Homogeneous Catalysis

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Esters, Including Triglycerides, and Hydrogen as Feedstocks for the Ruthenium-Catalyzed Direct N-Alkylation of Amines

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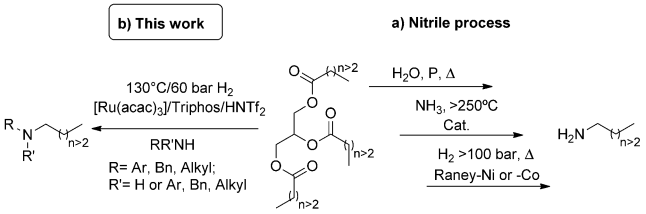
Dedicated to Professor Avelino Corma on the occasion of his 65th birthday

Abstract: *Triglycerides are used for the direct N-alkylation of amines with molecular hydrogen for the first time. A broad range of interesting and industrially relevant secondary and tertiary amines are obtained in the presence of an in situ formed Ru/Triphos complex. Notably, plant oil can be efficiently applied in this single-step process. Moreover, a variety of other methyl esters can be used as N-alkylation agents in the presence of hydrogen for the synthesis of more advanced building blocks.*

The development of processes and technologies that make use of sustainable feedstocks is an important goal for chemists in academia and industry.[1] In this context, biomass formed through CO_2 fixation is an excellent alternative to petroleum,[2] which also offers possibilities for new chemical transformations. Oils and fats, mainly composed of triglycerides, are among the most important biomass materials for the chemical industry.[2a–c,e–g,3] Currently, they are used as feedstocks for the production of bio-derived surfactants, polymers, lubricants, and plasticizers.[2b,e,3a–c,e,f] Another important class of compounds obtained from triglycerides are fatty amines, with a broad range of applications as emulsifiers, surfactants, corrosion inhibitors, anticaking agents, fuel additives, bactericides, and sludge inhibitors.[2f,3f] So far, the most common methodology for obtaining fatty amines is the nitrile process[2a,f,3f,4] (Scheme 1 a) in which a fatty acid, obtained after triglyceride hydrolysis, reacts with ammonia in the presence of a dehydrating catalyst, normally a metal oxide, at high temperature (>250 °C) to afford the corresponding nitrile. Subsequent hydrogenation, usually catalyzed by Raney-Ni or -Co at high temperatures, gives the desired amine. Despite the use of triglycerides as feedstocks, this process requires harsh conditions and several steps.

Traditional procedures for the N-alkylation of amines involve the use of toxic alkylating agents, such as alkyl halides or sulfonates,[5] or the combination of carboxylic acids or esters with stoichiometric amounts of metal borohydride reagents.[6] In recent years, many advances have been reached



Scheme 1. Comparing a) the nitrile process (hydrolysis, formation of nitrile and hydrogenation) with b) this work (direct N-alkylation with triglycerides).

in this field using mainly alcohols,[7] but also carbonyl compounds[8] or carboxylic acids.[9] For example, our group recently reported the first general N-alkylation of amines with carboxylic acids and hydrogen.[9e,10] The optimal catalyst for this procedure is the so-called ruthenium/Triphos catalyst system [Triphos = 1,1,1-tris(diphenylphosphinomethyl)-ethane], also successfully applied in the methylation of amines with CO_2,[11] as well as in the reduction of carboxylic acid derivatives and CO_2.[10,12] Inspired by this work, we started to explore the alkylation of primary and secondary amines with triglycerides (Scheme 1 b).

In a first approach to the direct N-alkylation of amines with triglycerides, we decided to study the ethylation of *N*-methylaniline **1** using ethylene glycol diacetate **2** as a model compound (Table S1). The [Ru(acac)$_3$]/Triphos/HNTf$_2$ combination was selected, as it has been shown to be effective in the alkylation of amines with carboxylic acids in the presence of H_2.[9e] A first screening of the reaction at 150 °C, 60 bar of H_2, and 2 mol % of ruthenium in THF as solvent using different amounts of ethylene glycol diacetate **2** (Table S1, entries 1–3), pointed out that improved yields of *N*-ethyl-*N*-methylaniline **3** were obtained in the presence of 4 equivalents of the diester **2**. When the reaction was performed with simple [Ru(acac)$_3$] or [Ru(acac)$_3$] with HNTf$_2$, only aromatic ring hydrogenation products were detected (Table S1, entries 4 and 6). Moreover, no reaction occurred in the absence of ruthenium or HNTf$_2$ (Table S1, entries 5 and 7). These experiments confirm that all three components of the catalytic system ([Ru(acac)$_3$]/Triphos/HNTf$_2$) are required for the reaction to proceed. Next, we explored the influence of several Bronsted and Lewis acids (Table S2). Among the different additives tested, HNTf$_2$ afforded the highest yield of *N*-ethyl-*N*-methylaniline **3**, and only HOTf gave the product in moderate yields (73 %, Table S2, entry 4). Varying the amount of co-catalyst (Table S3) revealed improved results with 5 mol % of HNTf$_2$ (2.5 equivalents with respect to Ru; Table S3, entry 5). Several ruthenium pre-catalysts and phos-

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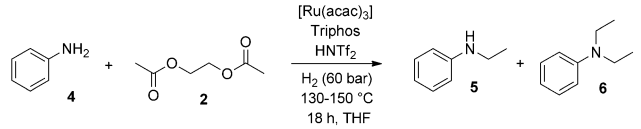
phine ligands were also evaluated for this transformation (Tables S4 and S5) and it was demonstrated that the initially used system with $[Ru(acac)_3]$/Triphos was the most effective one. Remarkably, $[Ru(cod)(methylallyl)_2]$ and $[Ru(PPh_3)_3(CO)H_2]$ (Table S4, entries 2 and 5) also afforded high yields of *N*-ethyl-*N*-methylaniline **3**. At this point, a more detailed investigation of the temperature and pressure parameters was interesting to us (Table S1, entries 8–10). Gratifyingly, the reaction proceeded well at 130 °C (Table S1, entry 8), while with < 60 bar of H_2 the yield of *N*-ethyl-*N*-methylaniline **3** notably decreased (Table S1, entry 10).

Next, the effect of different solvents was tested (Table S6). The best results were obtained when THF or *n*-Bu_2O was used (Table S6, entries 1 and 4), whereas toluene or 1,4-dioxane also gave high yields of the alkylated product **3** (Table S3, entries 2 and 5). To our delight, even at lower catalyst loading (1 mol %) excellent yields of *N*-ethyl-*N*-methylaniline **3** were obtained (Table S1, entry 12, 96 %). In all of these experiments, ethylene glycol and ethanol were detected as byproducts. Interestingly, also ethanol formed by hydrogenation of the ester can be used as alkylating agent under these conditions, albeit in much lower yield (Table S1, entry 14). From a mechanistic point of view, this demonstrates that the major reaction pathway proceeds directly through the ester.

Once the catalytic system was established, it was interesting to explore the N-alkylation of primary amines such as aniline **4** (Scheme 2, Table S7). Interestingly, it is possible to



T (°C)	**2** (eq.)	Ru/Triphos/$HNTf_2$ (mol%)	Conv. (%)[a]	Yield **5** (%)[a]	Yield **6** (%)[a]
130	1.5	1/ 1.5/ 2.5	92	83	9
150	6	6/ 9/ 15	100	12	86

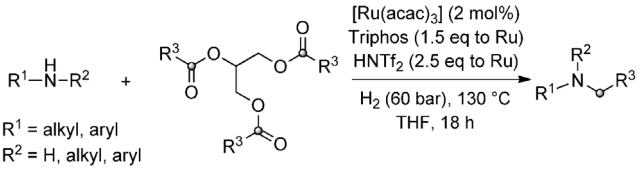
Scheme 2. Ruthenium-catalyzed selective mono and di-alkylation of aniline **4** with ethylene glycol diacetate **2**. [a] Determined by GC using hexadecane as internal standard.

perform both selective mono- and dialkylation simply by tuning the reaction conditions. Thus, when the reaction was carried out at 130 °C, 1 mol % of Ru, and 1.5 equivalents of **2**, *N*-ethylaniline **5** was obtained in 83 % yield with a 1:0.1 mono/dialkylation ratio. By contrast, at 150 °C using 6 mol % of Ru and 6 equivalents of the diester **2**, *N*,*N*-diethylaniline **6** was formed in a 86 %, with the inverse ratio.

To gain more insight in this process, yield/time kinetic profiles corresponding to the alkylation of *N*-methylaniline **1**, and mono- and di-alkylation of aniline **4** were performed (Figures S1–S3). No reaction intermediates were detected in any of these experiments, nor were induction periods observed. In the case of di-alkylation of aniline (Figure S3), high concentrations of *N*-ethylaniline **5** were observed at short reaction times that immediately reverted in favor of the formation of *N*,*N*-diethylaniline **6**.

With these findings in hand, we decided to explore the direct alkylation of amines using various triglycerides (Table 1). Gratifyingly, alkylated anilines were obtained in high yields using 1 equivalent of shorter chain triglycerides (Table 1, entries 2–4) or a larger excess for glyceryl tribenzoate or octadecanoate (Table 1, entries 1 and 5). Then, the

Table 1: Ruthenium-catalyzed N-mono-alkylation of aromatic and aliphatic amines with triglycerides and H_2.[a]



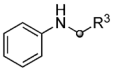
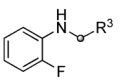
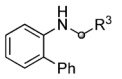
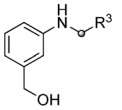
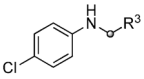
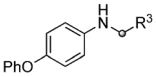
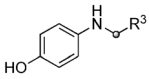
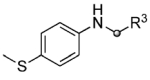
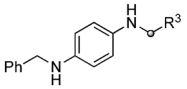
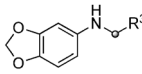
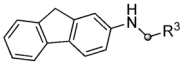
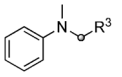
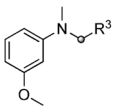
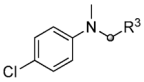
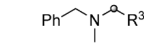
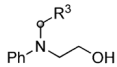
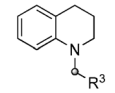
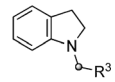
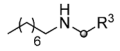
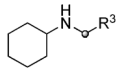
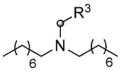
Entry	Alkylated Amine	R^3	Eq. Trig.	Conv. [%][b]	Yield [%][b]
1		Ph	2.5	90	87
2		C_2H_5	1	89	86
3		C_3H_7	1	91	86
4		C_7H_{15}	1	92	89
5		$C_{17}H_{35}$	2	100	[76][c]
6[d,e]		C_7H_{15}	2	89	[69]
7[d,e]		$C_{17}H_{35}$	3.5	92	[68][c]
8[d]		C_2H_5	2.5	100	[85]
9		C_7H_{15}	1	100	[65]
10		C_7H_{15}	1.5	95	[85]
11		$C_{17}H_{35}$	2.5	100	[80][c]
12		C_7H_{15}	1	97	[78]
13		C_7H_{15}	0.5	93	[85]
14		C_7H_{15}	2	84	[76]
15		$C_{17}H_{35}$	2.5	100	[82][c]
16[f]		C_3H_7	0.5	95	[80]
17		C_7H_{15}	1	100	[88]
18		$C_{17}H_{35}$	2	100	[70][c]
19		C_3H_7	1	97	[78]
20		C_7H_{15}	1	98	[90]
21		C_2H_5	4	97	[79]
22		C_3H_7	4	97	[90]
23		C_7H_{15}	4	98	[87]
24		$C_{17}H_{35}$	3	98	[80][c]
25		C_2H_5	4	91	[75]
26		C_7H_{15}	4	89	[74]
27		C_2H_5	4	90	[85]
28		C_7H_{15}	4	90	[79]
29		C_7H_{15}	3	100	[90]

Table 1: (Continued)

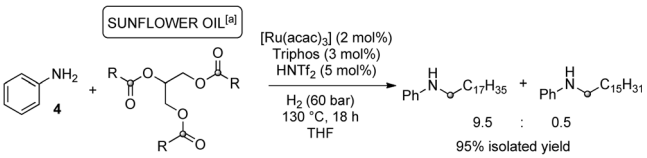
Entry	Alkylated Amine	R^3	Eq. Trig.	Conv. [%][b]	Yield [%][b]
30		C_2H_5	4	100	[93]
31		C_7H_{15}	4	100	[83]
32[d]		C_7H_{15}	4	88	[83]
33		C_2H_5	3.5	100	[94]
34		C_7H_{15}	3.5	100	[96]
35		C_3H_7	0.5	100	[89]
36		C_7H_{15}	0.5	100	[92]
37[d]		C_7H_{15}	0.5	94	80
38		C_3H_7	3	94	92
39[d]		C_7H_{15}	2	100	98

[a] Standard reaction conditions: amine (0.5 mmol), $[Ru(acac)_3]$ (2 mol%), Triphos (3 mol%), $HNTf_2$ (5 mol%), triglyceride (0.5-4 equiv), THF (2 mL), 60 bar H_2, 130°C, during 18 h. [b] Determined by GC using hexadecane as internal standard, values between brackets correspond to isolated yields. [c] Alkylating agent was used as a glyceryl tristearate: glyceryl tripalmitate (2:1) mixture, a 2:1 mixture of octadecylated and hexadecylated products was obtained. [d] 150°C. [e] $Ru(acac)_3$ (4 mol%). [f] >99% selectivity for alkylation of the primary amine.

alkylation of a series of aromatic and aliphatic amines was explored (Table 1). Both electron-donating and electron-withdrawing substituents were well tolerated. However, the alkylation of electron-rich primary amines proceeds more efficiently, and lower amounts of triglyceride were needed to avoid overalkylation (Table 1, entries 9, 12, 13, 16–20). *Ortho*-substituted fluorine- and phenylanilines were also alkylated in good yields, but required either higher temperatures and/or increased catalyst loading (Table 1, entries 6–8). Compared to traditional alkylation procedures, this methodology is highly selective (>99%) towards the functionalization of primary amines in the presence of secondary ones (Table 1, entry 16). However, secondary amines can also be alkylated in the presence of an excess of triglyceride (3–4 equiv; Table 1, entries 21–36). Notably, benzylic and aliphatic amines (Table 1, entries 29–31, 37–39), as well as amino alcohols (Table 1, entries 9, 13, and 32), were also smoothly alkylated.

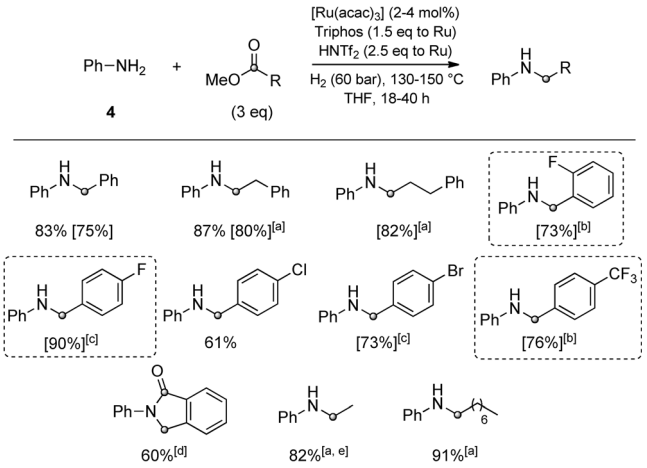
To demonstrate the practical utility of this procedure, we envisioned using vegetable oil as the source of triglycerides. Thus, the reaction of aniline with the Ru/Triphos/$HNTf_2$ system was performed using original sunflower oil[13] as the alkylating agent (Scheme 3). To our delight, this transformation proceeded smoothly to give a mixture of *N*-octadecylaniline and *N*-hexadecylaniline in 95% of isolated yield (9.5:0.5 ratio of octadecylated: hexadecylated product). It should be noted that, under the reductive conditions used, the natural unsaturated fatty acids were completely hydrogenated.

Finally, to further demonstrate the synthetic applicability of this methodology, N-alkylation of aniline **4** with a variety of



Scheme 3. Ruthenium-catalyzed N-alkylation of aniline **4** using sunflower oil as triglycerides source. [a] Sunflower oil contains: 59% R = $C_{17}H_{31}$, 30% R = $C_{17}H_{33}$, 6% R = $C_{17}H_{35}$, and 5% R = $C_{15}H_{31}$.

methyl esters was carried out (Scheme 4, Table S8). In general, aliphatic and benzylic esters worked as alkylating agents at 130°C, whereas for aromatic ones slightly higher temperature (150°C) and/or higher catalyst loadings were needed. For example, several fluorine-substituted amines can be obtained through this methodology. Moreover, using inexpensive dimethyl phthalate as the alkylating agent allows obtaining *N*-phenylisoindolinone.



Scheme 4. Ruthenium-catalyzed N-alkylation of aniline **4** using methyl esters and H_2. Yields determined by GC using hexadecane as internal standard, values between brackets correspond to isolated yields. Standard reaction conditions: **4** (0.5 mmol), methyl ester (3 equiv), $[Ru(acac)_3]$ (2 mol%), Triphos (3 mol%), $HNTf_2$ (5 mol%), THF (2 mL), H_2 (60 bar), 150°C, 18 h. [a] 130°C. [b] $[Ru(acac)_3]$ (3 mol%) over 40 h. [c] $[Ru(acac)_3]$ (4 mol%). [d] Dimethyl phthalate was used as alkylating agent. *N*-phenylisoindoline was found as by-product (25%). [e] *N*,*N*-diethylaniline was found as by-product (9%).

In conclusion, we have developed a new method for the valorization of triglycerides, an important part of biomass. With this method it is possible to perform the selective reductive alkylation of amines with triglycerides in a single step using molecular hydrogen. The in situ formed catalyst (Ru/Triphos/$HNTf_2$) enabled the selective N-mono-alkylation of a variety of primary and secondary amines with triglycerides. In principle, the synthesis of primary fatty amines from ammonia and triglycerides using this procedure should be also possible, and the development of further studies in this direction would be of high interest. Furthermore, plant oil can be employed as a benign and effective alkylating agent. The synthetic utility of this methodology is further demonstrated by the use of several methyl esters as

alkylating agents. Although this method still presents limitations related with the use of an excess of triglyceride and a valuable catalytic system, it opens the door to the development of direct and sustainable techniques for the synthesis of fatty amines using triglycerides.

Experimental Section

General procedure for the N-alkylation of amines with triglycerides: A 8 mL glass vial containing a stirring bar was sequentially charged with amine (0.5 mmol), *n*-hexadecane (50 mg) as an internal standard, $[Ru(acac)_3]$ (2–4 mol%), Triphos (3–6 mol%), THF (2 mL) as solvent, triglyceride (0.5-4 equiv), and a freshly prepared 0.2 M in THF solution of co-catalyst $HNTf_2$ (5–10 mol%). Afterwards, the reaction vial was capped with a septum equipped with a syringe and set in the alloy plate, which was then placed into a 300 mL autoclave. Once sealed, the autoclave was purged three times with 30 bar of hydrogen, then pressurized to 60 bar and placed into an aluminum block, which was preheated at 130–150 °C. After 18 h, the autoclave was cooled in an ice bath, and the remaining gas was carefully released. Finally, the reaction mixture was diluted with ethyl acetate and analyzed by GC and GC-MS. To determine the isolated yield of the alkylated amines, no internal standard was added and the reaction mixture was purified by silica gel column chromatography (*n*-heptane/ethyl acetate mixtures) to give the corresponding N-alkylated products. In the case of the reactions performed with glyceryl tristearate (technical grade, containing 33% aprox. of glyceryl tripalmitate), the ratio of the octadecylated and hexadecylated products was calculated by GC, using GC-MS to identify each compound.

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Communications

Homogeneous Catalysis

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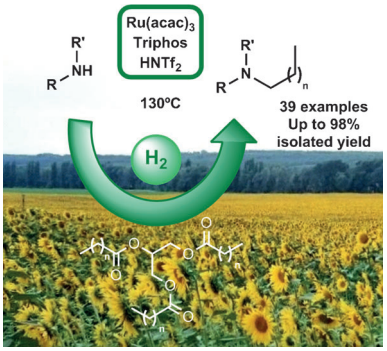
Esters, Including Triglycerides, and Hydrogen as Feedstocks for the Ruthenium-Catalyzed Direct N-Alkylation of Amines



Give me an alkyl group: Triglycerides are used as bio-based N-alkylating agents. In a single-step process with hydrogen, a broad range of amines are synthesized using a specific Ru catalyst.