JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

Recycling of Carbon and Silicon Wastes: Room Temperature Formylation of N–H Bonds Using Carbon Dioxide and Polymethylhydrosiloxane

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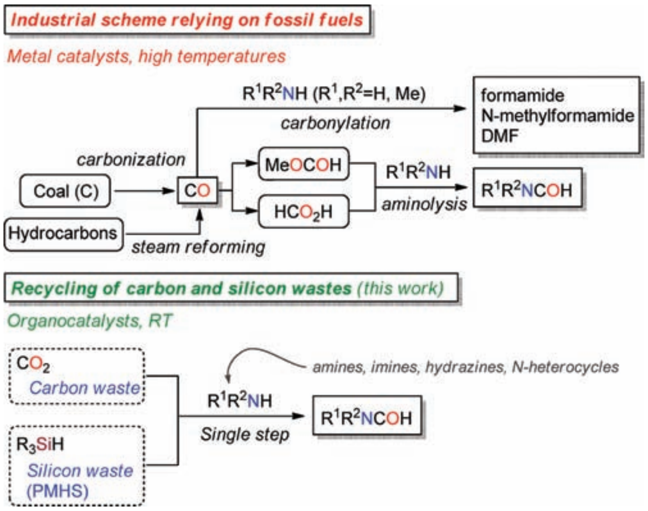
Ⓢ *Supporting Information*

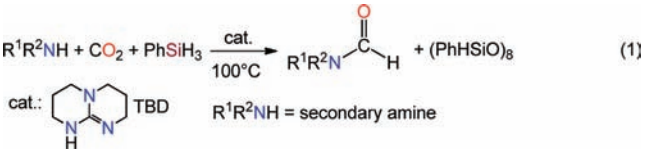
ABSTRACT: A highly active organocatalytic system based on N-heterocyclic carbenes has been designed for the formylation of N–H bonds in a large variety of nitrogen molecules and heterocycles, using two chemical wastes: CO_2 and polymethylhydrosiloxane (PMHS).

While greenhouse gases emissions are reaching alarming levels, fossil fuels still represent 80% of the world energy portfolio and 95% of our organic chemical commodities rely on nonrenewable resources, mostly hydrocarbons.[1] As CO_2 is the ultimate waste of this intensive utilization of carbon resources, its recycling urges the necessity to build a balanced carbon cycle.[2] In this context, utilizing CO_2 as a C_1 building block to produce platform chemicals as an alternative to petrochemistry has a double advantage of reusing CO_2 while sparing fossil resources and avoiding CO_2 emissions from their use. Formamide derivatives, such as *N*-methylformamide or *N*,*N*-dimethylformamide (DMF), are important solvents and key intermediates in the synthesis of adhesives, pesticides, and drugs and formulation of polymers.[3] In the industry, formamides are typical petrochemicals and are synthesized via a multistep process, by formylation of amines with CO or aminolysis of formic acid and methylformate, using carbon monoxide as a C_1-carbon source (Scheme 1).[3,4]

Scheme 1



Using CO_2, a carbon waste, for the formylation of N–H bonds is attractive yet challenging because of the thermodynamic stability of CO_2. Conversion of Me_2NH, Et_2NH, and $PhNH_2$ to their formamides using CO_2 and H_2, as an energy source, is a well-known process.[5] Nevertheless, hydrogenation of CO_2 in the presence of an amine requires metal catalysts working at high temperature and pressure. Using silanes as reductants, we recently developed an organocatalytic version of this reaction, with nitrogen bases (TBD) as catalysts (eq 1).[6] However, this so-called diagonal reaction is limited to basic amines and only proceeds at 100 °C with phenylsilane, whereas low working temperatures, renewable or disposable energy inputs, and large application spectra are required to develop efficient and meaningful methods for CO_2 recycling. To circumvent these limitations, it is critical to design highly active catalysts, and herein, we report that N-heterocyclic carbenes (NHCs) are excellent catalysts able to promote the formylation of a large variety of N–H bonds in amines, imines, hydrazines, and N-heterocycles using two wastes: CO_2 and polymethylhydrosiloxane (PMHS), an abundant and nontoxic byproduct of the silicone industry (Scheme 1).



Whereas preliminary theoretical calculations have shown that TBD is not nucleophilic enough to activate organosilanes,[6] NHCs are proven catalysts for transformations requiring activation of Si–H, Si–O, and Si–CN bonds.[7] The reductive functionalization of CO_2, using $PhSiH_3$ and morpholine, was therefore attempted using **IMes** as a catalyst. To our delight, formation of *N*-formylmorpholine (**2a**) was complete after only 2 h at room temperature (RT) and under 1 bar of CO_2, while TBD shows no activity under these conditions. A limited screening of NHCs was therefore explored to map the steric and electronic properties influencing the catalytic activity of the carbene (Table 1). The six NHCs tested in the formylation of morpholine proved to be active at RT. However, unsaturated carbenes, such as **IMes** and **IPr**, perform significantly better than their saturated analogues, **s-IMes** and **s-IPr**, and the

Received: December 9, 2011
Published: January 31, 2012

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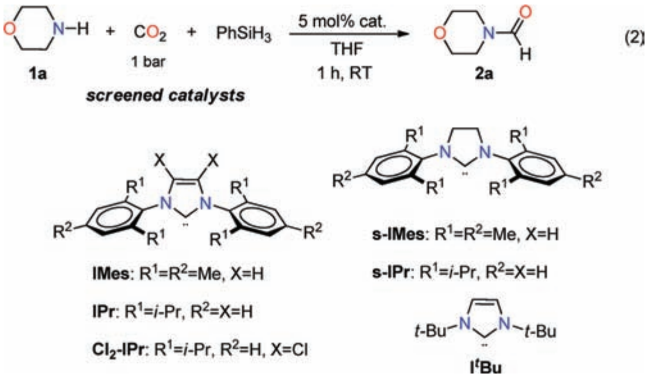
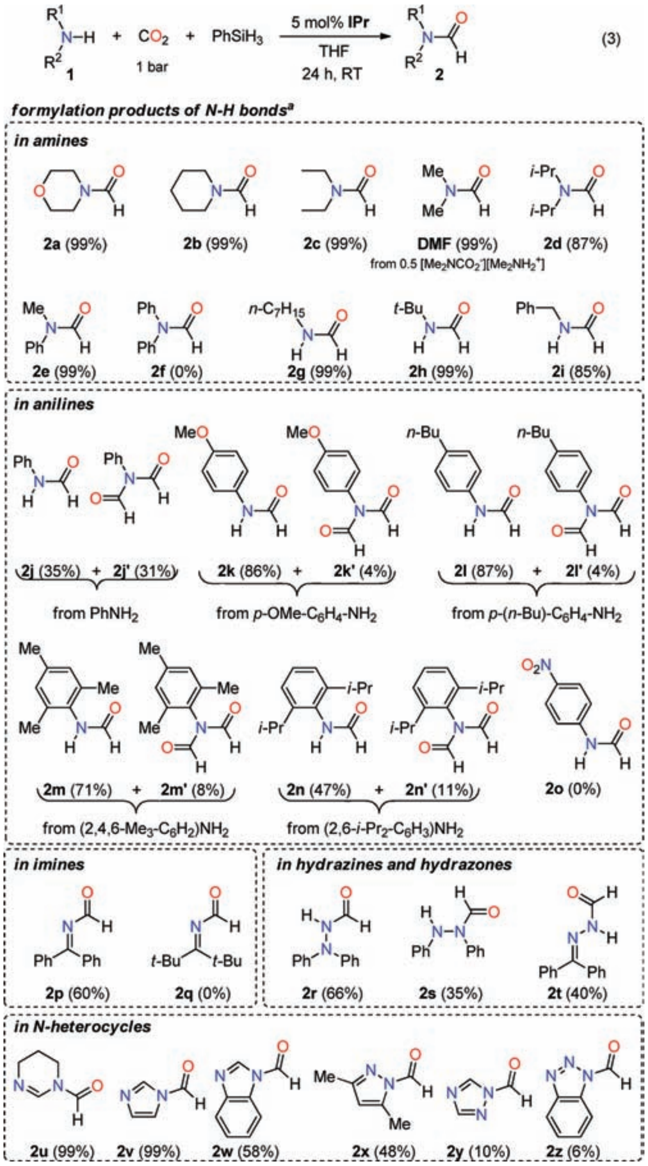
Table 1. Organocatalytic Formylation of Morpholine Using CO_2, $PhSiH_3$, and NHCs



entry	catalyst	yield [%][a]
1	**IPr**	99
2	**IMes**	69
3	**s-IPr**	24
4	**s-IMes**	25
5	**Cl_2-IPr**	35
6	**I^tBu**	30

Scheme 2. Scope of the Organocatalytic Formylation of N−H Bonds Using CO_2 and $PhSiH_3$[a]



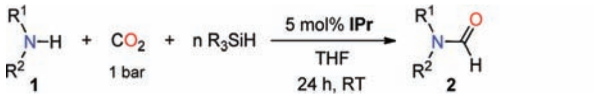
[a]Yields are given with respect to the amine substrate (**1**).

bulkier **IPr** NHC is more active than **IMes** (entries 1−4 in Table 1). In addition, **I^tBu** bearing aliphatic substituents on the nitrogen atoms exhibits a decreased activity compared to **IPr** and **IMes**. These results can be explained by the greater basicity of **s-IMes**, **s-IPr**, and **I^tBu** which is merely compatible with the acidity of the amine/CO_2 mixture. On the other hand, introduction of electron withdrawing groups on the imidazolidene ring somewhat deactivates the NHC and 35% **2a** is recovered from morpholine after 1 h at RT with 5 mol % **Cl_2-IPr**, whereas the yield is quantitative with **IPr**, demonstrating that a balance between basicity and nucleophilicity is required for the NHC catalyst (entries 1 and 5 in Table 1). Overall, **IPr** is about 2000 times more active than TBD in the catalytic formylation of morpholine, using CO_2 and $PhSiH_3$, with a RT turnover frequency (TOF) of 160 h^{-1} for **IPr** compared to 0.075 h^{-1} for TBD.

Having in hand a highly efficient catalytic system, we then investigated the scope of the reaction for the formylation of a variety of N−H bonds with $PhSiH_3$ as reductant and **IPr** as organocatalyst (Scheme 2). Aliphatic secondary amines, such as morpholine, piperidine and diethylamine, are converted to their formamides (**2a**−**2c**) quantitatively after 24 h at RT and under 1 bar of CO_2. Dimethylformamide (DMF) is obtained as the only product when dimethylammonium dimethylcarbamate is employed as a substrate. Interestingly, increasing the steric congestion at nitrogen does not shut down the reactivity of the amine and i-Pr_2NH is formylated at room temperature with an excellent 87% yield (**2d**), whereas **2e** is obtained in quantitative yield from PhMeNH, introducing two aromatic substituents on the nitrogen atom completely deactivates the reactivity of the corresponding diphenylamine. Though primary aliphatic amines proved to be reluctant substrates using nitrogen-bases as catalysts (e.g., TBD),[6] **IPr** is able to promote the formylation of benzylamine (87% yield), heptylamine and the bulky *tert*-butylamine (99% yield). The same catalyst is also active in the formylation of aniline derivatives. Interestingly, both N−H bonds of $PhNH_2$ proved reactive and a mixture of the mono- (**2j**, 35%) and bis-formylaniline (**2j′**, 31%) was recovered after 24 h at RT. Electron donating groups (p-methoxy, p-n-Bu, etc.) have a positive influence on the conversions observed for aniline derivatives. On the contrary, p-nitroaniline was found unreactive under the applied reaction conditions.

The formylation of N−H bonds in less reactive and more fragile substrates was explored. Formylation of benzophenone imine is efficient and affords the new formyl derivative **2p** in 60% yield, with no reduction of the C═N bond. Nonetheless, $(t\text{-Bu})_2C{=}NH$ did not yield **2q** and the starting material was fully recovered after 24 h at RT. Given the mild reaction conditions, functionalization of N−H bonds in hydrazine (**2r**, **2s**), and hydrazone (**2t**) derivatives was successfully performed in modest to good yields (>35%), without reduction of the N−N bond. Similarly, transposition of this strategy to N-heterocycles provided excellent results when applied to tetrahydropyrimidine (**2u**), imidazole (**2v**), benzimidazole (**2w**), and dimethylpyrazole (**2x**). Triazole ring systems (**2y**, **2z**) exhibit a lower reactivity and can be converted to formamides

Table 2. Organocatalytic Formylation of N−H Bonds Using CO_2 and $(EtO)_3SiH$, Ph_3SiH, TMDS, and PMHS



(4)

entry	amine (R^1R^2NH)	organosilane (R_3SiH)	n	product	yield [%][a]
1	morpholine	Ph_3SiH	3	**2a**	4
2	morpholine	$(EtO)_3SiH$	3	**2a**	28
3	morpholine	TMDS	1.5	**2a**	43
4	morpholine	PMHS	3	**2a**	90
5	$0.5[Me_2NCO_2][Me_2NH_2]$	PMHS	3	DMF	90
6	*n*-heptyl-NH_2	PMHS	3	**2g**	67
7	$PhCH_2NH_2$	PMHS	3	**2i**	30
8	$PhCH_2NH_2$	PMHS	9	**2i**	70
9	$PhNH_2$	PMHS	3	**2j**	83
10	Ph_2CNH	PMHS	3	**2p**	35
11	Ph_2NNH_2	PMHS	3	**2r**	83
12	dimethylpyrazole	PMHS	3	**2x**	29

[a] Yields are given with respect to the amine substrate (**1**).

only in low 5−10% yields. Despite the fact that formamides **2a**−**2z** do not have a vast market individually, these results significantly open the spectrum of chemicals directly available from CO_2.

Phenylsilane is a mild reductant for CO_2 and serves as an efficient energy source in eqs 1−3. Yet, its cost and reactivity toward moisture limit further applications of the methodology for multigram scale applications and, therefore, the impact of the reaction depicted in eq 3 for large-scale CO_2 recycling. However, within the diagonal approach framework, the reductant can be modified independently from the functionalizing reagent (the amine), and we therefore extended the scope of active organosilanes to less reactive and less expensive silanes (Table 2).[6] Among them, polymethylhydrosiloxane ($Me_3Si(OSiMeH)_nOSiMe_3$, PMHS) is especially attractive for CO_2 recycling applications because it is an abundant chemical waste produced by the silicone industry and it is cost-effective ($2−7 per mole), nontoxic, and moisture stable.[8,9] Formylation of morpholine using CO_2 was efficiently performed using Ph_3SiH, $(EtO)_3SiH$, tetramethyldisiloxane (TMDS), and PMHS (entries 1−4, Table 2). As expected, all four silanes exhibit a lower reactivity than $PhSiH_3$; yet, **2a** was isolated with an excellent 90% yield using PMHS.[9] Importantly, this reaction is the first metal-free reduction process utilizing PMHS.[10] PMHS is also active as reducing reagent for the formylation of N−H bonds in primary and secondary amines, anilines, imines, hydrazines, and N-heterocycles as attested with the good to excellent yields obtained in the synthesis of DMF, **2g**, **2i**, **2j**, **2p**, **2r**, and **2x** (entries 5−12, Table 2). Interestingly, PMHS shows a greater selectivity than $PhSiH_3$ in the formylation of aniline and **2j** is the only formamide obtained from $PhNH_2$ and PMHS (85% yield), whereas a mixture of **2j** (35%) and **2j′** (31%) is obtained with $PhSiH_3$.

In conclusion, we have disclosed an efficient catalytic system for the use of CO_2 and PMHS, two abundant and nontoxic chemical wastes, as formylation reagents, using NHCs as organocatalysts. NHCs and nitrogen bases, therefore, appear to be promising organic catalysts for large-scale CO_2 recycling because they are not limited by abundance and toxicity problems. Detailed mechanistic investigations are underway in our group to determine and control their active role in the reduction of CO_2.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Synthesis and characterization of all new compounds, detailed procedures for catalytic reactions. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

For financial support of this work, we acknowledge the CEA, CNRS, ANR (Fellowship to C.G. and Starting Grant to T.C.), the FP7 Eurotalents Program (PD Fellowship to O.J.), and the CEA Physical Sciences Division (PD Fellowship to O.J., Basic Research on Low Carbon Energies Grant to T.C.).

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