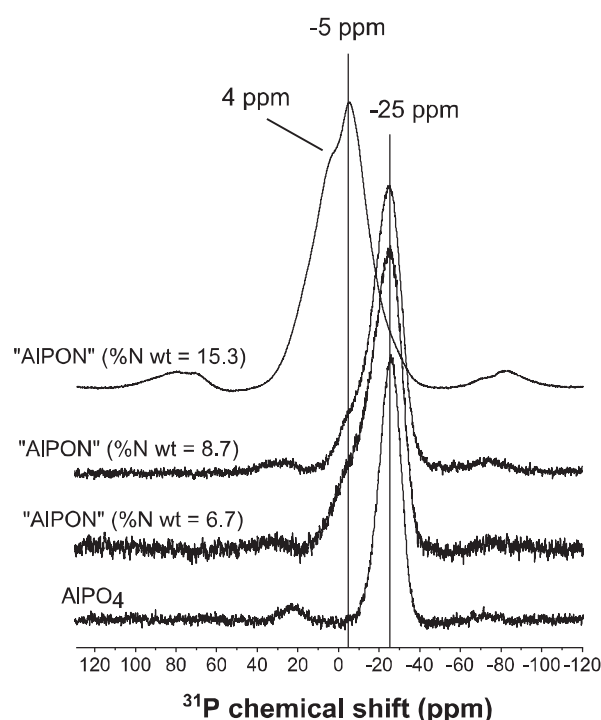


Figure 3 : NMR ^{31}P spectra of AlPO_4 and corresponding oxynitrides

Figure 3 indicates at low nitrogen contents the presence of a peak centered at -25 ppm (tetrahedral phosphorus) and a shoulder at -3 ppm corresponding to nitrated entities resulting from the O/N substitution. For the most nitrated sample, we observe two major peaks at 4 and -5 ppm. The component at -25 ppm attributed to PO_4 tetrahedra has nearly disappeared with significant nitrogen insertion. The component at -5 ppm may indicate the formation of PO_3N entities and the last one at 4 ppm may be related to PO_2N_2 without taking account of possible ^{27}Al - ^{31}P correlations. This attribution is in agreement with the signal measured in $\text{Na}_3\text{AlP}_3\text{O}_9\text{N}$ by Stein [21]. Usually, nitrogen substitutes for oxygen within PO_4 tetrahedra to form successively PO_3N and PO_2N_2 entities. These results confirm the work of Bunker et al. on "NaPON"

glasses where the components at -20, -10 and 0 ppm were assigned respectively to PO_4 , PO_3N and PO_2N_2 tetrahedra [41].

Aluminum and phosphorus atoms are principally in tetrahedral sites in AlPO_4 and "AlPON". The progressive nitrogen insertion in AlPO_4 is followed by a displacement of the resonance signals of ^{27}Al and ^{31}P towards higher chemical shifts.

Infrared characterizations

The adsorption of probe molecules followed by infrared spectroscopy is largely used to determine the nature, the number and the force of acid and basic sites at the surface of a catalyst [42]. The evidence of the acidity is quite easy using a basic probe molecule while the determination of the basicity from acid probes is more difficult. Indeed all acid molecules may contain nucleophilic (basic) atoms interacting also with acid sites at the surface.

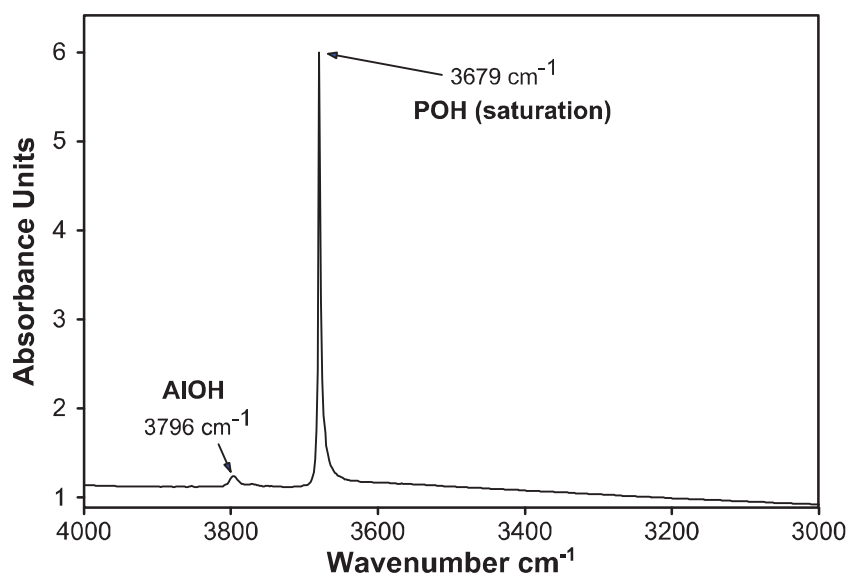


Figure 4: IR spectrum of AlPO_4 .

The IR spectrum of AlPO_4 in the -OH region ($3000\text{--}4000\text{ cm}^{-1}$) has two characteristic bands at 3796 cm^{-1} and 3679 cm^{-1} (Figure 4). The first one is attributed to the vibrational mode of -OH groups linked to P and the second one is due to vibration modes of -OH linked to tetrahedral Al [22, 43-44].

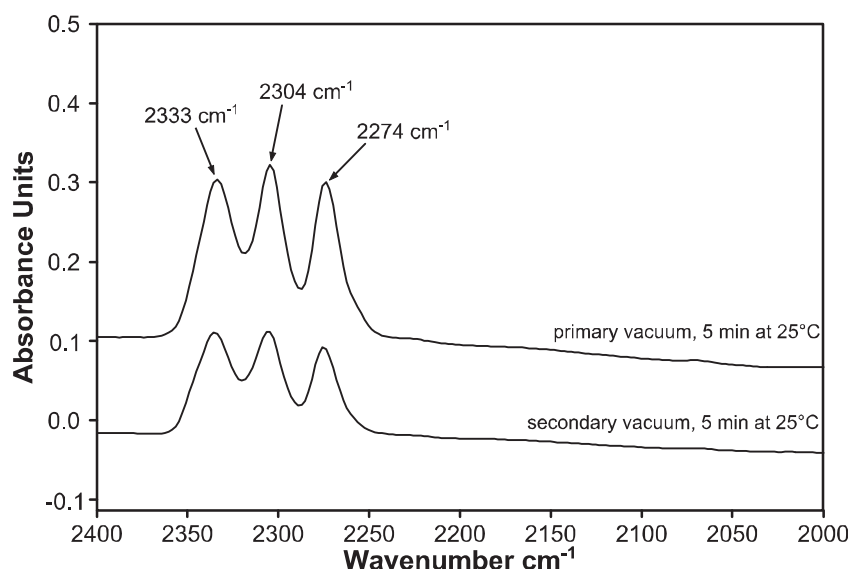


Figure 5: adsorption of acetonitrile on AlPO_4 sample.

Acetonitrile (CH_3CN) is an amphoteric molecule suitable for our study to detect both acid or basic sites in the $2350\text{--}2250\text{ cm}^{-1}$ and $2250\text{--}2050\text{ cm}^{-1}$ infrared windows respectively [45]. The adsorption of acetonitrile revealed the presence of three kinds of acidic sites (2333 cm^{-1} , 2304 cm^{-1} and 2274 cm^{-1}) (Figure 5). However, it is not possible to distinguish with this probe Brønsted from Lewis acid sites. Carbon monoxide (CO) is a basic probe and allow to differentiate between such acidic sites. The adsorption of CO at -196°C evidences different sites of AlPO_4 . Figure 6 shows the bands which result from the interaction of CO with Lewis acidic sites (2215 cm^{-1}) and at least two types of Brønsted sites at 2169 cm^{-1} and 2140 cm^{-1} , which were not distinguished by ^{31}P NMR.

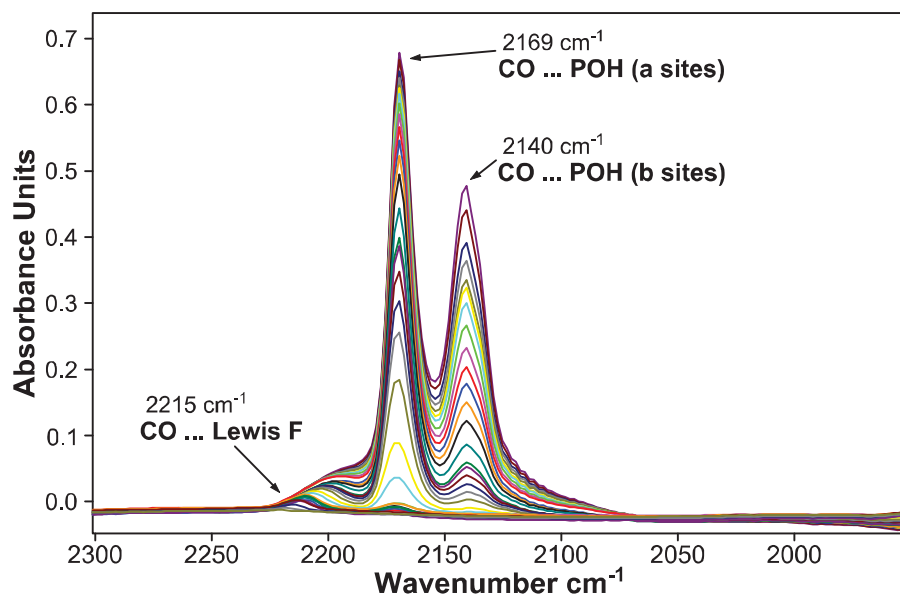


Figure 6: Adsorption of CO on AlPO_4 surface.

The introduction of nitrogen has a clear impact on the IR spectrum with the appearance of a large band centered around 3370 cm^{-1} with several shoulders between 3400 and 3600 cm^{-1} . Figure 7 gives an illustration for the sample containing 8.7 N wt.%. This large band is attributed to the vibrational stretching modes of NH_x species [46]. According to the observations of Climent et al., one of the shoulders located at 3480 cm^{-1} corresponds to NH_2 groups [47]. As for the precursor case, two fine bands at 3796 and 3676 cm^{-1} indicate the presence of hydroxyl groups linked respectively to aluminum and phosphorus atoms in tetrahedral sites. With increasing nitrogen content, we note a decrease in the relative intensity of $\nu_{\text{PO-H}}$ band (around 3680 cm^{-1}) compared with $\nu_{\text{AlO-H}}$ band. Ammonia interacts preferentially with P-OH sites at the surface of the aluminophosphates to form P- NH_x species.

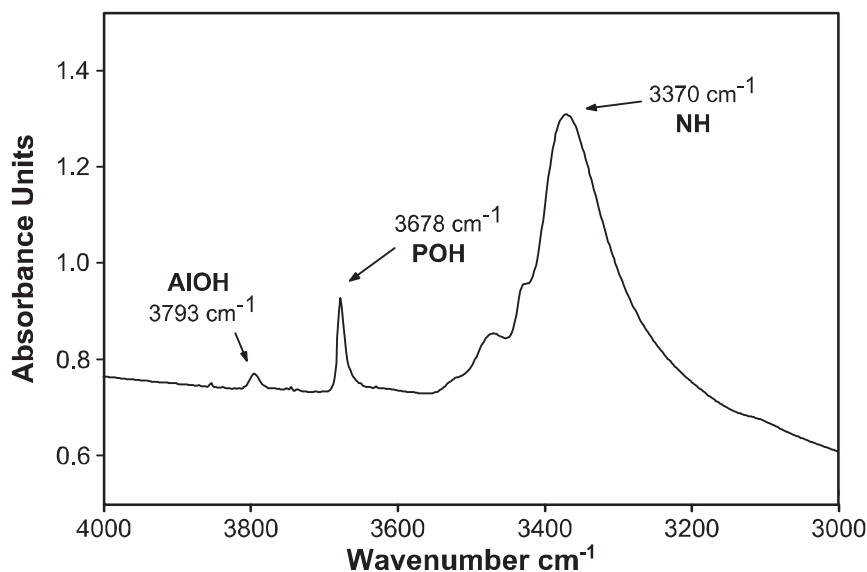


Figure 7: IR spectrum of AlPON (8.7 N wt.%).

With acetonitrile adsorption we observe for the nitrated sample (6.7 N wt.%) the same bands (2335, 2305 and 2272 cm^{-1}) related to acid sites as displayed by the oxide precursor (Fig. 5). By comparison with AlPO_4 , the intensity of the bands at 2272 and 2305 cm^{-1} are less intensive, proving the influence of the nitridation on some of these acid sites. With increasing nitrogen content, a supplementary band (acid site) is detected at 2364 cm^{-1} (2257 cm^{-1} is a physisorption band) (Fig.8). The adsorption spectrum of acetonitrile on the sample with 15.3 N wt.% is quite different from the others, with the presence of only two acidic sites at 2329 cm^{-1} and 2301 cm^{-1} .

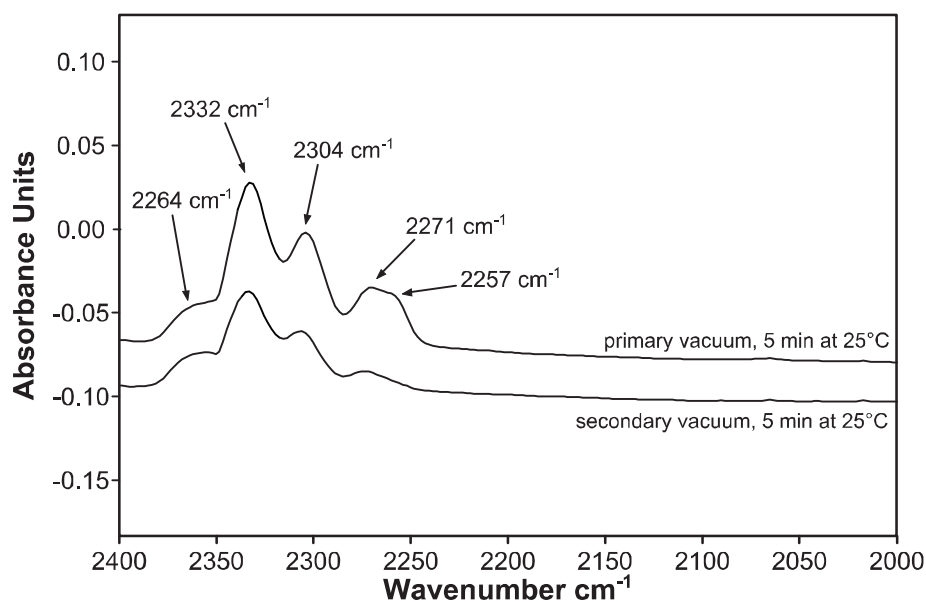


Figure 8: Adsorption of acetonitrile on ALPON - 8.7 N wt.% sample.

It has to be noticed that no basic sites were evidenced neither by acetonitrile adsorption or CO_2 adsorption (not shown). This probe molecules could not be efficient to reveal the basic sites of ALPON, revealed otherwise by the presence of $-\text{NH}_x$ groups visible in the IR spectrum.

The adsorption of CO on nitrated samples confirms the presence of two types of acidic sites. A Lewis site at 2203 cm^{-1} and three Brønsted sites at 2167 , 2152 and 2140 cm^{-1} . The nitridation also modifies the profile of the Brønsted acidity region around 2150 cm^{-1} in intensity (maybe linked to the modification of extinction coefficient or to a lower number of acid sites, as it can be thought regarding the decrease of the P-OH band intensity) and with the appearance of a band at 2152 cm^{-1} (Fig. 9).

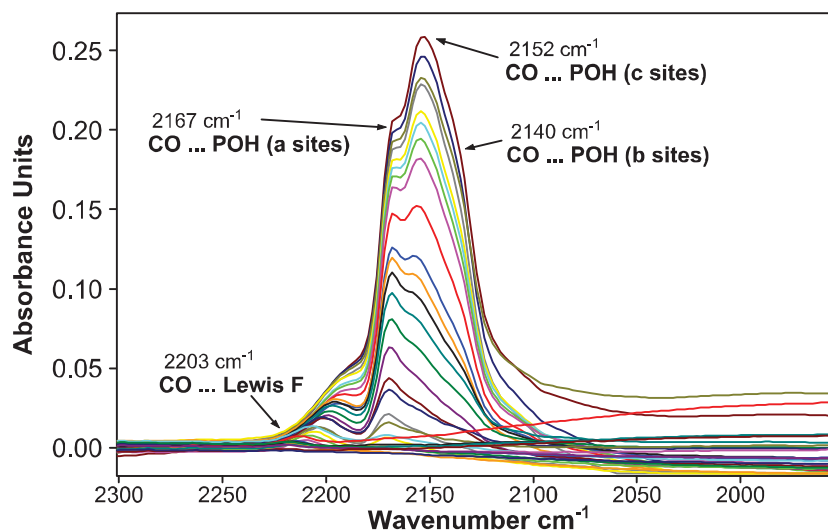


Figure 9: Adsorption of CO on AlPON- 6.7 N wt.% sample.

With higher nitrogen content (8.7 N wt.%) the spectra display two Lewis sites 2218 and 2196 cm^{-1} and three Brønsted sites (2168, 2154, 2140 cm^{-1}). At higher nitrogen content (15,3 N wt.%) the CO adsorption spectrum indicates a very weak proportion of Lewis acidic sites (2193 cm^{-1}) compared with Brønsted sites at 2169, 2149 and 2138 cm^{-1} (Fig. 10).

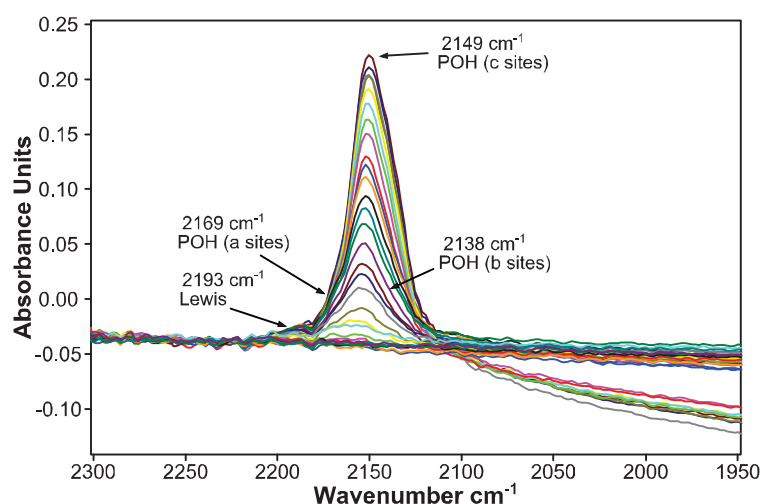


Figure 10: Adsorption of CO on AlPON-15,3 N wt.% sample.

If the presence of acid centers in the aluminophosphates was evidenced for both oxide and oxynitride catalysts, basic sites are more difficult to characterize. Infrared spectroscopy with acetonitrile adsorption never reveals, under our experimental conditions, basic sites and moreover the basicity was not even shown through our CO₂ TPD experiments. Despite of this impossibility to clearly detect basic sites, we have tested these (nitrido)aluminophosphates in heterogeneous catalysis for the transesterification reaction in order to study the influence of the nitrogen content on the catalytic activities.

Catalytic activity for the transesterification reaction.

A large part of the production of biodiesel is performed using soluble basic homogeneous catalysts, i.e. sodium hydroxide or sodium methoxide. In this case, the alcohol is deprotonated by the base and transformed into an alcoholate. However, several purification steps are necessary to reach a high level of purity for the targeted esters (biodiesel) and glycerine in agreement with the required standards. Indeed, glycerine is polluted with alkali salts or alcoholates so that the purification process has a major cost of the same order of that necessary to prepare esters.

Unlike homogeneous catalysts, heterogeneous catalysts present the appreciable advantage to produce esters and glycerine without any trace of catalyst which make them easier to purify. Basic heterogeneous catalyst based on zinc aluminate is the core of the IFPEN/Axens Esterfip-H® process, which is the only industrial heterogeneous catalyst for the transesterification of vegetable oils. This basic heterogeneous catalyst allows high activities as well as high selectivities for a high glycerine purity. Acid catalysts tend to be more active, but the formation of ethers is possible due to the presence of Brønsted acid sites at their surface, thus degrading the overall selectivity of the reaction.

In order to take advantage of the two types of heterogeneous catalysts - acid and basic - in the transesterification reaction, nitridophosphates AlPO_xN_y are catalysts of choice for which the acido-basicity can be modified by tuning the nitrogen content in these solid solutions.

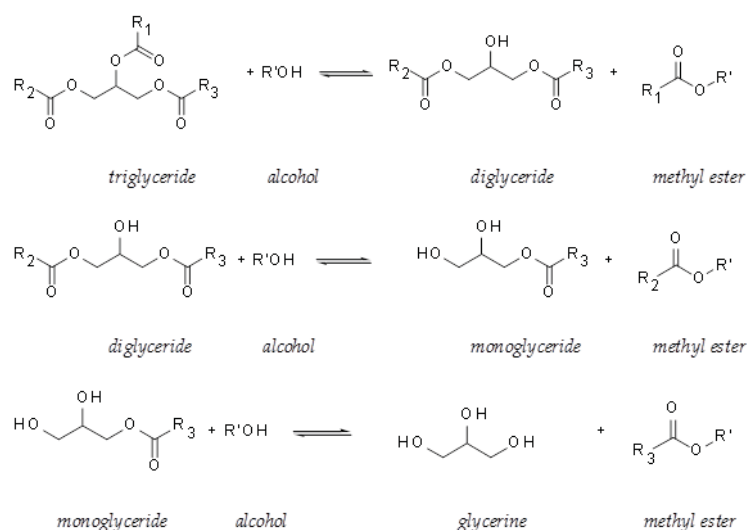


Figure 11: Transesterification reaction scheme.

Looking at the different steps of the reaction (Fig. 11), the formation of glycerine occurs only after three consecutive transesterification reactions of triglycerides into diglycerides and monoglyceride and the formation of the third fatty acid methyl ester (FAME) molecule. Our study was conducted as much as possible in agreement with the European specification EN 14214(2003) relative to the impurities content: FAME should contain at least 96.5 wt.% esters, less than 0.8 wt.% monoglycerides, 0.2 wt.% diglycerides and 0.2 wt.% triglycerides, few free fatty acids (<0.5 mg KOH/g) that can be corrosive, less than 0.25 wt.% glycerine and only metals as traces.

The catalytic activity was measured for all samples according to the procedure described in the experimental section. Figure 12 displays diverse catalytic behaviors for the triglycerides

conversion depending on the tested catalyst among ZnAl_2O_4 (spinel-type), the oxide AlPO_4 and three oxynitrides AlPO_xN_y with different anionic contents. ZnAl_2O_4 is a basic reference catalyst known for its high stability during the transesterification. At first sight, the most active catalyst is AlPO_4 with a conversion rate of 77% after only 6 hours of reaction. With increasing nitrogen content, we observe a decrease in the conversion rate of the triglycerides into methyl esters. The most nitrated sample with $\text{N} = 15.6\%$ presents only a yield of 16% after 6 hours reaction.

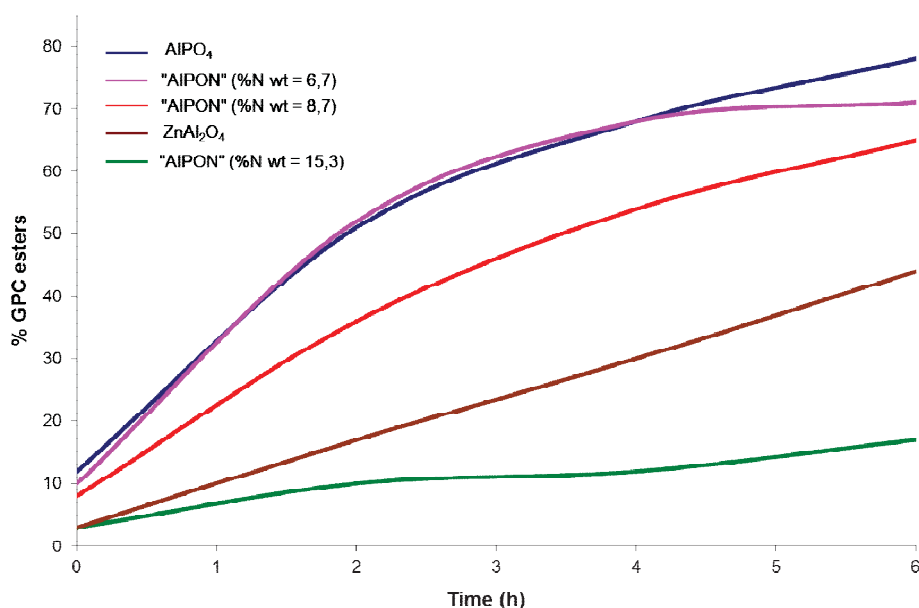


Figure 12: Triglycerides conversion rates with different catalysts vs. time.

Table 2 reports on the progressive weight evolution of the entities remaining in the reactor after a few hours when the oxide AlPO_4 is used as a catalyst. We observe clearly the consumption of the triglycerides (canola oil) towards the synthesis of methyl esters (FAME). An initial conversion (at $t=0$) is observed because the reaction starts before the experiment reaches the reaction temperature of 180°C .

Table 2: Triglycerides conversion in presence of AlPO_4 .

		Sampling (h)			
		0 ^b	2	4	6
wt. % in the organic phase ^a	triglycerides	73	34	20	12
	diglycerides	12	11	7	5
	monoglycerides	2	4	5	6
	FAME	13	51	68	77

^adetermined by GPC^b t=0 when the experimental device reaches 180°C

Compared to the performance of the reference ZnAl_2O_4 (Table 3), the AlPO_4 catalyst exhibits a much higher conversion yield of triglycerides into FAME.

Table 3: Triglycerides conversion in presence of ZnAl_2O_4 .

		Sampling (h)		
		0 ^b	4	6
wt. % in the organic phase ^a	triglycerides	92	44	29
	diglycerides	5	20	18
	monoglycerides	0	7	9
	FAME	3	29	44

^adetermined by GPC^b t=0 when the experimental device reaches 180°C

However, after reaction, the resulting glycerine presents a high ether (methoxyglycerol and dimethoxyglycerol) content close to 16 wt. %. It is necessary to limit drastically the formation of such phases to keep a high level of purity. In order to combine both an important production of

FAME and high purity glycerine, nitrided- AlPO_4 catalysts were tested under the same experimental conditions. Despite of a lower conversion rate observed on Figure 12(AlPO_xN_y 6.7 and 8.7wt. % N), the ether content measured in the glycerine phase is considerably lower ($< 0,1$ %), suggesting a high purity. Thus, the insertion of nitrogen was efficient to modify the acidity-basicity of the surface of the catalyst and to orientate the reaction towards pure final products.

The use of AlPO_xN_y oxynitrides allows to attain significant catalytic results, 70% and 65% conversion rates for the samples containing 6.7 and 8.7 wt.% nitrogen respectively. For this transesterification reaction both acid and basic sites are active to catalyse the reaction, but each of them manifests a different selectivity. Basic catalysts are the most selective whereas acid ones lead often to the formation of glycerol ethers affecting the formation of glycerine. Moreover, Lewis acid sites are more active for transesterification while Brönsted one are less selective. The ideal case is to favor the creation of Lewis acid sites and basic sites. Unfortunately, the comprehension of the formation of Lewis and Brönsted acid sites is really difficult; nitrogen seems however to impact some acid sites and contributes to the formation of basic sites.

The increase of the nitrogen content may be correlated to the reaction time and the ensuing decrease of the specific surface area, which one influences the catalytic activity through the number of active sites. In Table 4 are reported the kinetics constants related to the transformation of triglycerides by considering the hypothesis: the methanol concentration is kept constant and iso-mass compared to triglycerides. These constants are calculated per unit of surface to avoid any effect of BET surface variation.

Table4: Velocity constant of the reaction (triglycerides conversion) per unit of surface.

Catalyst	$k \text{ (s}^{-1} \cdot \text{m}^{-2}) \times 10^4$
ALPON 6.7% nitrogen	24
ALPON 8.7% nitrogen	19
AlPO_4	17
ZnAl_2O_4	11
ALPON 15.3% nitrogen	7

Nitridophosphates AlPO_xN_y with 6.7 and 8.7 wt.% nitrogen are characterized by the highest velocity constants in comparison with their oxide precursor although their catalytic activities are lower (see Figure 12). The catalyst with 15.3 wt.% nitrogen is less efficient than ZnAl_2O_4 . This observation indicates finally that in the iso-mass conditions the triglycerides conversion is more important when using AlPO_xN_y catalysts, although a too much important nitrogen substitution may involve a decrease in the catalytic activity. This assumption does not take account of the powder morphology that controls also the catalysis reaction.

These phosphate catalysts are stable in the reactor. No leaching was reported (dissolution of the catalyst in the formed phases). Indeed, in the ester phase, the aluminum content is lower than 1 ppm and phosphorus lower than 5 ppm. In the glycerine, aluminum and phosphorus are measured between 10 and 50 ppm. This rate is even lower than 10 ppm for phosphorus originating from AlPO_4 catalyst. Thus, both esters and glycerine we aim to prepare are of a high purity, except when using AlPO_4 where noxious ethers are formed.

As the acido-basic sites are extremely sensitive to air and water, a catalytic test was performed first by activating AlPO_xN_y catalysts (with 6.7 wt.% N) under vacuum for 2 hours, and then they were loaded in the reactor under inert atmosphere (Figure 13).

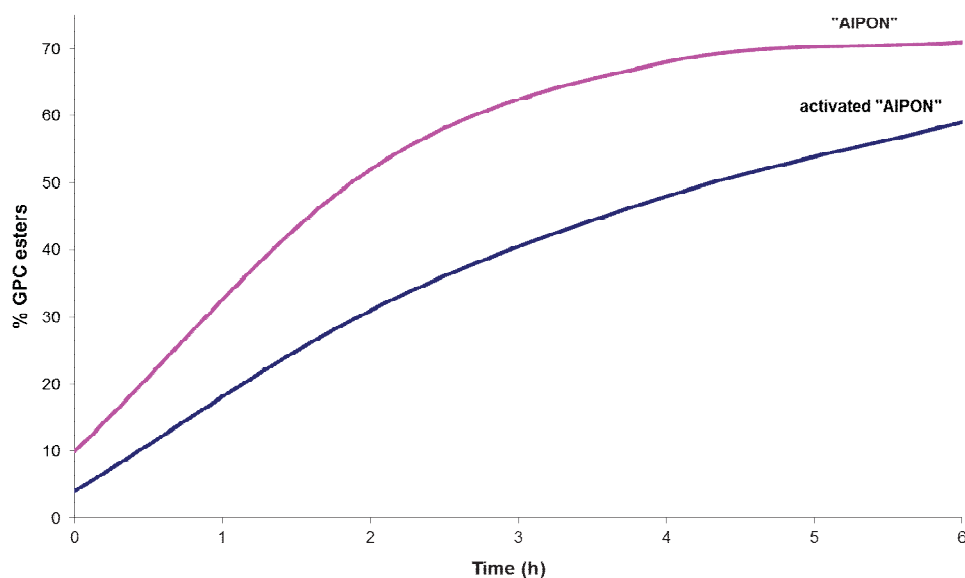


Figure 13: "AIPON" (%N wt = 6.7) activation under vacuum.

The activated catalyst appears less active than that stored in air without any precaution. This difference may be explained by the disappearance of some acido-basic sites (hydroxyles, carbonates...) due to the pretreatment. These sites of medium or weak strength may be active in transesterification. This hypothesis was not proven by infrared study because the activation is needed to subtract the water signal.

Influence of the reacting alcohol

The impact of the choice of the alcohol to react with the vegetable oils in presence of the catalyst AIPON (6.7 wt.% N) is shown on figure 14. Quantities of alcohol and vegetable oils have been adapted in order to keep a molar ratio alcohol/oil = 27.5 and a total mass of 50 g. The pKa of each alcohol/alcoholate couple is given in brackets.

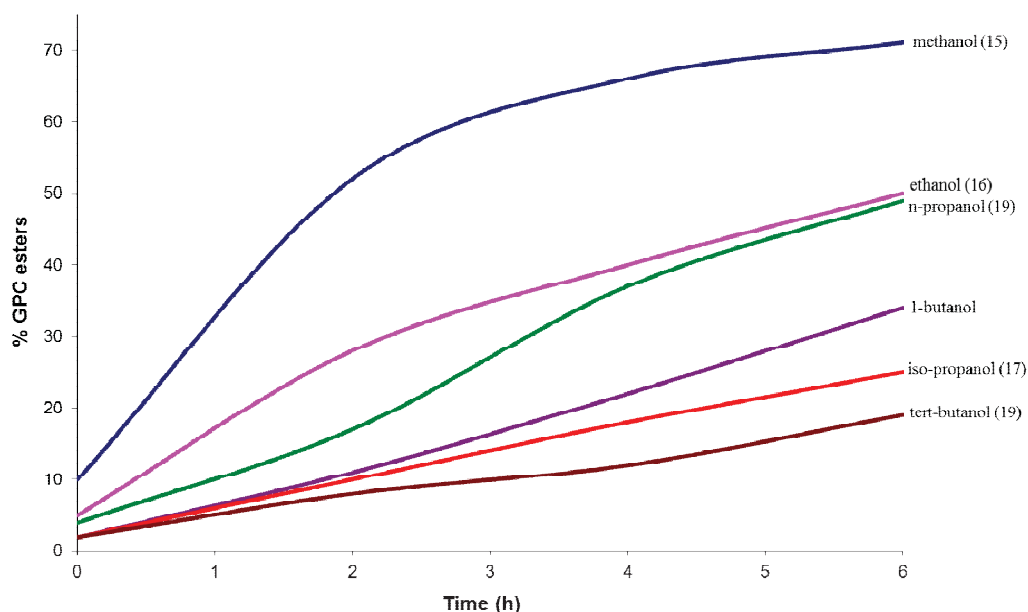


Figure 14: Activity of the catalyst "AIPON" (%N wt = 6.7) vs. a panel of alcohols.

These results point out a significant difference in activities between methanol and other alcohols. During the reaction, the catalyst (acid and/or basic) should be able to deprotonate the alcohol to form FAME. Depending on the chosen alcohol and its pKa, the catalysts -acid or basic- will not have the same ability to deprotonate.

Thus, as AIPON is an acid-base catalyst, the transesterification reaction may be driven by a basic or acid-base mechanism. The difference between ethanol and n-propanol is quite small regarding the activities, an acid mechanism may characterize them. Indeed, despite of an important pKa difference, the esters yield are similar. It seems that the reaction does not require the deprotonation of the alcohol on a basic site. The steric hindrance within the alcohols affects also the catalytic activity as branched alcohols lead only to poor conversion rates (less than 20% esters within 6 hours with *tert*-butanol).

Influence of the cation

Considering the substantial results measured for the catalytic activities of aluminophosphates (AlPO_4 et "AlPON") for the transesterification reaction, more phosphates based on different cations have been prepared and evaluated in the same conditions, for example GaPO_4 and TaPO_5 whose results are reported on figure 15. The main characteristics for this test are given in Table 5.

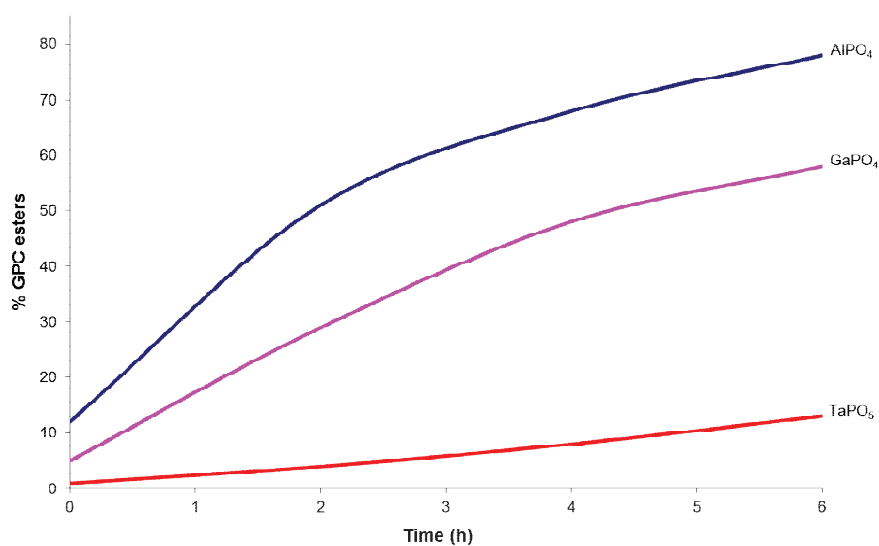


Figure 15: Catalytic activities vs. different cations.

In similar experimental conditions, AlPO_4 presents the best activity (conversion of 77%), GaPO_4 produces a conversion of 58% while TaPO_5 only 13 %.

Table 5: Triglycerides conversion kinetics constants per unit of surface.

Catalyst	Specific surface ($\text{m}^2\cdot\text{g}^{-1}$)	$k (\text{s}^{-1} \cdot \text{m}^{-2}) \times 10^4$
AlPO₄	340	17
GaPO₄	130	31
TaPO₅	280	4
ZnAl₂O₄	-	11

Converted per unit of surface, GaPO₄ offers the highest conversion kinetics constant (Table 5). Group III based phosphates (with Al and Ga) are active for the transesterification reaction. Tantalum-based phosphate does not have any interest for this reaction. Titanium was also tested with TiPON samples, but unfortunately give rise to an important leaching where the catalysts is dissolved at the end of the reaction.

Conclusion

Nitridoaluminophosphates have been prepared with different nitrogen contents (from 6 to 15 wt.%) and their spectroscopic characterizations were performed using infrared and NMR. Infrared analyses indicate the presence of Lewis and Brønsted sites at the surface of all catalysts. Although the basicity of AlPON was evidenced by CO₂ TPD (Conanec et al.), no basic sites was properly detected on the nitrated phases under our experimental conditions. ³¹P and ²⁷Al NMR studies show that phosphorus and aluminum atoms are mainly in tetrahedral sites of the "AlPON" structure. The progressive nitridation of AlPO₄ results in the shift of the resonance peaks towards higher chemical shifts, a typical feature encountered with nitrogen insertion.

AlPO_4 used as an acid catalyst provided the best catalytic activity compared to nitrated phosphates. However the triglycerides conversion velocity constants (per unit of surface) prove that some of the ALPON catalysts (containing 6.7 and 8.7 wt. % N) are more efficient for the transesterification reaction. The insertion of nitrogen within an acid catalyst has an impact on acid sites and more than likely on the formation of basic sites. Moreover acid catalysts like AlPO_4 lead to the formation of ethers that impair the quality of glycerine, but ALPONs bring a solution to overcome this pollution without affecting conversion rates. The choice of the alcohol and the cation plays a major role on the values of the conversion rates. ALPONs accommodate very well with methanol. AlPO_xN_y nitridophosphates, with tunable acido-basicity, produced significant better catalytic results in comparison with a ZnAl_2O_4 catalyst reference.

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