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Condition-Determined Multicomponent Reactions of 1,3-Dicarbonyl Compounds and Formaldehyde

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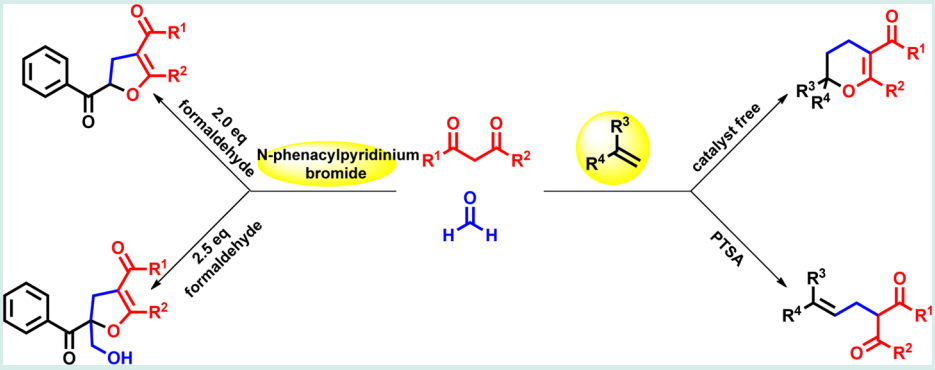
Supporting Information



ABSTRACT: By means of changing the reaction parameters, different products could be generated selectively starting from the same combination of substrates involving 1,3-dicarbonyl compounds and formaldehyde. This strategy enabled us to access diverse molecules without changing both starting material and reactor, maximizing thus the multifunctionality of the synthetic system. For example, starting from a 1,3-dicarbonyl compound, formaldehyde and 1,1-diphenylethylene, two kinds of products could be selectively formed including (i) a densely substituted dihydropyran and (ii) a C2-cinnamyl substituted 1,3-dicarbonyl compound. A one-pot three-component reaction of phenacylpyridinium salt, 1,3-dicarbonyl compound, and formaldehyde was also investigated, which produced either 2,4-diacyl-2,3-dihydrofuran or 2,4-diacyl-2-hydroxylmethyl-2,3-dihydrofuran in good to excellent yield.

KEYWORDS: *multicomponent reactions, diversity-oriented synthesis, condition-determined MCR, combinatorial chemistry*

INTRODUCTION

Multicomponent reactions (MCRs) are convergent reactions of three or more starting materials, which have emerged as an efficient method for rapidly generating complex molecules with diverse functional substituents.[1] MCRs have often been used to establish expedient and ecofriendly chemical methods for the discovery of new chemical entities required by pharmaceutical and agrochemical industries.[2] Most MCRs were established by a reaction sequence involving (i) generation of an active intermediate through a reaction of the first two or three components and (ii) trapping of the intermediate with the same or another component. The generated intermediates generally have a very high reactivity, which enabled us to construct new molecular scaffolds sometimes. Therefore, most of the research interests focus on either the exploration of a suitable trapping reagent or derivatization of the intermediate with the hope of establishing a new reaction sequence.[3] However, there is a perceived challenge in the face of the ever increasing demand for novel medicinally active compounds. This forced us to think how to maximize the efficiency of establishing molecule libraries for biological screening.

Control of the reaction selectivity, for example, chemo-, stereo-, and regioselectivity, is one of the most important objectives of organic chemistry.[4] Many different reaction parameters such as temperature, pressure, solvent, and catalyst type, and other factors can be utilized to modulate the selectivity of organic reactions. Because three or more substrates are involved in a MCR, it is conceivable that by carefully manipulating the reaction parameters, it might be possible to establish two or more MCRs with the same combination of substrates. This strategy can increase the number of MCRs without increasing the number of substrates. Previously, a few reports have disclosed some individual examples of the synthesis of different products from the same substrates.[5] It offered an effective means to us for enriching the diversity of

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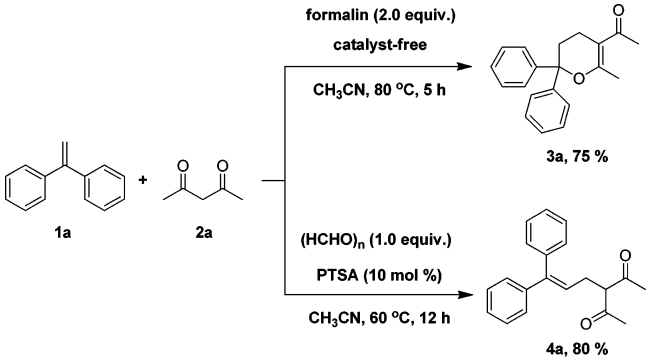
the MCR product libraries, which in turn facilitates biological screening.

We were attracted by the unique advantages of this strategy and started a research program on this topic some time ago. To utilize this strategy, we have to find a suitable intermediate, which not only has a high reactivity but also is amenable to diversified reaction modes, allowing us to trap it in different reaction pathways. Recently, the Knoevenagel reaction of 1,3-dicarbonyl compounds and formaldehyde has been used to create MCRs.[6] The generated 2-methylene-1,3-dicarbonyl intermediate not only acts as an *oxo*-diene in Diels–Alder reaction but also serves as a Michael acceptor in conjunction with some Michael donors, favoring thus construction of many MCRs.[7] We were attracted by the multifunctionality of this intermediate and started our MCR investigation with a combination of 1,3-dicarbonyl compounds and formaldehyde.

RESULTS AND DISCUSSION

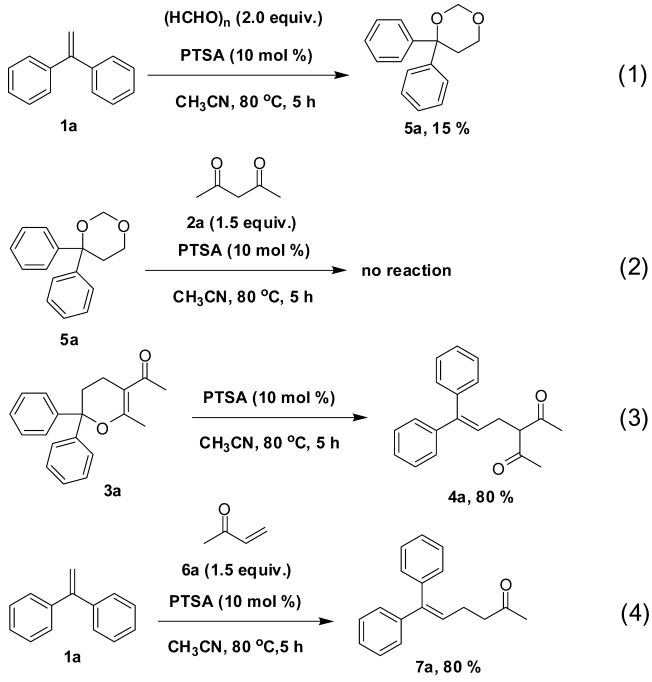
Initially, a three-component reaction of 1,1-diphenylethylene **1a**, acetoacetone **2a**, and formaldehyde was investigated. As shown in Scheme 1, when formalin was used as HCHO source, a dihydropyran **3a** was obtained in 75% yield after 5 h of reaction at 80 °C in acetonitrile. The reaction is very clean, and the unreacted 1,1-diphenylethylene can be fully recovered. Interestingly, when paraformaldehyde was used as the HCHO source, a different compound, **4a** was obtained in 80% yield in the presence of toluenesulfonic acid (PTSA) at 60 °C. These results imply that the source of HCHO and the reaction conditions played key roles in controlling the reaction selectivity.

Scheme 1. Three-Component Reaction of 1a, 2a, and Formaldehyde



These results also gave us impetus to investigate the reaction mechanism. It is well-known that **3a** was formed through a tandem Knoevenagel/oxo-Diels–Alder reaction pathway, in which **1a** acted as a dienophile to trap the generated 3-methylene-2,4-pantadione (intermediate **I**, Figure 1).[8] In order to shed light on the mechanism for the formation of **4a**, several control experiments were then carried out. First, although the Prins cyclization product of **1a** and paraformaldehyde, **5a**, could be formed with the aid of PTSA catalyst, it cannot be converted into **4a** under the reaction conditions (Scheme 2). Because **3a** could be also detected during the

Scheme 2. Control Experiments for Understanding the Mechanism of 4a Formation



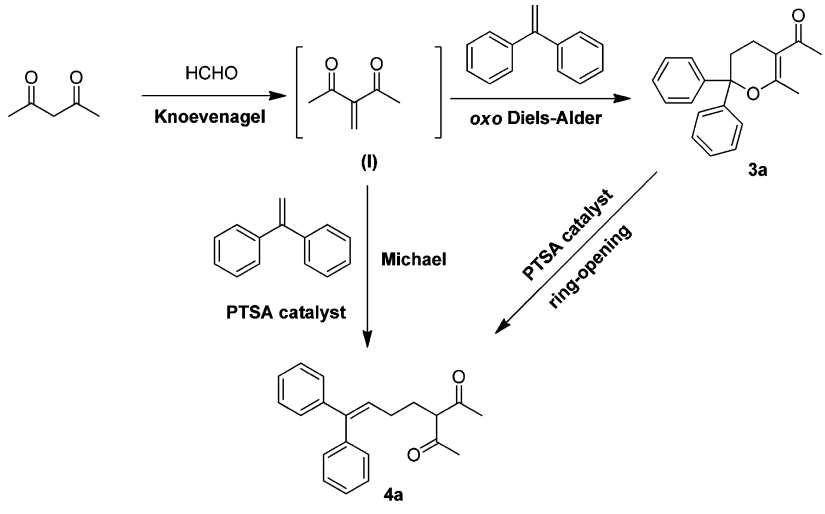


Figure 1. Proposed mechanism for the formations of **3a** and **4a**.

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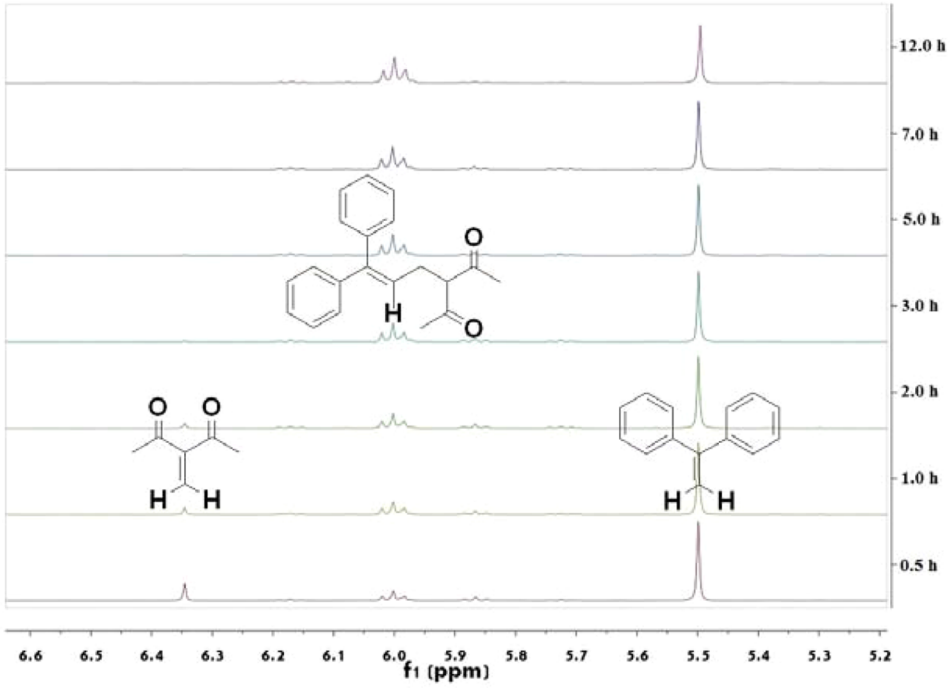

Figure 2. Progress of a PTSA-catalyzed reaction of **1a**, **2a**, and paraformaldehyde monitored by ^{1}H NMR.

reaction forming **4a** (Figure 2), we therefore treated **3a** with PTSA in acetonitrile. After 5 h of reaction at 80 °C, **4a** was formed in 80% of yield. However, this result is insufficient to lead us to draw a conclusion for the formation of **4a** because kinetic investigation of the reaction between **1a**, **2a**, and paraformaldehyde revealed that no significant accumulation of **3a** was observed during the reaction (Figure S2, Supporting Information). In addition, monitoring of the reaction progress by means of ^{1}H NMR demonstrated that (i) intermediate **I** was generated quickly in the first 30 min of the reaction and then its concentration gradually decreased and (ii) the formation of **4a** occurred in the beginning of the reaction and lasted all 12 h as the concentration of **4a** increased gradually during the reaction. All these results led us to deduce that **4a** might be formed through a direct Michael reaction of the intermediate **I** and **1a**. Because the isolation of pure intermediate **I** is not possible, methyl vinyl ketone **6a** was therefore used as a Michael acceptor, which has a relatively lower reactivity than the intermediate **I**. As shown in Scheme 2, the expected product **7a** was obtained in 80% of yield. This result implies that **4a** might be formed through a tandem Knoevenagel/Michael reaction pathway. Incidentally, because Knoevenagel/oxo-Diels–Alder reaction is a noncatalytic reaction sequence, formation of **3a** is inevitable during the synthesis of **4a**. A Knoevenagel/oxo-Diels–Alder/ring-opening reaction sequence may be also operative for the formation of **4a** (Figure 1). The ring-opening reaction pathway is able to convert **3a** into **4a**, ensuring thus a good selectivity of **4a**.

The PTSA/acetonitrile system was successfully used to establish the three-component reactions of a wide range of 1,3-dicarbonyl compounds, $(HCHO)_n$, and 1,1-diarylethylenes, and the results are shown in Figure 3. Many linear β-ketoesters or 1,3-diketones reacted readily with **1a** and paraformaldehyde, affording the corresponding products in generally excellent yields. Cyclopropyl and methoxy groups are tolerable in this system (**4g**). A secondary β-ketoamide can also be used uneventfully (**4i**). Some other 1,1-diphenylethylene derivatives could also be used. Particularly, a diarylethylene with thienyl group participated readily in this reaction as well (**4l**). It is significant to note that **1a** could be replaced by 1,1-diphenylethanol, which is less-expensive compared with **1a**, in this reaction. This offered a cost-effective alternative route to access **4a**-type products (Scheme 3). It should be noted also that the same products in Figure 3 could be synthesized by many reported methods, most of which involve the use of harsh conditions and expensive reagents and suffer from the lack of simplicity and also the yields and selectivities reported are sometimes far from satisfactory.[9] Therefore, the present three-component reaction opened a simple and effective route to access these compounds. However, attempts to use normal 1-arylethylenes, such as 4-methylstyrene and α-methylstyrene, as substrates in the PTSA/acetonitrile system were in vain. The reactions suffered from a lack of selectivity as messy mixtures were formed in these cases. By the same token, formaldehyde cannot be replaced by other aliphatic or aromatic aldehydes in this reaction.

The above-mentioned results demonstrated that the development of condition-determined MCRs based on a combination of a 1,3-dicarbonyl compound and formaldehyde is indeed possible. Encouraged by these results, we then investigated the condensation reaction of *N*-phenacylpyridinium bromide **7a**, 1,3-cyclohexanedione **2b**, and formaldehyde, which can hopefully produce a 2,4-diacyl-2,3-dihydrofuran derivative, **8a** through a cascade Knoevenagel/[4 + 1] annulation reaction under appropriate conditions.[10] The reaction was also triggered by a Knoevenagel condensation of **2b** with formaldehyde, which generated a 2-methylene-1,3-cyclohexanedione intermediate (**II**) that can be trapped by phenacylpyridinium salt through [4 + 1] annulation reaction (Figure 4). As shown in Table 1, a product was indeed formed in the presence of an inorganic base, $K_2HPO_4{\cdot}3H_2O$, in DMSO; however, it was the hydroxymethylation product of the expected one, **8a**′. Because compound **8a** was also detected at the end of the reaction, we therefore deduced that **8a**′ might be formed through a cascade

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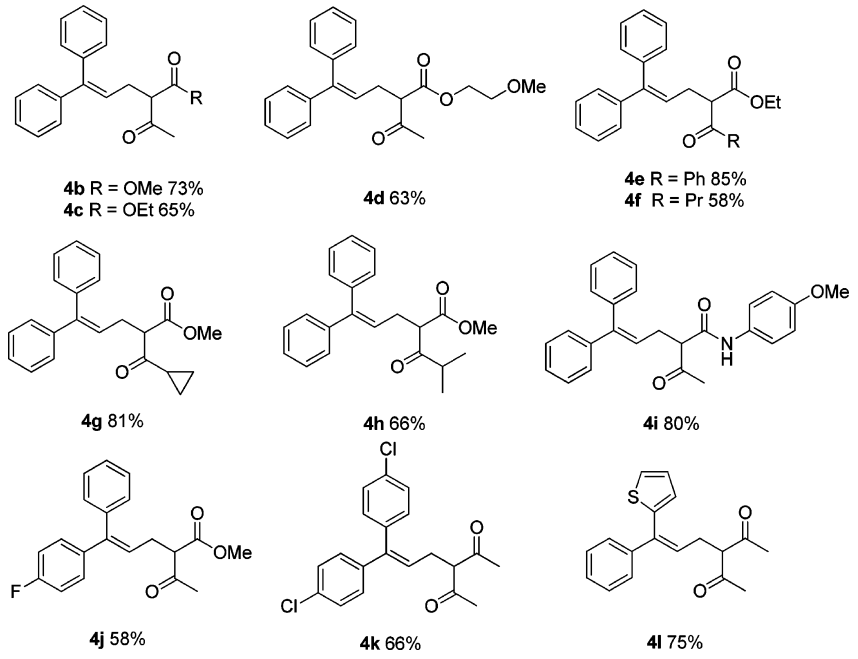
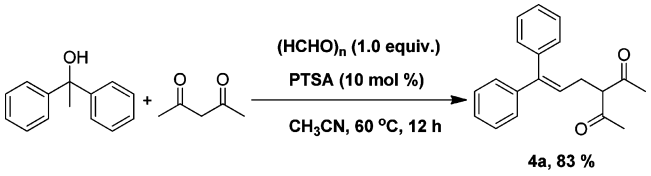


Figure 3. PTSA-catalyzed three-component reaction of 1,1-diarylethylene, 1,3-dicarbonyl compounds, and $(HCHO)_n$.

Scheme 3. PTSA-Catalyzed Three-Component Reaction of 1,1-Diphenylethanol, 2a, and Paraformaldehyde



Knoevenagel/[4 + 1] annulation/hydroxymethylation reaction (Figure 4). Indeed, treatment of **8a** in DMSO in the presence of paraformaldehyde resulted in an evident formation of **8a**′ (Scheme 4). To our great delight, the quasi-four-component reaction was found to be very efficient, and the yield of **8a**′ reached 83% after 4 h of reaction at 80 °C (entry 1). This observation encouraged us to scrutinize the effects of reaction parameters including base, solvent, and reaction temperature. No or only trace amount of product was obtained with inorganic bases, such as $K_3PO_4{\cdot}3H_2O$ and K_2CO_3 (entries 2 and 3). Organic bases like NEt_3 and DBU were also ineffective for this reaction (entries 4 and 5). Among different solvents tested in the reaction, DMSO clearly stood out, producing **8a**′ with the highest yield, with DMF and acetonitrile in a distant second place (ca. 40% yields). PEG400, ionic liquid [BMIm]-BF_4, and water resulted in significantly lower efficiency of the reaction (entries 8 to 10). Ratio of **7a**/**2b**/HCHO can also significantly affect the yield of **8a**′, and the best is **7a**/**2b**/HCHO = 1.0/2.0/2.5. Poor yields were obtained with much excess of **2b** or HCHO, which might result from an extensive formation of a byproduct through Knoevenagel/Michael reaction of **2b** and HCHO (entries 11 and 12). Interestingly, when ratio of the **7a**/**2b**/HCHO was changed to 1.0/1.5/2.0, **8a** was produced as a major product, and **8a**′ was formed only in tiny amounts (entry 13). These results imply that substrate ratio has a subtle influence on the reaction selectivity, and amounts of **2b** and formaldehyde are both important to determine the reaction selectivity. It offered us a possible means to control the reaction selectivity by tuning the reaction parameters. It should be noted that, in all the previous reports on Knoevenagel/[4 + 1] annulation sequential reaction of

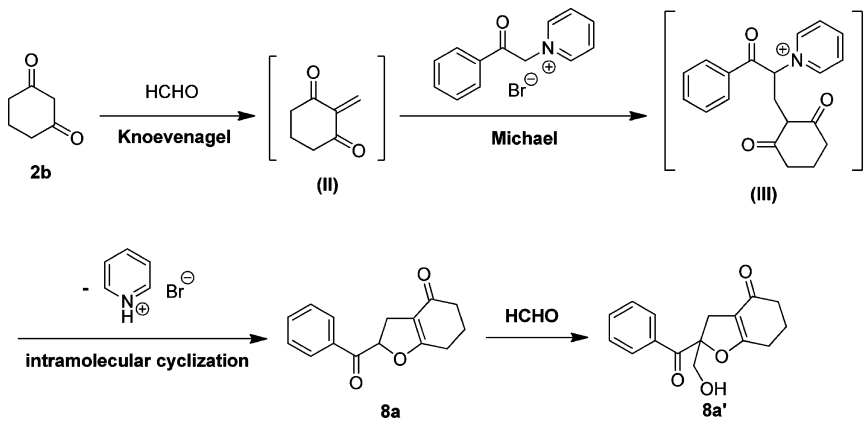


Figure 4. Proposed mechanism for the formation of **8a** and **8a**′.

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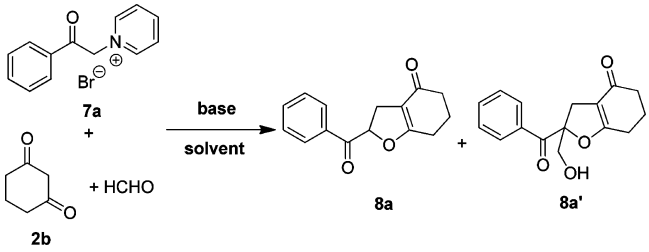
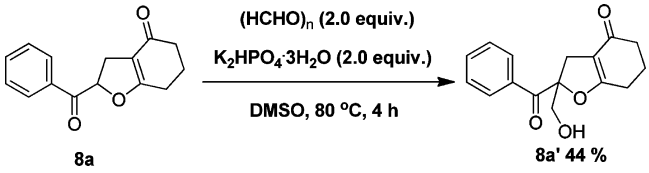
Table 1. Three-Component Reaction of *N*-Phenacylpyridinium Bromide, Acetylacetone, and Formaldehyde under Different Conditions[a]



entry	base	solvent	ratio of 7a/2b/HCHO	temp (°C)	yield (%) 8a	yield (%) 8a′
1	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	80	<5	**83**
2	$K_3PO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	80	<5	<5
3	K_2CO_3	DMSO	1.0/2.0/2.5	80	0	0
4	Et_3N	DMSO	1.0/2.0/2.5	80	8	5
5	DBU	DMSO	1.0/2.0/2.5	80	0	0
6	$K_2HPO_4{\cdot}3H_2O$	DMF	1.0/2.0/2.5	80	<5	36
7	$K_2HPO_4{\cdot}3H_2O$	CH_3CN	1.0/2.0/2.5	80	<5	39
8	$K_2HPO_4{\cdot}3H_2O$	PEG400	1.0/2.0/2.5	80	<5	<5
9	$K_2HPO_4{\cdot}3H_2O$	$[BMIm]BF_4$	1.0/2.0/2.5	80	9	<5
10	$K_2HPO_4{\cdot}3H_2O$	H_2O	1.0/2.0/2.5	80	8	<5
11	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/1.0/2.0	80	<5	67
12	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.5/3.0	80	9	22
13	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/1.5/2.0	80	**80**	<5
14	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	50	0	5
15	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	100	5	10
16[b]	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	80	24	51
17[c]	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	80	<5	11
18[d]	$K_2HPO_4{\cdot}3H_2O$	DMSO	1.0/2.0/2.5	80	0	0

[a]Conditions: **1a**, 1.0 mmol; paraformaldehdye was used as HCHO source; solvent 1.0 mL; reaction time 4 h. [b]Reaction time 2 h. [c]Aqueous solution of formaldehyde was used as HCHO source. [d]Trioxymethylene was used as HCHO source.

Scheme 4. Hydroxymethylation of 8a to 8a′



phenacylpyridinium salt, the use of aromatic aldehyde is mandatory in order to facilitate control of the reaction selectivity.[11] The present synthesis of **8a**-like 2,3-dihydrofurans represents the first example of using nonaromatic aldehyde as substrate. Additionally, the reaction was also affected by temperature and reaction time, and the maximum yield of **8a′** was obtained at 80 °C after 4 h of reaction (entries 14 to 16). It is worthwhile to note that, under the optimal conditions, efforts to replace paraformaldehyde with either formalin (37 wt %) or trioxymethylene were in vain (entries 17 and 18).

We also probed the scope of the reaction with respect to both the pyridinium bromide and the 1,3-dicarbonyl compounds. As evidenced by the results in Table 2, *N*-phenacylpyridinium bromides with both electron-donating and moderately electron-withdrawing groups smoothly reacted with **2b**, producing 2-hydroxymethylated 2,3-dihydrofuran derivatives in generally good yields (entries 1−5). By decreasing the ratio of **7**/**2**/HCHO, we are able to suppress the hydroxymethylation. Particularly, when *N*-(4-methoxyphenacyl)pyridinium bromide was used, yield of the tandem Knoevenagel/[4 + 1] annulation product, **8e**, reached 95% with the ratio of **7**/**2**/HCHO = 1.0/1.5/2.0. However, increasing the ratio to 1.0/2.0/2.5 was in vain to obtain its hydroxymethylated counterpart, **8e′**. In this case, high excess of paraformaldehyde has to be used in order to get a good yield of **8e′** (entry 4). Acetoacetone **2a** reacted readily with **7a** and formaldehyde; however, extra effort has to be paid to control the reaction selectivity because change of the substrate ratio cannot alter significantly the product distribution. Addition of solvent amount of xylene, which constructed a biphasic system along with DMSO, proved to be an effective way to suppress the hydroxymethylation reaction of **8g** (entry 6). In order to get **8g′**, the reaction has to be performed at 30 °C. Fortunately, when the other *N*-phenacylpyridinium bromide derivatives were used to react with **2a**, it was quite easy to control the reaction selectivity. In the presence of a large excess of paraformaldehyde, the hydroxymethylated product will be preferentially formed as usual, whereas the major products are the non-hydroxymethylated 2,3-dihydrofurans when the ratio of **7**/**2b**/HCHO is 1.0/2.0/2.5 (entries 7−14). This strategy is particularly effective for tuning the selectivity of condensation between *N*-(4-phenylphenacyl)pyridinium bromide, **2a**, and formaldehyde. Both hydroxymethylated and nonhydroxymethylated products could be obtained in more than 90% yields in this case (entry 10). 1-(2-Naphthoylmethyl)pyridinium bromide also proved to be an eligible substrate that reacted smoothly with either **2b** or **2a**, providing both hydroxymethylated and nonhydroxymethylated products in good yields (entries 5 and 11). It should be noted that the OH group in the phenacylpyridinium salt can be delivered uneventfully (entry 12). This facilitates further conversions of the obtained 2,3-dihydrofurans. A heterocyclic group, such as thienyl, is also tolerable in the present reaction (entry 13). Reactions with *β*-ketoesters also proceeded very well, and the products succeeded the ester moieties without any damage (entries 14−17). The ether fragment in 2-methoxyethyl acetoacetate is also tolerable. Due to an insusceptibility of the reaction toward the change of the substrate ratio, the DMSO/xylene biphasic system was employed when methyl isobutyrylacetate and 2-methoxyethyl acetoacetate were used to react with **7a** (entries 16 and 17). It should be noted that when an aqueous solution of acetaldehyde was used instead of paraformaldehyde, no expected substituted dihydrofuran derivative was formed.

Because the hydroxymethylated products contain some reactive groups, we suspected that these molecules might be susceptible under acidic conditions. As we expected, treatment of **8g′** in ethanol in the presence of $Sc(OTf)_3$ resulted in selective formation of diphenyl derivative **9a** (Scheme 5). The existence of the hydroxyl group in **8g′** proved to be crucial for rendering this reaction possible because no reaction was observed when **8g** was used as substrate under the identical conditions. The initial step of the reaction might be an intramolecular ring-opening and ring-closing reaction of **8g′** with the aid of acid catalyst, which generated an epoxide intermediate (**IV**). The following ring-opening of **IV** with ethanol produced an intermediate **V** that underwent an intramolecular aldol reaction[12] and subsequent retro-Claisen condensation[13] to form the final product **9a**. This reaction not only displayed an interesting reaction sequence but also offered us the first

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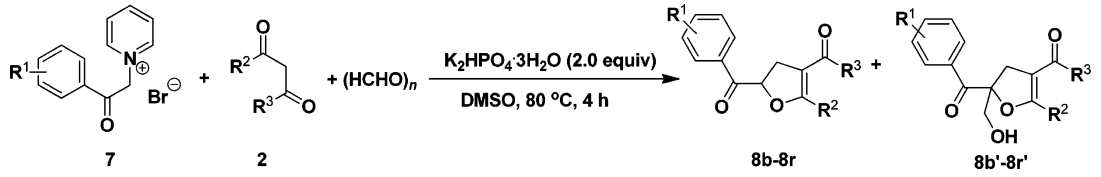
Table 2. Substrate Scope of Three-Component Reaction of *N*-Phenacylpyridinium Bromides, 1,3-Dicarbonyl Compounds, and Paraformaldehyde[a]



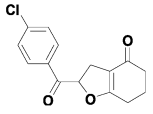
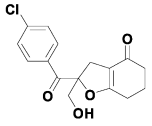
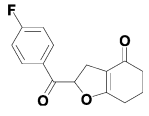
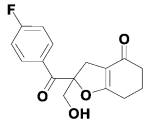
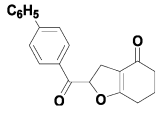
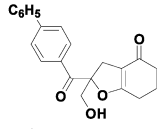
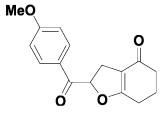
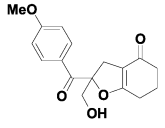
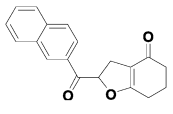
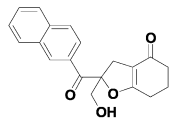
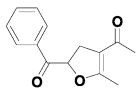
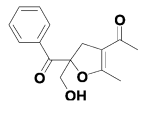
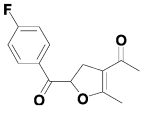
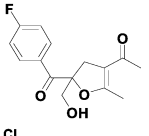
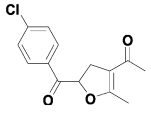
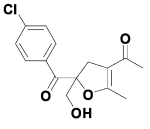
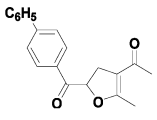
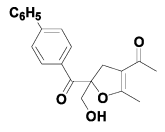
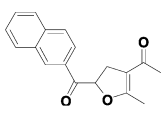
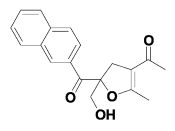
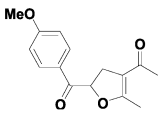
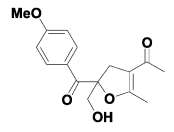
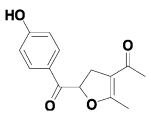
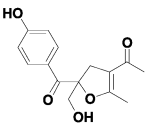
entry	**1**/**2**/HCHO	major product		yield (%)[b]	**1**/**2**/HCHO	major product		Yield (%)[b]
1	1.0/1.5/2.0		**8b**	74 (12)	1.0/2.0/2.5		**8b'**	60 (14)
2	1.0/1.5/2.0		**8c**	62 (9)	1.0/2.0/2.5		**8c'**	68 (13)
3	1.0/1.5/2.0		**8d**	70 (8)	1.0/2.0/2.5		**8d'**	70 (10)
4	1.0/1.5/2.0		**8e**	95 (< 1)	1.0/2.0/7.0		**8e'**	71 (19)
5	1.0/1.5/2.0		**8f**	86 (7)	1.0/2.0/7.0		**8f'**	76 (14)
6	1.0/2.0/2.5		**8g**	82[c] (6)	1.0/2.0/2.5		**8g'**	85[d] (7)
7	1.0/2.0/2.5		**8h**	69 (16)	1.0/2.0/7.0		**8h'**	70 (11)
8	1.0/2.0/2.5		**8i**	73 (8)	1.0/2.0/7.0		**8i'**	51 (9)
9	1.0/2.0/2.5		**8j**	94 (< 5)	1.0/2.0/7.0		**8j'**	93 (< 5)
10	1.0/2.0/2.5		**8k**	72 (12)	1.0/2.0/7.0		**8k'**	57 (18)
11	1.0/2.0/2.5		**8l**	65 (17)	1.0/2.0/7.0		**8l'**	62 (15)
12	1.0/2.0/2.5		**8m**	75 (11)	1.0/2.0/7.0		**8m'**	50 (13)

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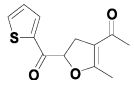
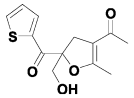
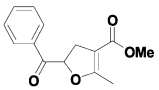
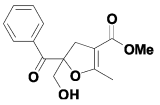
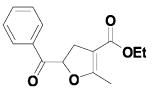
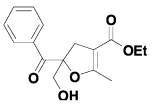
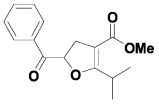
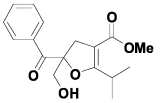
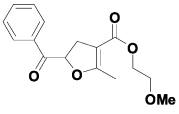
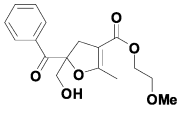
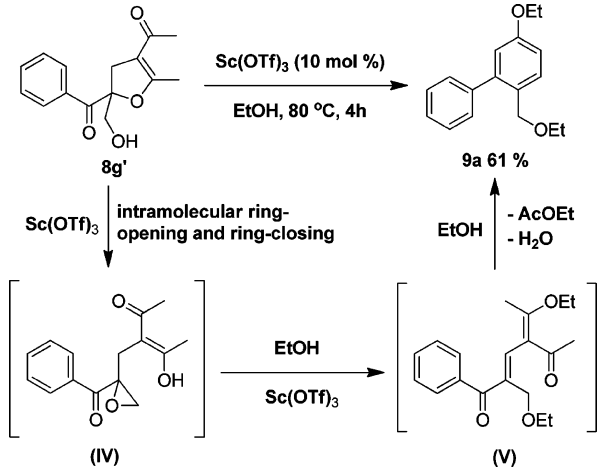
Table 2. continued

entry	1/2/HCHO	major product		yield (%)[b]	1/2/HCHO	major product		Yield (%)[b]
13	1.0/2.0/2.5		**8n**	81 (10)	1.0/2.0/7.0		**8n'**	61 (16)
14	1.0/2.0/2.5		**8o**	49 (8)	1.0/2.0/7.0		**8o'**	54 (< 5)
15	1.0/2.0/2.5		**8p**	60 (14)	1.0/2.0/7.0		**8p'**	71 (7)
16	1.0/2.0/2.5		**8q**	50[c] (9)	1.0/2.0/2.5		**8q'**	76 (13)
17	1.0/2.0/2.5		**8r**	50[c] (11)	1.0/2.0/2.5		**8r'**	97 (< 1)

[a]Conditions: *N*-Phenacylpyridinium bromide 0.5 mmol; DMSO 1.0 mL; $K_2HPO_4{\cdot}3H_2O$ 1.0 mmol; 80 °C, 4 h. [b]Value in parentheses is the yield of the minor product. [c]Xylene was added. [d]Reaction performed at 30 °C.

Scheme 5. Conversion of 8g′ to 9a



example that can produce aromatic ether from five-member ring heterocycles without oxidation.[14]

CONCLUSION

Some condition-determined MCRs of 1,3-dicarbonyl compounds and formaldehyde were reported. Reaction of a 1,3-dicarbonyl compound, formaldehyde, and 1,1-diphenylethylene produced either a densely substituted 3,4-dihydropyran or a C2-cinnamyl substituted 1,3-dicarbonyl compound. A pseudo-four-component reaction of *N*-phenacylpyridinium bromide, 1,3-dicarbonyl compound, and formaldehyde was also developed, which involved a hitherto unreported Knoevenagel/[4 + 1] annulation/hydroxymethylation reaction sequence. All these examples demonstrated that the concept of condition-determined MCR is indeed useful for divergence-oriented organic synthesis.

EXPERIMENTAL SECTION

General. Melting points were determined by microscopic melting point meter and were uncorrected. IR spectra were recorded on a FT-IR, Bruker (EQUINOX 55), using KBr pellets or neat liquid technology. ^1H and ^{13}C NMR spectra were recorded on a Bruker AV-400. Chemical shifts are expressed in ppm relative to Me_4Si in solvent. All chemicals used were of reagent grade and were used as received without further purification. All reactions were conducted in a 10 mL V-type flask equipped with triangle magnetic stirring.

Reaction of 1,1-Diarylethylene, 1,3-Dicarbonyl Compounds, and $(HCHO)_n$. In a typical reaction, the 1,3-dicarbonyl compound (0.2 mmol) was mixed with paraformaldehyde (0.2 mmol), 1,1-diarylethylene (0.25 mmol), and PTSA (0.02 mmol, 3.8 mg, 10% mol) in acetonitrile (1.0 mL), The mixture was then stirred at 60 °C for 12 h. After reaction, the mixture was cooled to room temperature, and the product was obtained by isolation with preparative TLC (eluting solution, petroleum ether/ethyl acetate = 5/1 (v/v)). Tests for substrate scope were all performed with an analogous procedure.

Three-Component Reaction of *N*-Phenacylpyridinium Bromides, 1,3-Dicarbonyl Compounds, and $(HCHO)_n$. *N*-Phenacylpyridinium bromide (0.25 mmol) was mixed with the 1,3-dicarbonyl compound (0.375 mmol), and paraformaldehyde (0.5 mmol). The mixture was then stirred at 80 °C for 4 h. After reaction, the mixture was cooled to room temperature, and the product 2,4-diacyl-2,3-dihydrofuran derivative was obtained by isolation with preparative TLC (eluting solution, petroleum ether/ethyl acetate = 10/1 (v/v)). Tests for substrate scope were all performed with an analogous procedure. The hydroxymethylation product was obtained by only changing the ratio of *N*-phenacylpyridinium bromide, 1,3-dicarbonyl compound, and paraformaldehyde to 1.0/2.0/2.5.

Synthesis of 9a from 8g′. Compound 8g′ (52 mg, 0.2 mmol) and $Sc(OTf)_3$ (10 mg, 10% mol) was added to ethanol

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(1 mL), and the mixture was then stirred at 80 °C for 4 h. After reaction, the product **9a** was obtained by isolation with preparative TLC (eluting solution, petroleum ether/ethyl acetate = 20/1 (v/v)) with yield of 61%.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional experimental details, reaction progress of the three-component reaction of **1a**, **2a**, and paraformaldehyde, characterization data of new compounds, and NMR spectra of compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

§Changhui Liu and Meng Shen contributed equally to this work.

Notes

The authors declare no competing financial interest.

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