

FULL PAPER

Biginelli reaction catalyzed by elemental bromine as a novel Lewis acid catalyst, under mild conditions

Eskandar Kolvari*  | Ali Arab  | Maryam Robati 

Department of Chemistry, Semnan University,
Semnan, P.O. BOX 35195-363, Semnan, Iran

In the present study, we discussed that, the elemental bromine is a highly efficient and selective homogeneous Lewis acid catalyst for the synthesis of 3,4-dihydropyrimidin-2(1*H*)-ones. Biginelli three-component condensation was carried out by the reaction of an aromatic aldehyde, urea/thiourea, and methyl/ethyl acetoacetate in ethanol, to afford the desired product in high yields. The influence of reaction parameters including the solvent type and the bromine quantity on catalytic activity were also investigated. In addition, the quantum computations were employed to clarify the effect of the Lewis acid catalyst. The structure of the products was validated using the FT-IR, ¹HNMR, and ¹³CNMR. Our procedure offered several advantages including, the mild reaction conditions, employing an inexpensive catalyst, and easy workup.

***Corresponding Author:**

Eskandar Kolvari

Email: kolvari@semnan.ac.ir

Tel.: +98 (23) 33654058

KEYWORDS

Elemental bromine; multi-component; one-pot synthesis; Biginelli reaction; quantum computations.

Introduction

Using compounds bearing electrophile bromine such as *N*-halo [1], tribromides [2] and molecular bromine as catalysts in organic synthesis is attractive because of broad synthesis and transformations such as protection [3,4], deprotection [5], oxidation [6] esterification [7], and synthesis of organic compounds *via* multicomponent reactions [8,9] can be easily accomplished at the presence of aforementioned compounds. Although inexpensive elemental bromine is considered to be a vital reagent in chemistry history [10,11], there are a few reports utilized it as a catalyst [12-16]. Despite the fact that the molecular iodine is expensive, it is used broadly as a catalyst because of its convenience and safety to use [17-20]. Meanwhile, inexpensive elemental bromine is neglected to be promising due to its high vapor

pressure and corrosiveness. Additionally, its solid alternatives, including various Lewis bases such as *N*-halo compounds and complexes of bromine [2], drew much attention. In most cases, molecular bromine is utilized as a starting material for preparing *N*-halo and tribromide compounds which are not consistent with atom-economy as a green chemistry principle. A detailed study about these alternatives using green metrics has been done by Eissen and Lenoir [21].

In recent years, accomplishing organic synthesis *via* multicomponent reactions has attracted attention from many research groups due to the improved reaction efficiency and atom economy [22-24]. Among the different multicomponent reactions, Biginelli reaction is prominent because of producing diverse biologically active 3,4-dihydropyrimidone derivatives [25-27].

Experimental Section

Material and Instruments

All the chemicals reagents were used without any further purification and purchased from the Merck and Aldrich chemical companies. Solvents were purified using the conventional methods. Fourier transform infrared spectroscopy (FT-IR) was recorded by a Shimadzu 8400s spectrometer using KBr pressed powder discs. The purity of products was checked by thin layer chromatography (TLC) using n-hexane/ethyl acetate mixture as a mobile phase. The melting points were recorded using the electrothermal 9100 apparatus and are uncorrected.

General Procedure

A mixture of aromatic aldehyde **1** (0.106 g, 1 mmol), urea/thiourea **2** (0.09/0.11 g, 1.5 mmol), methyl/ethyl acetoacetate **3** (0.116/0.130 g, 1 mmol), and ethanol (3 mL) in the presence of a solution of Br₂ (0.0025 mL, 0.097 mmol) in ethanol (1 mL) was stirred under reflux conditions at 85 °C. After completion of the reaction as indicated by TLC, the resulting mixture was cooled to room temperature and cold water was added. Afterwards, the precipitate was separated by filtration and suppressed with saturated aqueous solution of Na₂S₂O₃. The solid was recrystallized from the ethanol to afford the pure products.

Spectral Data

Methyl 3, 6-dimethyl-2-oxo-4-(p-tolyl)-1, 2, 3, 4-tetrahydropyrimidine-5-carboxylate (4a):

Mp: 199-202 °C; ¹HNMR (CDCl₃, 300 MHz): δ (ppm): 10.34 (s, 1H), 9.65 (d, 1H, NH), 7.16-7.08 (m, 4H), 5.13 (d, 1H), 3.54 (s, 3H), 2.29 (s, 3H), 2.26 (s, 3H); ¹³CNMR (CDCl₃, 75 MHz): δ (ppm): 174.2, 165.7, 145.2, 140.4, 136.9, 129.1, 126.2, 100.5, 53.6, 51.1, 20.7, 17.2;

IR(KBr) cm⁻¹: 3334, 3200, 2970, 1669, 1570, 1470, 1183.

Ethyl 6-methyl-2-oxo-4-(p-tolyl)-1, 2, 3, 4-tetrahydropyrimidine-5-carboxylate (4k):

Mp: 210-213 °C; ¹HNMR (CDCl₃, 300 MHz): δ (ppm): 8.75 (s, 1H, NH), 7.09-7.21 (m, 4H), 6.22 (s, 1H, NH), 5.34 (s, 1H), 4.04 (q, 2H), 2.3 (s, 3H), 1.15 (t, 3H); ¹³CNMR (CDCl₃, 75 MHz): δ (ppm): 14.16, 18.50, 21.09, 55.18, 59.93, 101.35, 126.45, 129.30, 137.52, 140.91, 146.41, 153.99, 165.74; IR(KBr)cm⁻¹: 3245.97, 3114.82, 2979.82, 1724.24, 1649.02.

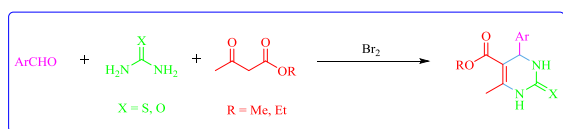
Ethyl 6-methyl-4-(3-nitrophenyl)-2-thioxo-1, 2, 3, 4-tetrahydropyrimidine-5-carboxylate (4s):

Mp: 208-210 °C; ¹HNMR (CDCl₃, 300 MHz): δ (ppm): 1.12 (t, 3H), 2.33 (s, 3H), 3.99-4.08 (m, CH₃CH₂), 5.36 (d, 1H), 7.65-7.72 (m, 2H), 8.09 (s, 1H, NH), 8.15-8.18 (m, 1H), 9.77 (s, 1H), 10.51 (s, NH); ¹³CNMR (CDCl₃, 75 MHz): δ (ppm): 14.4, 17.6, 53.9, 60.2, 100.3, 121.6, 123.1, 130.8, 133.4, 145.9, 146.4, 148.3, 165.3, 175.0; IR(KBr)cm⁻¹: 3363, 3232, 3114, 2976, 1691, 1631, 1571, 1458, 1365, 1311, 1301, 1255, 1231, 1146, 1092, 1020.

Results and discussion

To reach better insights about the effect of bromine in reactions progress, we tested bromine as a catalyst for the first time in the heterocycle chemistry by the construction of 3,4-dihydropyrimidone via Biginelli three-component reaction. Therefore, we discussed a simple procedure for the synthesis of DHPMs using 10 mol% of Br₂ as a catalyst.

To investigate the efficiency of Br₂ as a catalyst and to determine the optimum reaction conditions, we performed various reaction conditions using a mixture of benzaldehyde, methyl acetoacetate and urea as a model reaction (Table 1) (Scheme 1).

**SCHEME 1** Biginelli reaction catalyzed by Br₂

Surveying different bromine quantities show that 10 mol% is the optimum amount to obtain the desired product while further increase in the amount of bromine did not improve the yield. Lowering the amount of

bromine to 5% increased the reaction time to 5 h as well as the yield (to 75%) (Table 1, Entry 1). Different solvents were used at presence of 10% bromine such as MeOH, THF, DMF and EtOH. Ethanol was found to be the best solvent amongst all the tested solvents.

Therefore, using 10 mol% of bromine in ethanol under reflux conditions was selected as the optimized reaction conditions for the synthesis of DHPMs (Table 1, Entry 2).

TABLE 1 Optimization of the reaction conditions^a

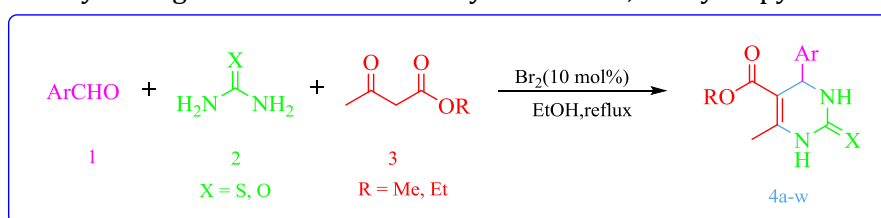
Entry	Bromine (mol%)	Solvent	Time (h)	Yield ^b (%)
1	5	EtOH	5	74
2	10	EtOH	4	99>
3	15	EtOH	4	65
4	15	EtOH	3	65
5	20	EtOH	4	60
6	10	MeOH	2	91
7	10	MeOH	4	91
8	10	THF	3	55
9	10	DMF	2	N.R.
10	10	CH ₃ CN	4	96

^a benzaldehyde-methyl acetoacetate-urea=1:1:1.5

^b isolated products

The scope of Br₂-catalyzed Biginelli reaction was investigated using a wide range of benzaldehyde derivatives, methyl acetoacetate or ethyl acetoacetate, and urea or thiourea as substrates (Table 2). The catalytic system revealed an excellent functional group tolerance, and aromatic aldehydes, different ureas (urea Table 2, Entries 1-16 or thiourea Table 2, Entries 17-22) and 1, 3-dicarbonyl compounds (methyl acetoacetate Table 2, Entries 1-10, ethyl acetoacetate Table 2,

Entries 11-22) reacted effectively to form DHPMs in good to excellent yields. Benzaldehyde derivatives bearing different substitutions at different positions on the phenyl ring had not much effect on the formation of the final products and they could afford the expected products in good to high yields. The products were characterized using the FT-IR, ¹H NMR, and ¹³C NMR techniques, and the results were compared with the authentic samples.

TABLE 2 Br₂-catalyzed Biginelli reaction for the synthesis of 3,4-dihydropyrimidin-2(1H)-ones^a

Entry	Ar	R	X	Product	Time (h)	Yield ^b (%)	Aldehydes Weight (g)
1	4-MeC ₆ H ₄	Me	O	4a	2	93	0.120
2	4-(CH ₃) ₂ NC ₆ H ₄	Me	O	4b	4	73	0.149
3	4-O ₂ NC ₆ H ₄	Me	O	4c	4	80	0.151
4	4-HO-3-CH ₃ OC ₆ H ₃	Me	O	4d	2	80	0.152
5	3-O ₂ NC ₆ H ₄	Me	O	4e	3	95	0.151
6	2-ClC ₆ H ₄	Me	O	4f	2	70	0.140
7	4-CH ₃ OC ₆ H ₄	Me	O	4g	3	80	0.136
8	4-ClC ₆ H ₄	Me	O	4h	2	60	0.140
9	4-HOC ₆ H ₄	Me	O	4i	2	80	0.122
10	2-HOC ₆ H ₄	Me	O	4j	3	84	0.122
11	C ₆ H ₄	Me	O	4k	4	99>	0.106
12	4-MeC ₆ H ₄	Et	O	4l	2	80	
13	4-O ₂ NC ₆ H ₄	Et	O	4m	2	75	
14	3-O ₂ NC ₆ H ₄	Et	O	4n	3	99	
15	2-ClC ₆ H ₄	Et	O	4o	2	50	
16	4-ClC ₆ H ₄	Et	O	4p	3	50	
17	4-(CH ₃) ₂ NC ₆ H ₄	Et	O	4q	1	70	
18	4-MeC ₆ H ₄	Et	S	4r	3	60	
19	4-O ₂ NC ₆ H ₄	Et	S	4s	1	70	
20	3-O ₂ NC ₆ H ₄	Et	S	4t	2	80	
21	4-(CH ₃) ₂ NC ₆ H ₄	Et	S	4u	2	70	
22	2-ClC ₆ H ₄	Et	S	4v	1	93	
23	4-ClC ₆ H ₄	Et	S	4w	2	87	

^a products were characterized by spectroscopic data such as IR, ¹H NMR, and ¹³C NMR and melting points.

^b isolated products

We also compared the efficiency of the Br₂ with other catalysts such as I₂, BF₃·OEt₂, FeCl₃·6H₂O, H₃PMo₁₂O₄₀, and CuBr₂ for the synthesis of 3,4-dihydropyrimidin-2(1H)-

ones (Table 3). It was found that, the Br₂ was superior to other catalysts in terms of the yield and reaction time.

TABLE 3 Comparative study of various catalysts in the Biginelli reaction^a

Entry	Catalyst	Solvent	Time (h)	Yield (%)	Ref.
1	I ₂	CH ₃ CN	6	93	[28]
2	BF ₃ ·OEt ₂ /CuCl	THF	18	88	[29]
3	FeCl ₃ ·6H ₂ O	EtOH	4	86.2	[30]
4	H ₃ PMo ₁₂ O ₄₀	HOAc	5	65	[31]
5	CuBr ₂	EtOH	4	93	[32]
6	Br ₂	EtOH	4	100	This work

To be able to better clarify the effect of Lewis acids, inspired by Liang [12], we also employed computational methods [33,34]. Three methods including, B3LYP [35], B97D [36] and MP2 [37] combined with the 6-311g (d,p) basis set were used for all the calculations. The geometry of benzaldehyde and methyl acetoacetate in the free form as well as at the presence of different Lewis acids

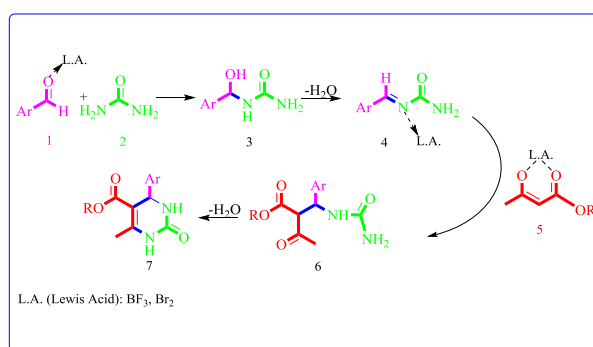
was firstly optimized. Then the frequency calculations were performed on the fully relaxed geometries to confirm the absence of the imaginary frequencies. The NBO 3.1 program was employed for natural bonding orbital (NBO) analyses [38]. All the computations were done in the ethanol solvent considering polarizable continuum

model (PCM) [39] using the Gaussian03 program package [40].

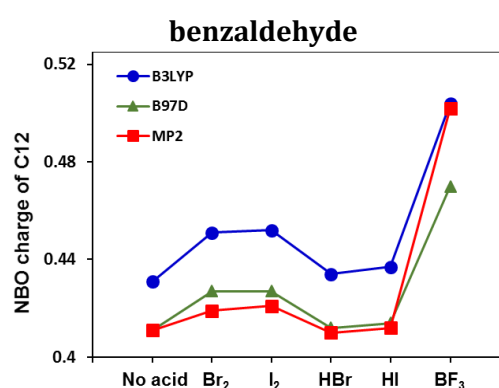
The optimized geometries of benzaldehyde and methyl acetoacetate in the free form at the presence of different Lewis acids obtained at B3LYP/6-311 g (d,p) level of theory in ethanol solvent are presented in Figs. S1 and S2 of supplementary materials. In all optimized geometries, the Lewis acid is relaxed in the vicinity of the carbonyl group of benzaldehyde and methyl acetoacetate. The NBO charge of carbon atom of carbonyl group for benzaldehyde (C12) and methyl acetoacetate (C5) was investigated and their variations versus different Lewis acids are demonstrated in Figure 1. For both benzaldehyde and methyl acetoacetate, upon coordination of oxygen end of the carbonyl group with the Lewis acids, the positive charge on the carbon end of the carbonyl group is intensified. The enhancing of positive charge is as the following order: $\text{HBr} < \text{HI} < \text{I}_2 \approx \text{Br}_2 < \text{BF}_3$. Considering these results, it can be suggested that BF_3 should display the best performance for this reaction while Br_2 and I_2 are also better than HBr and HI . Liang et al. [12] also considered the charge of carbon atom of the carbonyl group as an efficient parameter at the presence of different Lewis acids by quantum computations. They concluded that, the Br_2 was not so superior and it was indeed a potent Lewis acid for this reaction. They also suggested that, the activation of the carbon atom of the carbonyl group was not probably the main reason for the unique activity of Br_2 . Therefore, we calculated the Wiberg bond index (WBI) as another efficient parameter to investigate the interaction between benzaldehyde and methyl acetoacetate with different Lewis acids. The covalent bond strength between Lewis acid and carbonyl oxygen was shown by the WBI. Variations of calculated WBIs for benzaldehyde and methyl acetoacetate versus different Lewis acids are presented in Figure 2. It is clear that the WBI between BF_3 and the oxygen atom of the carbonyl group is significantly larger compared to the other

Lewis acids. This indicates that the strong covalent bond existed between BF_3 with benzaldehyde and methyl acetoacetate.

According to the theoretical calculations, Lewis acid catalyst (BF_3) could more activate the carbon atom of the carbonyl group in benzaldehyde and β -ketoester and could form a strong bond with the oxygen atom of the carbonyl group (Scheme 2, intermediate 1, 4 and 5). So, detaching of catalyst from oxygen is difficult. The reaction proceeded slowly towards the generation of the products (Scheme 2, intermediate 7). In comparison with the BF_3 , Br_2 is a less activator for the carbonyl group; however, it can be easily detached from the oxygen with significant performance.



SCHEME 2 Proposed mechanism for the synthesis of DHPMs catalyzed by Lewis acid



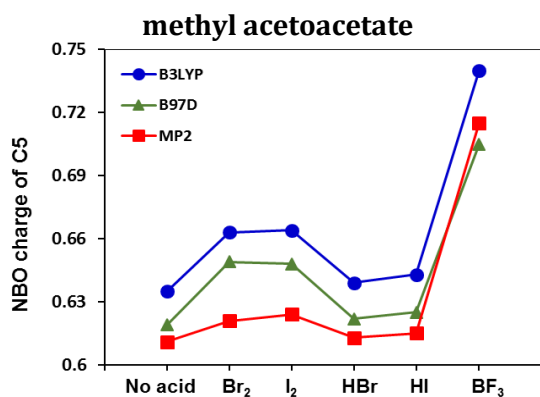


FIGURE 1 The NBO charges of carbon atom of carbonyl group of benzaldehyde (C12) and methyl acetoacetate (C5) versus different Lewis acids

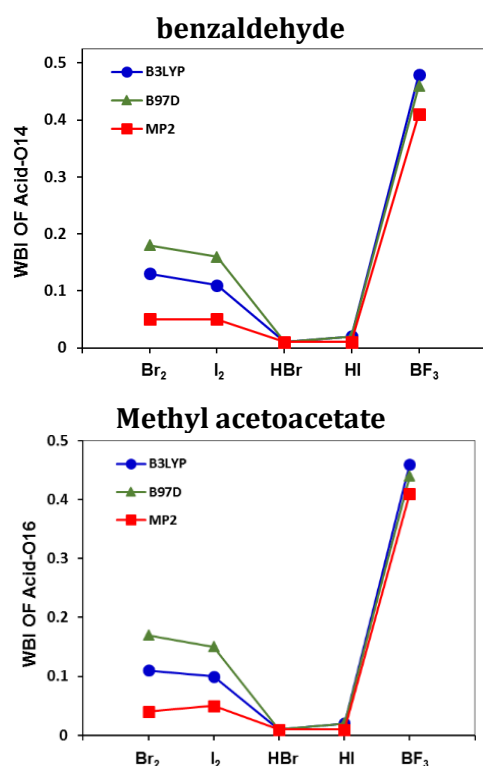


FIGURE 2 The Wiberg bond index (WBI) between benzaldehyde and methyl acetoacetate with different Lewis acids

Conclusion

In this work, we established a simple and efficient protocol for the synthesis of 3,4-dihydropyrimidin-2(1*H*)-ones by using a range of aromatic aldehydes in the presence of Br₂ as a Lewis acid catalyst. The advantages of the present protocol include compatibility

with many functional groups, use of a mild and an inexpensive catalyst, a simple experimental procedure, a low catalyst loading, and high yields. Molecular bromine easily activated the carbon atom of the carbonyl group. In addition, bromine which was detached quickly from the oxygen atom of the carbonyl group resulted in easy reaction progress. The theoretical computations also confirm the better performance of Br₂ compared to the other studied Lewis acids.

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Orcid:

Eskandar Kolvari: <https://orcid.org/0000-0003-0484-5273>

Ali Arab: <https://orcid.org/0000-0003-1271-8899>

Maryam Robati: <https://orcid.org/0000-0001-5991-4227>

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