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RESEARCH ARTICLE

Strategy for Synthesizing Novel Acetamidines as CO_2-Triggered Switchable Surfactants via Acetimidates

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Abstract
In this study, we developed a strategy for using the Scoggins procedure in the synthesis of acetamidines as novel CO_2-triggered switchable surfactants via acetimidates by effectively tuning the chemical equilibrium. The as-synthesized *N*'-alkyl-*N*,*N*-diethylacetamidines exhibit excellent CO_2/N_2 switchability and their bicarbonate salts have the ability to emulsify oil–water mixtures.

Keywords CO_2 switchable surfactants · Acetimidate · Acetamidine · Consecutive reaction

Introduction

Surfactants, whose amphiphilic structures enable the stabilization of emulsions with two immiscible phases, are widely applied in many processes such as cleaning [1], viscous oil transportation [2], and enhancing oil recovery [3]. Excellent stabilization is required in these processes, usually followed by a subsequent emulsion-destabilization step to effectively recover the two immiscible phases. However, this remains a challenging task for most commonly used surfactants. To tackle this problem, it is necessary for the surfactants that can be "switched on and off" to reversibly stabilize/destabilize the emulsion under certain trigger conditions. The switchable surfactants reported in the literature can undergo reversible interconversions from surface-active to surface-inactive forms upon command, and their switchability can usually be triggered by altering the external conditions, such as pH [4], electrochemical redox [5], magnetic-field intensity [6], or light source (UV or visible light) [7]. Compared with these triggers, CO_2 is environmentally benign, inexpensive, and renewable, and more important, it does not accumulate in a system after repeated cycles. Therefore, it has been identified as an innovative and ideal "trigger" for stimuli-responsive surfactants and has recently been studied for use in reversible solvents [8–10], switchable Pickering emulsions [11, 12], and repeatable polymer-based materials [13, 14], particularly for application in enhanced oil recovery [15, 16].

Thus far, the majority of CO_2/N_2 reversible surfactants include guanidines, imidazoles, tertiary amines, and amidines. In their inactive forms, these surfactants can be protonated to form charged bicarbonates that become active upon the addition of CO_2 in aqueous media, increasing their solubility in water. The bicarbonate ions can then be deprotonated by bubbling with N_2 or air [17]. However, these common CO_2/N_2 reversible surfactants have some inherent drawbacks that hinder their wide application. The headgroup of imidazole surfactants limits their triggering efficiency due to their hydrolysis in aqueous media [18]. Surfactants containing a hydrophilic headgroup of guanidine are generally basic and require more rigorous conditions to achieve deprotonation (such as high temperature, long reaction time, or heavy flow rate of bubbling gas) [19].

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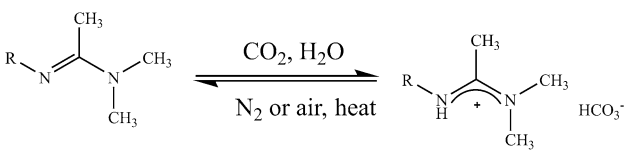
With respect to tertiary amines, their basicity is so weak that stable emulsions can hardly be formed [20]. As such, compounds containing an amidine head [21, 22] are attracting more attention due to their mild basicity and superior stability. In addition, the exceptional demulsifying ability of amidines in their neutral form is an unexpected advantage. Scheme 1 illustrates the protonation and deprotonation processes of amidines stimulated by CO_2 and N_2 (or air), respectively, in aqueous media, where R represents a long-chain alkyl or ethoxylated groups. Amidine surfactants can easily and reversibly transform into bicarbonate salts.

Amidines can be synthesized using various strategies, such as the nucleophilic addition of amines to nitriles [23], reaction of catalytic three-component coupling [24], displacement reaction of imidates with amines [25, 26], and the Scoggins procedure [27, 28]. Of these synthetic methods, the Scoggins procedure involving primary amines and *N*,*N*-dimethylacetamide dimethyl acetal can synthesize long-chain aliphatic amidines and aromatic amidines with a high yield of 90% accompanied by the formation of a small amount of imidates as a by-product [27, 28]. This is particularly attractive since an encouraging acetamidines yield of 99% was achieved by Jessop et al. [21] when they added an excess amount of dimethylamine to the reaction system. However, the types of amidines used in this synthesis method have been fairly limited thus far, due to the limitation of commercially available reactants. The structure of amidines generated by this method differed from those in the hydrophobic tail group, which are mainly long-chain alkyl or ethoxylated groups, or both [16, 21], and the hydrophilic head is bonded only with the dimethyl group.

As stated earlier, imidates were the only by-product of the Scoggins procedure. At the same time, the potent electrophilicity of imidates supports the synthesis of amidines through displacement reactions with amines. Therefore, imidates have potential for use in the synthesis of new CO_2/N_2 switchable amidines if various imidates can be generated as the main product by modifying the Scoggins procedure. We also believe it is important to gain insight into the reaction path of the Scoggins procedure to facilitate the development of this novel synthesis strategy. In this study, we mainly investigated the reaction path of the Scoggins procedure for use in developing a new approach for the synthesis of novel CO_2/N_2 switchable surfactants.



Scheme 1 Protonation and deprotonation processes of amidines and bicarbonate salts

Experimental Section

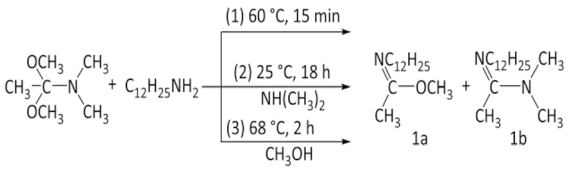
Materials and Methods

To avoid light and moisture, we conducted all the reactions in the dark environment. We purchased *N*,*N*-dimethylacetamide dimethyl acetal (> 90%, stabilized by 5–10% methanol) and a series of primary amines (dodecylamine (AR) > 98%, tetradecylamine (AR) > 96%, hexadecylamine (AR) > 95%, octadecylamine (GC) > 98%) from Aladdin Reagent Company (Shanghai, China) without further purification. We prepared *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**) in experiments 1 and 2, as shown in Table 1, according to methods reported in Refs. [21, 28]. We recorded the proton nuclear magnetic resonance (^{1}H NMR) and carbon-13 nuclear magnetic resonance (^{13}C NMR) of the reaction products on a Varian Inova spectrometer (Varian, America, 500 MHz), for which all the chemical shift values refer to $CDCl_3$ ($\delta(^1H)$, 7.26 ppm; $\delta(^{13}C)$, 77.16 ppm). We obtained high-resolution electrospray ionization mass spectrometry (ESI-HRMS) data on a Bruker micrOTOF-QII mass spectrometer (Bruker, America) and infrared (IR) spectra on a Nicolet Avatar 320 spectrometer (Thermo Fisher, America) with a smart miracle accessory.

General Procedure for the Synthesis of *N*-alkyl-*O*-Methylacetimidates

We put *N*,*N*-dimethylacetamide dimethyl acetal (1.72 g, 0.012 mol) and dodecyl amine (1.89 g, 0.01 mol) into a three-neck round-bottom brown flask in a dark environment and an oil bath, to which we then added methanol (40 mL). We kept this mixture at 68 °C for 2 h with a methanol reflux in the condenser. To determine when the conversion of the dodecylamine was complete, we used the thin-layer chromatography method (Merck TLC plates, silica gel 60 F254, with chloroform and methanol as developing solvents, $V_{CHCl3}/V_{CH3OH} = 3{:}1$). Then, we removed the methanol and dimethylamine from the reaction mixture by rotary evaporation at 50 °C and − 0.1 MPa for 20 min, obtaining a light-yellow liquid product consisting of *N*-dodecyl-*O*-methylacetimidate (**1a**, 71.7% yield) and *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**, 28.3% yield). We calculated the yield based on its ^{1}H NMR spectrum. Then, we subjected the resulting mixture to flash column chromatography on aluminum oxide (active, neutral, 200–300 mesh) using ethyl acetate and dichloromethane ($V_{CH3COOCH2CH3}/V_{CH2Cl2} = 1{:}2$) as mobile phases to obtain purified *N*-dodecyl-*O*-methylacetimidate (**1a**) as a colorless liquid. We also synthesized

Table 1 Product distribution results using the Scoggins procedure



Experiment	Additive	X_{amine}[a] (%)	Y_{1a}[b] (%)	Y_{1b}[c] (%)
1	—	100	8.7	91.3
2	$NH(CH_3)_2$	100	2.4	97.6
3	CH_3OH	100	71.7	28.3

[a]Conversion of dodecylamine

[b]Yield of **1a** was calculated based on the relative integration of the peak at $\delta_H = 3.60$ (the group of $-O(CH_3)$) [29] with respect to the peak at $\delta_H = 2.87$ (the group of $-N(CH_3)_2$) [21]

[c]Yield of **1b** was calculated based on the relative integration of $\delta_H = 2.87$ with respect to $\delta_H = 3.60$

other *N*-alkyl-*O*-methylacetimidates, including *N*-tetradecyl-*O*-methylacetimidate (**2a**), *N*-hexadecyl-*O*-methylacetimidate (**3a**), and *N*-octadecyl-*O*-methylacetimidate (**4a**), by the same method, using different primary amines as the reactants, i.e., tetradecylamine (0.22 g), hexadecylamine (0.25 g), and octadecylamine (0.28 g), respectively.

N-dodecyl-*O*-methylacetimidate (**1a**): Colorless oil, ^{1}H NMR (500 MHz, $CDCl_3$) $\delta = 7.27$ (s, 1H), 3.60 (s, 3H), 3.18 (t, 2H), 1.86 (s, 3H), 1.54–1.49 (m, 2H), 1.33–1.26 (m, 18H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) $\delta = 161.10$, 77.67–76.74, 52.07, 49.40, 32.13, 31.74, 29.90, 29.87, 29.86, 29.77, 29.57, 27.54, 22.89, 14.59, 14.28; HRMS m/z (ESI) calcd for $C_{15}H_{31}NO$ $(M+H)^+$ 242.2478, found 242.2512. IR absorption $W_{-N=C-}$ at 1685.48 cm^{-1}, $W_{-C-O-C-}$ at 1253.50 cm^{-1}.

N-tetradecyl-*O*-methylacetimidate (**2a**): Colorless oil, ^{1}H NMR (500 MHz, $CDCl_3$) $\delta = 7.27$ (s, 1H), 3.60 (s, 3H), 3.18 (t, 2H), 1.86 (s, 3H), 1.55–1.49 (m, 2H), 1.30–1.26 (m, 22H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) $\delta = 161.02$, 77.67–76.74, 52.07, 49.50, 32.04, 31.57, 29.81, 29.78, 29.68, 29.49, 27.51, 22.79, 14.47, 14.17; HRMS m/z (ESI) calcd for $C_{17}H_{35}NO$ $(M+H)^+$ 270.2791, found 270.2811; IR absorption $W_{-C=N-}$ at 1685.48 cm^{-1}, $W_{-C-O-C-}$ at 1253.50 cm^{-1}.

N-hexadecyl-*O*-methylacetimidate (**3a**): Colorless oil, ^{1}H NMR (500 MHz, $CDCl_3$) $\delta = 7.27$ (s, 1H), 3.60 (s, 3H), 3.17 (t, 2H), 1.86 (s, 3H), 1.59–1.49 (m, 2H), 1.30–1.26 (m, 26H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) $\delta = 161.17$, 77.67–76.74, 52.21, 49.53, 32.16, 31.68, 29.94, 29.90, 29.89, 29.79, 29.61, 27.63, 22.91, 14.63, 14.30; HRMS m/z (ESI) calcd for $C_{19}H_{39}NO$ $(M+H)^+$ 298.3104, found 298.3128; IR absorption $W_{-C=N-}$ at 1685.48 cm^{-1}, $W_{-C-O-C-}$ at 1253.50 cm^{-1}.

N-octadecyl-*O*-methylacetimidate (**4a**): Colorless oil, ^{1}H NMR (500 MHz, $CDCl_3$) $\delta = 7.27$ (s, 1H), 3.58 (s, 3H), 3.17 (t, 2H), 1.85 (s, 3H), 1.54–1.49 (m, 2H), 1.30–1.25 (m, 30H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) $\delta = 161.01$, 77.67–76.74, 52.14, 49.51, 32.16, 31.71, 29.94, 29.90, 29.79, 29.61, 27.63, 22.91, 14.56, 14.28; HRMS m/z (ESI) calcd for $C_{21}H_{43}NO$ $(M+H)^+$ 326.3417, found 326.3444; IR absorption $W_{-C=N-}$ at 1685.48 cm^{-1}, $W_{-C-O-C-}$ at 1253.50 cm^{-1}.

General Procedure for Reaction Pathway Studies Using ^{1}H NMR

Experimental Process for the Results Shown in Fig. 1

We added *N*,*N*-dimethylacetamide dimethyl acetal (1.72 g) and dodecyl amine (1.89 g) to a three-neck round-bottom brown flask in a dark environment, to which we added 40 mL of methanol. Then we maintained the mixture at 68 °C for 2 h by controlling the temperature of the oil bath with a methanol reflux in the condenser. We extracted 1 mL samples at intervals and immediately transferred them into an ice bath. Then, we removed the methanol and dimethylamine from the samples using a rotary evaporator at 10 °C and − 0.1 MPa. The remaining product was a mixture of *N*-dodecyl-*O*-methylacetimidate (**1a**) and *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**). Based on their ^{1}H NMR spectra, we calculated the selectivities of **1a** and **1b** at different reaction times.

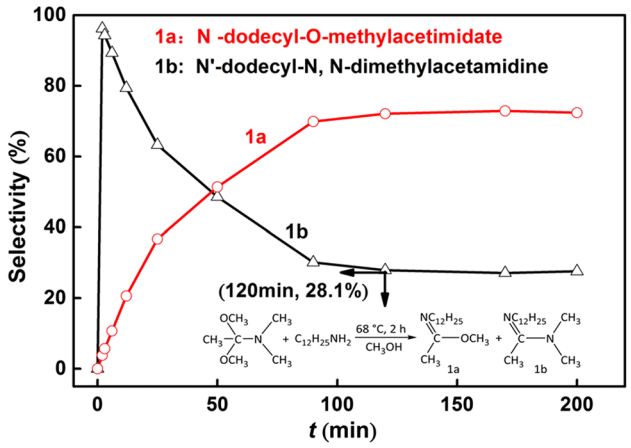


Fig. 1 Product distributions of **1a** and **1b** as a function of reaction time in the Scoggins procedure in the presence of methanol

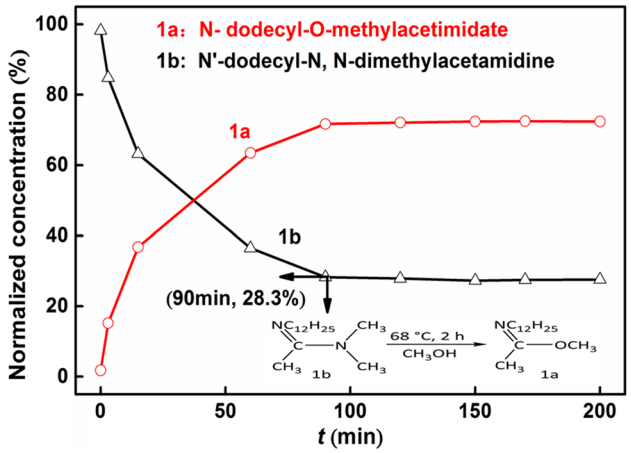


Fig. 2 Normalized concentrations of **1a** and **1b** as a function of reaction time in the reaction between acetamidine and methanol

Experimental Process for the Results Shown in Fig. 2

First, we prepared a certain amount of purified *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**) using the method developed by Jessop et al. [21]. We added about 0.012 mol of *N*,*N*-dimethylacetamide dimethyl acetal (1.72 g) and 76.4 mmol of Me_2NH (38 mL, 2 mol/L solution in tetrahydrofuran) into a three-neck round-bottom brown flask and stirred the mixture (100 r/min) at 25 °C. After that, we added about 0.01 mol dodecylamine (1.89 g) dropwise to this mixture at room temperature, stirred it for 10 min, and then left it for 18 h in the dark. To remove most of the tetrahydrofuran and Me_2NH, we kept the mixture at 55 °C and −0.1 MPa in a rotary evaporator for 8 h, which yielded a yellow liquid consisting of *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**, yield = 97.6%) and a trace impurity of *N*-dodecyl-*O*-methylacetimidate (**1a**, yield = 2.4%), which we identified based on its ^{1}H NMR spectrum. We then reacted the above product (2.54 g) with methanol (40 mL) in a three-neck round-bottom brown flask with a condenser and thermometer and kept this mixture at 68 °C for 2 h. We extracted 1 mL samples at intervals, which we immediately transferred into an ice bath. Then, we removed the methanol and dimethylamine from the samples using a rotary evaporator at 10 °C and −0.1 MPa. By ^{1}H NMR, we identified the remaining product as a mixture of *N*-dodecyl-*O*-methylacetimidate (**1a**) and *N*'-dodecyl-*N*,*N*-dimethylacetamidine (**1b**). Based on their ^{1}H NMR spectra, we calculated the normalized concentrations of **1a** and **1b** at different reaction times.

General Synthesis of *N*'-Alkyl-*N*,*N*-Diethylacetamidines

We obtained purified *N*-hexadecyl-*O*-methylacetimidate (**3a**) and *N*-octadecyl-*O*-methylacetimidate (**4a**) by the method described above in section "General Procedure for the Synthesis of *N*-alkyl-*O*-Methylacetimidates". We put the obtained *N*-hexadecyl-*O*-methylacetimidate (1.48 g, 0.005 mol) into a three-neck round-bottom brown flask and reacted it with diethylamine (7.31 g, 0.1 mol) in the solvents triethylamine (20 mL) and dioxane (30 mL) at 85 °C (reaction temperature) for 36 h. After the reaction, we removed the volatile components from the mixture, including diethylamine and the solvents triethylamine and dioxane, using a rotary evaporator at 60 °C and −0.1 MPa for 30 min, obtaining *N*'-hexadecyl-*N*,*N*-diethylacetamidine (**3c**, 60.5% yield) as a yellow liquid. We also synthesized *N*'-octadecyl-*N*,*N*-diethylacetamidine (**4c**, 53.7% yield) by the same method, using 1.63 g *N*-octadecyl-*O*-methylacetimidate (0.005 mol) as the reactant.

N'-hexadecyl-*N*,*N*-diethylacetamidine (**3c**): Yellow oil, ^{1}H NMR (500 MHz, $CDCl_3$) δ = 7.27 (s, 1H), 3.29 (q, 4H), 3.17 (t, 2H), 1.87 (s, 3H), 1.52–1.47 (m, 2H), 1.30–1.26 (m, 26H), 1.08 (t, 6H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 156.57, 49.73, 41.68, 32.31, 31.46, 29.68–27.38, 22.65, 14.34, 14.04, 13.67; HRMS m/z (ESI) calcd for $C_{22}H_{46}NO$ $(M+H)^+$ 339.3733, found 339.3752; IR absorption $W_{-N=C-N-}$ at 1620.76 cm^{-1}.

N'-octadecyl-*N*,*N*-diethylacetamidine (**4c**): Yellow oil, ^{1}H NMR (500 MHz, $CDCl_3$) δ = 7.27 (s, 1H), 3.29 (q, 4H), 3.17 (t, 2H), 1.88 (s, 3H), 1.53–1.48 (m, 2H), 1.30–1.26 (m, 30H), 1.08 (t, 6H), 0.88 (t, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 156.55, 49.77, 41.63, 32.32, 31.89, 29.67– 26.94, 22.64, 14.34, 14.03, 13.67; HRMS m/z (ESI) calcd for $C_{22}H_{46}NO$ $(M+H)^+$ 367.4046, found 367.4064; IR absorption $W_{-N=C-N-}$ at 1621.46 cm^{-1}.

General Procedure for the Switchable Characterization Tests on *N*′-Octadecyl-*N*,*N*-Diethylacetamidine

We determined the conductivity of the solution bubbled by CO_2 or N_2 using a DDSJ-308F conductivity meter (Shanghai Leici, China) and controlled the gas-flow rate using a mass flow controller (Beijing Shengye, China). We bubbled the solution of DMSO and water (V_{DMSO}/V_{water} = 45 mL/5 mL) with *N*′-octadecyl-*N*,*N*-diethylacetamidine (**4c**, 0.22 g) by CO_2, followed by N_2 at 65 °C, during which we recorded the conductivity. We obtained four reversible cycles by bubbling CO_2 (400 mL/min) for 40 min and then N_2 (800 mL/min) for 40 min. We also determined the conductivity of the solution containing purified *N*-octadecyl-*O*-methylacetimidate (**4a**, 0.08 g) using the same method as that in the blank experiment. We examined the capability of stabilizing an emulsion by mixing dodecane and water (5 mL, *v*/*v* = 1:1) containing *N*′-octadecyl-*N*,*N*-diethylacetamidine (**4c**, 0.022 g) and observed the state of the oil–water emulsion layers formed by the bubbling CO_2 at different stages.

Results and Discussion

Consecutive Reactions of Scoggins Procedure in the Presence of Excess Methanol

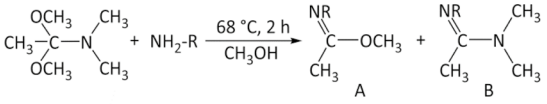
To effectively regulate product distribution in the Scoggins procedure, we conducted this reaction by varying the organic additives. Table 1 summarizes the reaction results based on the ^{1}H NMR characterization. Compared with the results (Fig. S2) obtained in experiment 1 using the Oszczapowicz' method [28] without any additives, we obtained a high *N*′-dodecyl-*N*,*N*-dimethylacetamidine (**1b**) yield of about 97.6% (Fig. S3) when using $NH(CH_3)_2$ as the additive, as developed by the Jessop et al. [21]. It seems that $NH(CH_3)_2$ can inhibit the formation of *N*-dodecyl-*O*-methylacetimidate. Interestingly, the addition of methanol (experiment 3) led to a dramatic decrease in the yield of **1b**, which represents only 28.3% of the total conversion of dodecylamine, whereas we found **1a** to be the only by-product with a yield of 71.7% (Fig. S4). This remarkable decline in the acetamidine yield and the formation of such a large amount of acetimidate demonstrates that the presence of methanol may control the product distribution to a great extent.

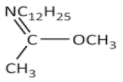
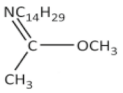
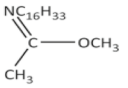
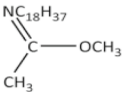
To further understand the reaction path of the Scoggins procedure in the presence of excess methanol, we designed an experiment (experiment 3), in which we performed interval sampling during the reaction process to obtain a detailed product distribution as a function of the reaction time. We used ^{1}H NMR to analyze the relative selectivity of acetamidine and acetimidate during the reaction. Figure 1 shows plots of the evolution of the selectivities of **1a** and **1b** versus reaction time. In Fig. 1, we can see that the selectivity of **1b** increases rapidly to its peak within 2 min and then decreases slowly until reaching a constant selectivity of 28.1%, whereas the selectivity of **1a** increases gradually until reaching 71.9% at 120 min. These results indicate that the process is likely a consecutive reaction, in which **1b** is easily formed as an intermediate in the first step and then reacts with methanol to generate **1a** in the second step. The fact that **1b** is readily generated in this reaction may be due to a bimolecular nucleophilic substitution reaction (SN2) between *N*,*N*-dimethylacetamide dimethyl acetal with high electrophilicity and the nucleophilic reagent dodecylamine. This reaction may be constrained by a thermodynamic equilibrium, in which the excess methanol in the mixture promotes the generation of acetimidates.

To better confirm the consecutive reaction pathway of this reaction system, we performed a reaction between **1b** (synthesized during experiment 2 in advance) and methanol. Using ^{1}H NMR analysis, we identified only **1a** and **1b** in the resulting mixture by after removing the volatile phase from the samples in high vacuum conditions. Figure 2 shows the normalized concentrations of **1a** and **1b** in the samples as a function of reaction time. We can see that the normalized concentration of **1b** significantly decreases with reaction time, reaching a constant value of about 28.3% after about 90 min. The normalized concentration of **1a** shows the opposite trend at first and ultimately remains constant at 71.7%. The time required to reach the equilibrium concentration is about 90 min, which is shorter than that of the Scoggins procedure (120 min) in the conditions described above. These results indicate that **1a** is generated from the reaction between **1b** and methanol, thereby providing further evidence that the Scoggins procedure involves a consecutive reaction. In addition, the higher selectivity of **1b** at the beginning stage of the Scoggins procedure and the lower equilibrium yield of **1b** due to the limiting effect of the thermodynamic equilibrium prove that the reaction of **1b** with methanol in the second step is the control step for the formation of **1a**.

Based on the above findings, we successfully synthesized a class of *N*-alkyl-*O*-methylacetimidates (**A**, Fig. S1) by enhancing the Scoggins procedure with the excess methanol (using the same reaction conditions as experiment 3 in Table 1). As listed in Table 2, all the yields of **A** are around 70% (Figs. S4–S7), which means that all these reactions reach roughly the same level of equilibrium regardless of the different hydrophobic groups of the primary amines. Next, we purified a series of product **A** to colorless liquids using flash column chromatography with Al_2O_3 as the stationary phase and ethyl acetate/hexane (*v*/*v*, 2:3) as the eluent. We then confirmed the resulting structures by HRMS (Figs. S8–S11), ^{1}H NMR (Figs. S14,

Table 2 Yield of **A** in experiment 3 of Table 1



Entry	R-group	Products	$Yield_A$[a] (%)	$Yield_B$[b] (%)	$Purity_A$[c] (%)
1	$C_{12}H_{25}$		71.7	28.3	100
2	$C_{14}H_{29}$		72.2	27.8	100
3	$C_{16}H_{33}$		70.4	29.6	100
4	$C_{18}H_{37}$		69.1	30.9	100

The conversion of primary amines is 100%

[a]The acetimidates yield was calculated based on the relative integration of the peak at $\delta_H = 3.60$ with respect to $\delta_H = 2.87$, which represents the groups of $-O(CH_3)$ and $-N(CH_3)_2$, respectively

[b]The acetamidines yield was calculated based on the relative integration of the peaks at $\delta_H = 2.87$ and $\delta_H = 3.60$

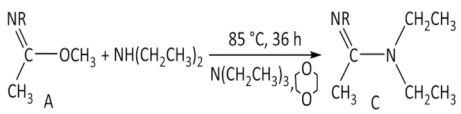
[c]We observed no characteristic peak at $\delta_H = 2.87$

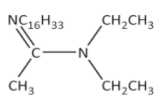
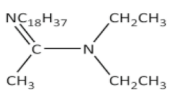
S17, S20, S23), ^{13}C NMR (Figs. S15, S18, S21, S24), and IR spectroscopy (Figs. S32–S35). Taking into consideration the characteristic of the equilibrium reaction, these acetimidates might have potential for use as precursors in the preparation of novel acetamidines via reactions with different primary or secondary amines.

Synthesis of Novel Acetamidines via Acetimidates

To verify the feasibility of generating new acetamidines from acetimidates, we performed a series of reactions between purified **A** and $NH(CH_2CH_3)_2$. As expected, we successfully produced two *N*'-alkyl-*N*,*N*-diethylacetamidines (**C**) with a diethyl group linked to the amidine group for the first time via a displacement reaction (Table 3) with an

Table 3 Production of acetamidines from acetimidates



Entry	R-group	Products	$Conversion_A$[a] (%)	$Yield_C$[b] (%)
1	$C_{16}H_{33}$		60.5	60.5
2	$C_{18}H_{37}$		53.7	53.7

The selectivity to **C** is 100%, from which **C** is obtained as the exclusive product

[a]The conversion of acetimidates

[b]The yields of **3c** and **4c** were calculated from the relative integration of the quartet near $\delta_H = 3.30$ (4H, $-N(CH_2CH_3)_2$) [30] with the triplet at $\delta_H = 3.60$ (3H, $-OCH_3$) based on the ^1H NMR spectrum

extremely high selectivity of nearly 100%. We confirmed the structures of *N*'-hexadecyl-*N*,*N*-diethylacetamidine (**3c**) and *N*'-octadecyl-*N*,*N*-diethylacetamidine (**4c**) by HRMS (Figs. S12, S13), ^{1}H NMR (Figs. S26, S29), ^{13}C NMR (Figs. S27, S30) and IR spectroscopy (Figs. S36, S37). The quartets at $\delta_H = 3.29$ in the ^{1}H NMR spectra and at $\delta_C = 41.68$ in the ^{13}C NMR spectra indicate methylene in the -N(CH_2CH_3)$_2$ group. We also detected solution peaks of trace 1,4-dioxane at $\delta_H = 3.70$ and $\delta_C = 67.03$ [30]. This strategy opens a new possible way to design and efficiently synthesize novel acetamidines with various terminal alkyl groups by simply replacing NH(CH_2CH_3)$_2$ with other dialkylamines.

CO_2-Triggered Switchable Characterization of Novel Acetamidines

Next, we examined the CO_2/N_2 switchability of *N*'-octadecyl-*N*,*N*-diethylacetamidine by monitoring the conductivity in wet dimethyl sulfoxide. As shown in Fig. 3, *N*'-octadecyl-*N*,*N*-diethylacetamidine (**4c**) exhibited excellent switchability when CO_2 and then N_2 were bubbled through the solution over four cycles, which indicates the reversible transformation between neutral amidine and bicarbonate ions. We also examined the capability of *N*'-octadecyl-*N*,*N*-diethylacetamidine bicarbonates salts to stabilize an emulsion by mixing dodecane and water containing **4c**. As shown in Fig. 4, the two immiscible phases became a homogeneous emulsion after the bubbling of CO_2. When kept at room temperature for 12 h, the emulsion volume still accounted for about 90% of the oil–water system, including a thin cloudy liquid at the bottom of the measurement cylinder (Fig. 4c). Then, bubbling N_2 rapidly breaks the emulsion into two separate phases (Fig. 4d). The conductivity and emulsification tests

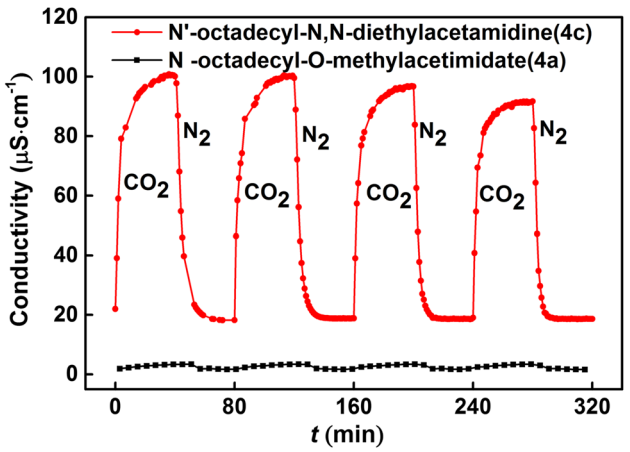


Fig. 3 Conductivity of wet DMSO solution containing **4c** and purified **4a** as a function of time during four cycles of treatment with CO_2 followed by N_2. Conditions: $T = 65$ °C, $V_{DMSO}/V_{water} = 45$ mL/5 mL, $F_{CO2} = 400$ mL/min, 40 min, $F_{N2} = 800$ mL/min, 40 min; **4c**: 0.22 g/50 mL; **4a**: 0.08 g/50 mL (as blank experiment)

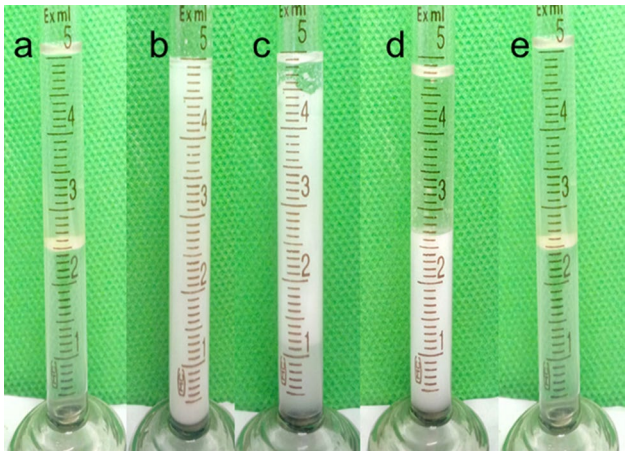


Fig. 4 Photographs of dodecane/water system (5 mL, *v*/*v* = 1:1) containing **4c** (0.022 g) at different stages. **a** Sample a after shaking for 5 min without CO_2 at 25 °C; **b** sample b bubbled with CO_2 at 25 °C; **c** sample c standing for 12 h at 25 °C; **d** sample d bubbled with N_2 for 30 min at 45 °C; **e** dodecane/water containing **4a** (0.011 g) after bubbling CO_2 for 5 min at 25 °C

containing only **4a** evidenced that the rest of **4a** had little effect and can be ignored. These results demonstrate that the synthesized *N*'-alkyl-*N*,*N*-diethylacetamidines have CO_2/N_2 switchability in the emulsification and demulsification of the oil–water system.

Conclusions

In conclusion, in this study, we developed a new approach for synthesizing CO_2-triggered switchable surfactants by the reaction between amines and imidates, produced using an enhanced Scoggins procedure. This reaction process consists of two reactions in a series, and the yield of acetimidates can be significantly improved by shifting the reaction equilibrium using excess methanol as an additive. This method provides an effective route for synthesizing varieties of CO_2/N_2 switchable acetamidines with the desired functional groups bonded to the amidine group.

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