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Microwave-assisted Cannizzaro reaction—Optimisation of reaction conditions

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ABSTRACT

The microwave-assisted Cannizzaro reaction was studied in order to develop fully reproducible synthetic protocols for transformation of aldehydes to carboxylic acid and alcohols. Optimised were the following process parameters: power, temperature, and time. Aromatic, heteroaromatic and aliphatic aldehydes were used in the studies. It was found that furfural, thiophene-2-carbaldehyde, pyridinecarboxal-dehyde and aromatic aldehydes react under mild conditions, while 1-methyl-pyrrole-2-carboxaldehyde derivatives and aliphatic aldehydes require more drastic reaction conditions and a longer exposure time to microwave radiation.



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KEYWORDS

Aromatic and aliphatic aldehydes; crossed Cannizzaro reaction; microwave irradiation; optimal conditions; reproducibility; synthetic protocols

Introduction

Cannizzaro reaction is a disproportionation of an aldehyde to an equimolar mixture of primary alcohol and carboxylic salt with a maximum yield 50% of both products. The reaction occurs with aldehydes without α -hydrogens in the presence of strong bases,^[1-3] although there are also reports indicating that the reaction can be efficiently catalysed by Lewis Acids.^[4] The Cannizzaro reaction is used in the synthesis of structurally differentiated intermediates that are substrates for a variety of biologically active compounds.^[5-9]

The hydride transfer was found to take place directly between substrates without participation of reaction medium, which gives the possibility of carrying out the reaction under solvent free conditions.^[10] The reaction in which the oxidant aldehyde differs from the reductant aldehyde are also known as the cross (or crossed) Cannizzaro reaction. Depends on reactants used, this approach was found useful for synthesis focussed on either alcohol or carboxylic acid with increased yield.

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Figure 1. Aldehydes used in microwave-assisted Cannizzaro reaction.

Currently, for a significant reduction of reaction time, increase of selectivity and specificity of transformations,^[11] many chemical processes are conducted under microwave irradiation conditions. The Cannizzaro reaction is not an exception and can also be carried out under microwave irradiation.^[12–14]

The aim of the research was to apply microwave radiation in the Cannizzaro reaction to perform systematic studies on optimisation of the process conditions allowing the reproducible preparation of the target alcohol and carboxylic acid.

This research goal was promoted by encouraging results of the preliminary studies described by Sharifi et al.,^[15] where the results of experiments involving a wide range of aromatic aldehydes in the Cannizaro reaction were presented. However, reported process conditions were not precise (commercial microwave oven was used), what made the reproducibility difficult and sometimes even impossible. Therefore, to eliminate this limitation, attempts have been made to develop a fully reproducible synthetic protocol under standard and optimised Cannizzaro reaction assisted by microwave radiation.

Results and discussion

Eleven aldehydes **1a-k** (Figure 1) were selected to experiment with microwave-assisted Cannizzaro reaction.

The search for reproduce reaction conditions in microwave assisted Cannizzaro reaction started with furfural (1a) (Table 1). The choice of this substrate was dictated by the fact that furfural is one of the key-compounds formed in biorefinery processes and it is often transformed into other valuable compounds.^[16–18]

The use of Cannizzaro's reaction allows the simultaneous synthesis of both furfuryl alcohol (2a) and furan-2-carboxylic acid (3a).

It was found that careful grinding all reagents in the mortar resulted in the increase of conversion from 35% (based on ¹H NMR) (Table 1, entry 1) to 100% (Table 1, entry 2–4, and entry 7). The yield of isolated alcohol **2a** and carboxylic acid **3a** was increased from 40% to 49% when microwave radiation was prolonged from 1 min to 2 min (Table 1, entry 2 and 3). In the next stage, the influence of regents on the course of the reaction was checked. Performing the reaction without catalytic amount of water resulted in decreasing yield of products **2a** and **3a** to 35% (Table 1, entry 4). In the absence of both H₂O and Al₂O₃ the conversion was 83% (Table 1, entry 5) while in the case of reaction without NaOH, decrease the conversion to 12% (Table 1, entry 6) was observed. For comparison, in the absence of Al₂O₃ the conversion of furfural reached 100% and products **2a** and **3a** were isolated in 45% of yield, each (Table 1, entry 7).

In the next stage, attempts were made to check whether amount of furfuryl alcohol (2a) can be increased in a mixture of products by using paraformaldehyde (1k) as reducing agent. In the studies, 1–3 equivalents of 1k were used and it was found that it

	O H 1a	MW NaOH, Al ₂ O _{3,} H ₂ O	оон + о́ 2а	о ОН За	
	MW	conditions ^b		Produc	:ts (%) ^c
Entry	Temp (°C)	Time (min)	according to ¹ H NMR	2a	3a
1 ^d	100	1	35	_	_
2	100	1	100	40	40
3	100	2	100	49	49
4 ^e	100	2	100	35	35
5 ^f	100	2	83	-	_
6 ^g	100	2	12	-	-
7 ^h	100	2	100	45	45

Table 1.	Optimisation	of process	condition for	or furfural	aldehyde (1a).	d
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^aConditions: **1a** (0.16 mL, 2 mmol), NaOH (0.5 g, 12.5 mmol), Al₂O_{3 base} (2 g, 19.6 mmol), H₂O (400 μL), all substrates grinded in a mortar.

^bStandard mode – 200 W.

^cYields without purification.

^dSubstrates not mixed in a mortar.

^eReaction without H₂O.

^tReaction without H_2O and Al_2O_3 .

⁹Reaction without NaOH.

^hReaction without Al₂O₃.

Table	2.	The	effect	of	paraformaldehyde	(1k)	addition	to	Cannizzaro	reaction	of	furfural
aldehy	de	(1a). ^a										

	ОН	+ H H	<u>MW: 2 m</u> NaOH, A	<u>nin, 100 °C</u> N₂O _{3,} H₂O	O OF	н + О ОН	
	1a	1k			2a	3a	
Entry	Rat	io of substrates 1	a:1k (eq)	Conversior	of 1a (%) ^b	Ratio of products 2a/3a ^c	
1		1:1		1	00	1.00/0.50	
2 ^d		1:1		1	00	1.00/0.70	
3 ^d		1:3		1	00	1.00/0.50	

^aConditions: **1a** (0.16 mL, 2 mmol), **1k** (for details see Table 2), NaOH (0.5 g, 12.5 mmol), AI_2O_3 _{base} (2 g, 19.6 mmol), H_2O (400 µL).

^bConversion based on ¹H NMR.

^cRation of products **2a/3a** based on ¹H NMR.

^dReaction without Al₂O₃.

is possible to increase the amount of alcohol 2a in the mixture with acid 3a to ratio 2:1 according to ¹H NMR (Table 2).

The optimal conditions found for furfural aldehyde (1a) (Table 1, entry 3) have been applied for thiophene-2-carbaldehyde (1b), aromatic aldehydes 1c-e (Table 3), and heteroaromatic analogues of pyridinecarboxaldehyde 1f-g (Figure 2). In the presence of 2 g of Al₂O₃, 0.5 g of NaOH and 400 µL of H₂O in reaction proceeding at 100 °C after 2 min microwave radiation (standard mode) 100% of conversion of 1b to 2-thiophenemethanol (2b) and 2-thiophenylcarboxylic acid (3b) isolated both in 47% yield (Table 3,







Figure 2. MW assisted Cannizzaro reaction of 4-pyridinecarboxaldehyde (1f) and 2-pyridinecarboxaldehyde (1g).

entry 1). The use of the described above conditions for aromatic aldehydes 1c-e also resulted in 100% conversion and high yields. Benzyl alcohol (2c) and benzoic acid (3c) were obtained both in 45% yield when benzaldehyde (1c) was uses as a substrate (Table 3, entry 2). The presence of the methyl group in the para position in 4-methylbenzaldehyde (1d) did not affect the yield of both products. Both 4-methylbenzyl alcohol (2d) and 4-methylbenzoic acid (3d) were obtained with 45% yield (Table 3, entry 3). Replacement the methyl group with a chlorine atom in 4-chlorobenzaldehyde (1e) resulted the slightly increase the yields of 4-chlorobenzyl alcohol (2e) and 4-chlorobenzoic acid (3e) to 47% (Table 3, entry 4).

Application the optimal conditions for 4-pyridinecarboxaldehyde (1f) and 2-pyridinecarboxaldehyde (1g) resulted 100% conversion (Figure 2). In both cases, corresponding alcohols pyridin-4-ylmethanol (2f) and pyridin-2-ylmethanol (2g) were obtained with high yields (47%), and the position of nitrogen atom in the ring was not important. However,

R O N	`H MW NaOH, H₂O → Me N OH +	Me O N OH
1h: R= M 4: R= H 5: R= Bo 6: R= Ts	Me 2h	3h
Entry Substrate; R	Conversion (%) according to ¹ H NMI	R Result
1 ^a H (4)	0	Substrate 4
2 ^a Boc (5)	0	Substrate 4
3 ^a Ts (6)	0	Substrate 4
4 ^a Me (1h)	6	6% conversion
5 ^b Me (1h)	90	2h (39%) ^c and 3h (39%)

Table	4.	Optimisation	of	Cannizzaro	reaction	condition	for	of	N-methyl-pyrrole-2-carboxaldehyde
(1h) a	nd	compounds 4	-6.						

^aAldehyde **4**, **5**, **6** or **1 h** (2 mmol), Al₂O₃ (19.6 mmol), NaOH (12.5 mmol), H₂O (400 μ L), all reagents grinded in a mortar; MW conditions: standard mode, 100 °C, 2 min.

 b Aldehyde **1 h** (2 mmol), NaOH (12.5 mmol), (CH_2O)_n (4 mmol), H_2O (400 μ L); MW conditions: standard mode, 120 °C, 30 min.

^cYield after flash chromatography.

attempts to isolated target acids—isonicotinic acid and picolinic acid—were failed. Due to the presence of the carboxyl group and the nitrogen atom in the pyridine ring, the standard procedure for the isolation by acidification and extraction has not a positive effect. For this reason, the mixture was acidified to an isoelectric point (pH 5.5)^[19] and the products were isolated as zwitter ions (**3f** and **3g**) with 47% of yields (Figure 2).

Encouraged by the results of studies using **1a** and **1b**, we have attempted to apply the optimal conditions of microwave-assisted Cannizzaro reaction for conversion of pyrrole-2-carboxaldehyde (4) (Table 4). However, in this case, all attempts were unsuccessful and only unreacted substrate 4 was recovered (Table 4, entry 1). Increasing the temperature (up to $140 \,^{\circ}$ C) and extending the reaction time (up to $10 \,\text{min}$) resulted also in the recovery of the substrate. Experiments with replacement of NaOH by KOH or $Ba(OH)_2 \times 8 H_2O$ also were fruitless. Performing the reaction under optimised conditions with N-Boc protected aldehyde 5 resulted deprotection of Boc group and isolation of aldehyde 4 (Table 4, entry 2). The same result was obtained for N-Ts protected aldehyde 6 (Table 4, entry 3). Under standard conditions, Ts group has been removed and the only reaction product was an aldehyde 4. To our knowledge, the observed deprotection of both Boc and Ts groups from 2-pyrrole aldehyde derivatives under the Cannizzaro reaction conditions is the first noted example. Therefore, attempts have been made to apply N-methyl-pyrrole-2-carboxaldehyde (1h). Under standard mode condition (100 °C, 2 min) 6% conversion to the product 2h based by ¹H NMR (Table 4, entry 4) was observed. Elongation time of reaction to 30 min and increase the temperature to 150 °C did not improve conversion. However, in the absence of Al₂O₃, at temperature raised to 160 °C, after 30 min reaction conversion of substrate increased to 88%. However, due to drastic conditions, the reaction was unrepeatable because under mentioned conditions the vials were breaking in MW reactor. Lowering the temperature to 120 °C and performing the irradiation for 30 min in the presence of paraformaldehydem (2 eq) and without Al₂O₃ allowed to obtain a conversion of 90% and to isolate

	$\begin{array}{c} CI \xrightarrow{CI} H \\ CI \\ CI \\ 1i \end{array} \xrightarrow{H} \begin{array}{c} MW \\ \overline{AI_2O_3, H_2} \end{array}$	$\xrightarrow{O} CI \xrightarrow{CI} OH + C$	
	MW d	conditions	
Entry	Temp (°C)	Time (min)	Conversion (%) ^a
1 ^b	100	2	_c
2 ^d	100	2	6
3 ^d	100	15	31
4 ^d	100	30	63
5 ^d	120	15	13
6 ^e	100	30	44



^aConversion based on ¹H NMR.

^bAldehyde 1i (2 mmol), Al_2O_3 (19.6 mmol), NaOH (12.5 mmol), H_2O (400 µL), all reagents grinded in a mortar. ^cNo product and substrate.

^dAldehyde 1i (2 mmol), Al₂O₃ (19.6 mmol), H₂O (400 μL), all reagents grinded in a mortar.

^eAldehyde 1i (2 mmol), Al₂O₃ (19.6 mmol), H₂O (400 μ L), (CH₂O)_n (4 mmol) all reagents grinded in a mortar.

pure (1-methyl-1H-pyrrole-2-yl)-methanol (**2h**) after flash chromatography with 39% of yields and pure 1-methyl-2-pyrrolecarboxylic acid (**3h**) also with 39% (Table 4, entry 5), respectively.

The reaction of the aldehyde **4** in the presence of the paraformaldehyde resulted in the recovery of unreacted starting material **4**.

In the next stage, attempts were made to adapt the optimal reaction conditions to the transformation of aliphatic aldehydes **1i–k**. Performing the reaction of trichloroacetaldehyde (**1i**) under condition optimised for furfural, resulted in the consumption of substrate **1i** but no expected product **2i** (Table 5, entry 1) were isolated. After removing NaOH from reacting mixture and repeating the process under the standard conditions 6% conversion of substrate to **2i** (Table 5, entry 2) was obtained. Extending the reaction time to 15 and then to 30 min (Table 5, entries 3 and 4) increased the conversion to 31 and 63%, respectively. However, further extension of time did not improve the conversion. Rising the temperature to 120 °C for 15 min resulted in decreasing of conversion to 13% (Table 5, entry 5). Addition of formaldehyde (2 eq) increased the conversion to 44% (Table 5, entry 6), however an attempts to isolate pure alcohol **2i** from the mixture of substrate **1i** and alcohol **2i** were unsuccessful. The use of optimal conditions (100 °C, 30 min) for trimethylacetaldehde (**1j**) was unsuccessful. It was not possible to obtained the target 2,2-dimethylpropan-1-ol and pivalic acid, or even recover an unreacted substrate **1j**.

Transformation of formaldehyde (1k) to methanol (2k) under the conditions optimal for 1a, as the expected target alcohol proceeded with 22% of yield (Table 6, entry 1). Increasing the reaction temperature to $120 \,^{\circ}$ C, or to $140 \,^{\circ}$ C resulted in increase of yield to 27 and 39%, respectively (Table 6, entries 2 and 3). However, further elevating temperature to $160 \,^{\circ}$ C resulted in a slight decrease of the methanol yield to 36% (Table 6, entry 4). Extending the reaction time to 30 min at the $140 \,^{\circ}$ C allowed to obtain product 2e with 39% (Table 6, entry 5).

	HHH Nac	MW DH, Al₂O _{3,} H₂O►	⁰ ^H ₃ C _{0H} + H ОН 2k 3k	
	MW cor	nditions		
Entry	Temp (°C)	Time (min)	Yield (%) ^b	Area under peak ^c
1	100	2	22	2436
2	120	2	27	3741
3	140	2	39	5158
4	160	2	36	4741
5	140	30	39	5217

Table 6. Condition of Cannizzaro reaction assisted MW irradiation for paraformaldehyde (1k).^a

^aAldehyde 1k (2 mmol), Al₂O₃ (19.6 mmol), NaOH (12.5 mmol), H₂O (400 μ L), all reagents mixed in a mortar. ^bYield based on GC.

^cBased on GC.

In all cases, the yield of the Cannizzaro reaction of paraformaldehyde (1k) was determined using used gas chromatography method after calibration of GC peak (see Supplementary Material, Section 8, Fig. S31).

Conclusions

Optimisation of the Cannizzaro reaction conditions assisted by microwave radiation allowed the development of fully reproducible synthetic protocols. Aromatic, heteroaromatic and aliphatic aldehydes were used in the studies, and the mixture of Al_2O_3 and NaOH was used as a catalyst. It has been found that the optimal for the aromatic and heteroaromatic aldehydes is to conduct the reaction at temperature 100-120 °C for 1-2 min using standard mode - 200 W. Under these conditions, the conversion was 100%, and alcohols 2a-e and carboxylic acids 3a-e were isolated with almost quantitative yields. For analogues of pyridinecarboxaldehyde 1f-g conversion was also 100% and both alcohols 2f-g were isolated with high yields, and acids were isolated as zwitter ions 3f-g. In case of pyrrole-2-carboxaldehyde (4) and Boc- and Ts-N-protected derivatives, 5 and 6 the expected products were not obtained. For both protected pyrrole-2-carboxaldehyde derivatives under Cannizzaro reaction conditions deprotection and formation pyrrole-2-carboxaldehyde (4) was observed, which was not disproportionate to the expected carboxylic acid and alcohol. However, it turned out that the application N-methyl-pyrrole-2-carboxaldehyde (1h) as substrate allowed 90% conversion and obtaining (1-methyl-1H-pyrrole-2-yl)-methanol (2h) isolated with 39% yield and 1-methyl-2-pyrrolecarboxylic acid (3h) also with 39% yield. The transformation in the presence of 2 equivalents of paraformaldehyde required 30 min microwave radiation at 120 °C.

Optimisation of reaction conditions also allowed for efficient transformation of trichloroacetaldehyde (1i). The conversion rate of 63% was obtained in the reaction carried out at $100 \,^{\circ}$ C for 30 min under standard mode—200 W. In the case of aldehyde 1i, the addition of paraformaldehyde did not increase the conversion. Despite attempts, it was not possible to obtain the target alcohol and acid from trimethylace-taldehyde (1j).

It was also found that paraformaldehyde (1k) disproportionate to methanol and formic acid. The optimal transformation conditions: temperature 120-140 °C, time 2 min, standard mode 200 W.

Experimental part

NMR spectra were measured on a Bruker Avance II Plus spectrometer (700 MHz for 1 H NMR and 176 MHz for ¹³C NMR) and a Bruker Avance DPX spectrometer (250.13 MHz for ¹H NMR) in CDCl₃ solution. ¹H and ¹³C NMR spectra are referenced according to the residual peak of the solvent based on literature data. Chemical shifts (δ) are reported in ppm and coupling constants (1) in Hz. ¹³C NMR spectra were proton-decoupled. Flash chromatography was performed with a glass column packed with Baker silica gel (30-60 µm). For TLC, silica gel on aluminum-backed TLC plates (Sigma-Aldrich) with indicator 254 mm were used. A monomode microwave reactor (CEM Discover) equipped with an IntelliVent pressure control system was used. The standard method was applied, and the maximum pressure was set to 250 psi. Melting points were obtained using a Büchi SMP-20 apparatus. Reactions were monitored by gas chromatograph Hewlett Packard Series II 5890, gc column Zebron ZB-5MS. Gas chromatography conditions: temperature 35 °C, 5 min, 35-65 °C, 1 °C/min, 65 °C, 5 min. ESI/MS: micrOTOF-Q III spectrometer Bruker Daltonics equipped with electrospray source and time of flight detector. N-Boc protected aldehyde 5 was prepared according to the procedure described by Waser et al.^[20] N-Ts protected aldehyde 6 was prepared according to the procedure given by Abell et al.^[21] N-methyl-pyrrole-2-carboxaldehyde (1c) was obtained according to the procedure described by Li et al.^[22]

General procedure for compounds 1a-e

NaOH (0.5 g, 12.5 mmol), Al_2O_3 (2.0 g, 19.6 mmol), aldehyde 1a-e (2 mmol) and H_2O (400 µL) were grinded in a mortar. Next, the paste was placed in a glass pressure vials (10 mL) and reaction was carried out in microwave reactor: standard mode (200 W), 100 °C, 2 min. After that, reaction mixture was extracted with DCM (2 × 20 mL). Organic layer was evaporated under reduce pressure yielding **2a–e**. Solid residue was washed by water (2 × 15 mL). Aqueous phase was diluted and acidify with 1 N HCl (30 mL), and extracted by DCM (2 × 80 mL). Organic layer was dried under anhydrous MgSO₄ and evaporated under reduce pressure to give pure **3a–e**.

Furfuryl alcohol (2a)

Colorless oil. Yield 49% (0.096 g). ¹H NMR (CDCl₃, 700 MHz): δ 7.39 (dd, 1 H, $J_{HH} =$ 1.8 Hz, $J_{HH} =$ 0.8 Hz, CH_{Ar}), 6.34 (dd, 1 H, $J_{HH} =$ 3.2 Hz, $J_{HH} =$ 1.8 Hz, CH_{Ar}), 6.28 (dd, 1 H, $J_{HH} =$ 3.2 Hz, $J_{HH} =$ 0.6 Hz, CH_{Ar}), 4.60 (s, 2 H, CH_2), 2.00 (bs, 1 H, OH). ¹³C NMR (CDCl₃, 176 MHz): δ 154.14 (s, 1 C, C_{Ar}), 142.69 (s, 1 C, C_{Ar}), 110.48 (s, 1 C,

 C_{Ar}), 107.86 (s, 1 C, C_{Ar}), 57.58 (s, 1 C, CH_2). The analytical data are in agreement with those reported previously in the literature.^[23]

Furan-2-carboxylic acid (3a)

Brown solid, mp 129–130 °C (lit.^[24] 130–132 °C). Yield 49% (0.110 g). ¹H NMR (CDCl₃, 700 MHz): δ 11.6 (bs, 1 H, OH), 7.64 (s, 1 H, CH_{Ar}), 7.33 (d, 1 H, J_{HH} = 3.4 Hz, CH_{Ar}), 6.56 (d, 1 H, J_{HH} = 2.3 Hz, CH_{Ar}). ¹³C NMR (CDCl₃, 176 MHz): δ 163.8 (s, 1 C, CO), 147.6 (s, 1 C, C_{Ar}H), 143.9 (s, 1 C, C_{Ar}), 120.3 (s, 1 C, C_{Ar}H), 112.4 (s, 1 C, C_{Ar}H). The analytical data are in agreement with those reported previously in the literature.^[25]

General procedure for compounds 1f-g

NaOH (0.5 g, 12.5 mmol), Al_2O_3 (2.0 g, 19.6 mmol), aldehyde 1f-g (2 mmol) and H_2O (400 µL) were grinded in a mortar. Next, the paste was placed in a glass pressure vials (10 mL) and reaction was carried out in microwave reactor: standard mode (200 W), 100 °C, 2 min. After that, reaction mixture was extracted with DCM (2 × 20 mL). Organic layer was evaporated under reduce pressure yielding 2f-g. Solid residue was washed by water (2 × 15 mL). Aqueous phase was acidified with 1 N HCl to pH 5.5 and centrifuged. After that aqueous layer was pour down and precipitate was lyophilized. Products 3f-g were obtained as white solids.

Procedure for compound 1h

NaOH (0.50 g, 12.5 mmol), formaldehyde **1k** (0.12 g, 4 mmol), aldehyde **1h** (2 mmol) and water (400 μ L) were placed in a glass pressure vials (10 mL) and mixed. Reaction was carried out in microwave conditions: standard mode, 120 °C, 30 min. After that, reaction mixture was diluted by water (15 mL) and extracted with DCM (2 × 25 mL). Organic layer was dried under anhydrous MgSO₄ and evaporated under reduce pressure. Alcohol **2h** was isolated and purified by flash chromatography on silica gel in hexane:EtOAc 5:1. Water layer was diluted and acidify by 1 N HCl (30 mL), and extracted by DCM (2 × 50 mL). Organic layer was dried under anhydrous MgSO₄ and evaporated under reduce pressure to give pure acid **3h**.

General procedure for compound 1i

Al₂O₃ (2.0 g, 19.6 mmol), aldehyde **1i** (2 mmol) and H₂O (400 μ L) were grinded in a mortar. Next, the paste was placed in a glass pressure vials (10 mL) and reaction was carried out in microwave reactor: standard mode, 100 °C, 30 min. After that, reaction mixture was extracted with DCM (2 × 20 mL). Organic layer was evaporated under reduce pressure to give mixture of substrate **1i** and product **2i** in rate 0.60:1.00 (¹H NMR).

General procedure for compound 1k

NaOH (0.50 g, 12.5 mmol), Al₂O₃ (2.0 g, 19.6 mmol), aldehyde **1k** (2 mmol) and H₂O (400 μ L) were grinded in a mortar. Next, the paste was placed in a glass pressure vials (10 mL) and reaction was carried out in microwave reactor: standard mode, 140 °C, 2 min. After that, reaction mixture was extracted with DCM (2 × 20 mL). The yield of alcohol **2k** was determined by GC, $t_{\rm R} = 2.765$ min. Yield of reaction is 39%.

The exact experimental procedures and full characteristics of the obtained compounds are included in the Supplementary Information.

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