


Self- and Cross-Aldol Condensation of Propanal Catalyzed by Anion-Exchange Resins in Aqueous Media

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 Supporting Information

ABSTRACT: Carbon–carbon bond formation using strong and weak anion-exchange resins as green catalysts for self- and cross-aldol condensation of propanal in aqueous media was investigated. The reaction pathway followed the route of aldol condensation to a β -hydroxy aldehyde and dehydration to an α,β -unsaturated aldehyde. The resulting products were further converted to hemiacetal, and/or acetal moieties, which were confirmed by FT-IR and NMR. In self-condensation using strong anion-exchange resin, 97% conversion of propanal was achieved with 95% selectivity to 2-methyl-2-pentenal within 1 h using 0.4 g/mL resin at 35 °C. The conversion and selectivity using weak anion exchanger was lower. During cross-aldol condensation of propanal with formaldehyde, 3-hydroxy-2-methyl-2-hydroxymethylpropanal was obtained as the main product through first and second cross-condensation followed by hydration reaction in acidic aqueous conditions. The strong anion-exchange resin provided maximal propanal conversion of 80.4% to the product with 72.4% selectivity after 7 h reaction at 35 °C and resin concentration of 1.2 g/mL. Using weak anion-exchange resin, the optimal conversion of propanal was 89.9% after 24 h at 0.8 g/mL resin and 35 °C, and the main product was 3-hydroxy-2-methylpropanal by first cross-aldol condensation along with relatively minor amounts of methacrolein and 3-hydroxy-2-methyl-2-hydroxymethylpropanal.

INTRODUCTION

Aldol reaction is one of the important means to form a C–C bond using chemical or enzymatic catalysts.^{1–4} Carbon–carbon bond formation is the essence of organic synthesis and provides the foundation for generating more complex organic compounds from the simpler ones.⁵ Propanal, a building block molecule of three carbons, is one of the important chemicals in the chemical industry and is extensively used in rubber, plastic, coating, pharmaceutical, pesticide, and feed additive industries.⁶ Conversion of propanal by aldol reaction can be employed as a very useful method for new C–C bond formation leading to the synthesis of larger building blocks. A self-aldol condensation product of propanal, 2-methyl-2-pentenal, is a commercially important chemical intermediate used in pharmaceuticals, fragrances, flavors, and cosmetics industry.⁷ 2-Methyl-2-pentenal is produced by self-aldol condensation using a stoichiometric amount of NaOH solution at 100 °C and 0.76–1.86 MPa with 99% conversion of propanal and 86% selectivity.⁷ This process using higher than stoichiometric amount of a liquid base (KOH or NaOH) is not eco-friendly and requires large amount of water for removal and neutralization of the base during downstream processing of the product.

Recently, there have been many efforts to provide a more clean approach for the production of 2-methyl-2-pentenal.^{7–11} The product was obtained with 99% selectivity by aldol condensation using the hydrotalcite of Mg/Al, which was activated at 450 °C for 4 h.⁷ The self-aldol reaction in supercritical CO₂ using various catalysts like Amberlyst15 provided 76% conversion with 88% selectivity, or 43% conversion with 99% selectivity to 2-methyl-

2-pentenal at 135 °C.⁸ The basic resins were used for aldol condensation of 1-butanal or hexanal and gave only poor conversion and product selectivity.⁹ By using benzene as solvent with anion-exchange resin as the catalyst for self-aldol condensation of propanal, 2-methyl-2-pentenal was obtained at 93.5% yield.¹⁰

The cross-aldol condensation of aliphatic aldehydes, especially propanal with formaldehyde under more environmentally benign conditions, has not been much studied. BASF has employed this type of reaction to form methacrolein, which is an industrially important intermediate for manufacture of methacrylic acid, a monomer for acrylate polymers.¹¹ Methacrolein can be effectively synthesized from formaldehyde, syngas, and ethylene using a tandem oxo-Mannich sequence of reactions.¹² Butyraldehyde was aldolized with formaldehyde at 40–80 °C over an anion-exchange resin catalyst in aqueous and methanolic solutions to form two main products: 2-ethyl-3-hydroxy-2-hydroxymethylpropanal (trimethylolpropane aldol) and 2-ethylpropenal (ethylacrolein).^{13,14}

In spite of the great interest in applying more environmentally friendly approaches for new C–C bond formation from propanal, there is little information available on the aldol condensation reaction in aqueous media. Under aqueous conditions, the aldol condensation should be more complicated due to additional reactions such as hydration and acetalization of aldol products.^{15,16} Although enzymatic processes in nature must occur in an aqueous environment by necessity, water has been a solvent to be avoided

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for common organic reactions.⁵ However, as a result of the explosion of research activities in recent years in the field of Green Chemistry, organic reactions in water have become some of the most exciting research endeavours.

In this investigation, strong and weak anion-exchange resins were employed in aqueous media for self- and cross-aldol condensation of propanal, and the reaction pathways were compared.

RESULTS AND DISCUSSION

1. Self-Aldol Condensation of Propanal. *1.1. Self-Aldol Condensation of Propanal Using Strong Anion-Exchange Resin.* The anion-exchange resin Amberlite IRA-401 was used as a catalyst at low temperature for self-aldol condensation of propanal in an aqueous medium. The reaction progressed quickly, yielding high conversion of propanal within 1 h at 35 °C (Figure 1).

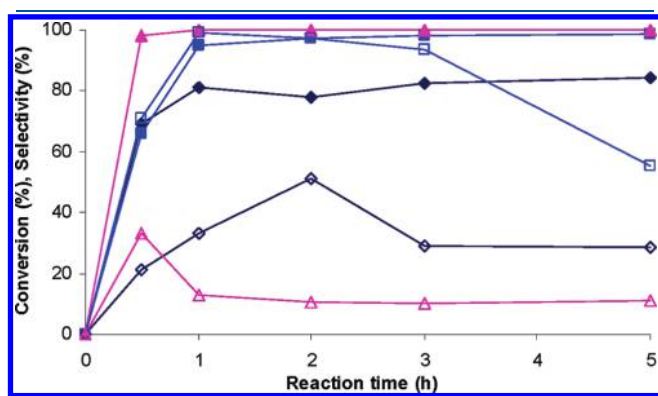


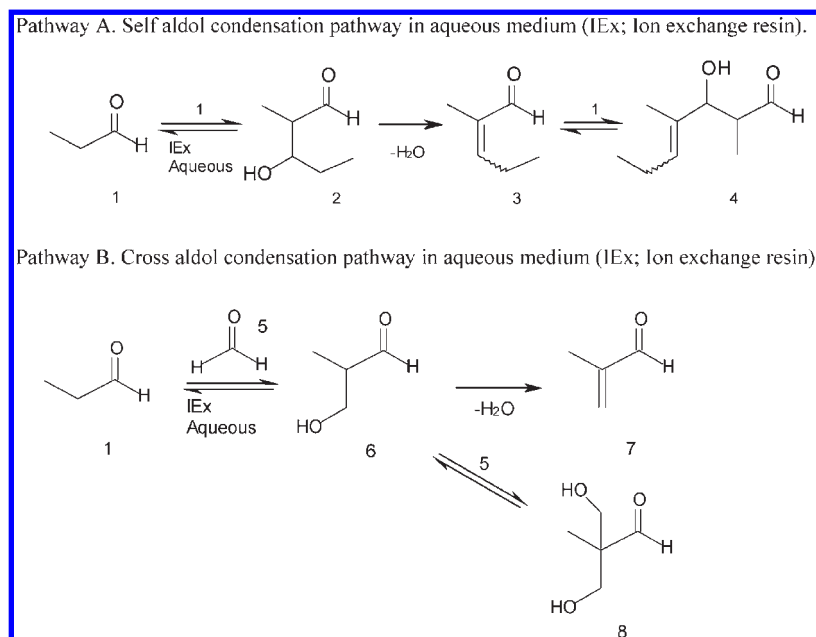
Figure 1. Self-aldol condensation of propanal at 35 °C using different amounts of strong anion-exchange resin, Amberlite IRA-401: 0.2 g/mL (diamond), 0.4 g/mL (square), and 0.6 g/mL (triangle). Percent conversion of propanal is shown as filled symbols, and selectivity for production of 2-methyl-2-pentenal is shown as empty symbols.

The degree and rate of propanal consumption increased with an increase in the amount of the Amberlite IRA-401 used as the catalyst; however, only at a resin concentration of 0.4 g/mL, was the propanal converted with 95% selectivity to 2-methyl-2-pentenal (3, retention time (RT) in HPLC of 16.2 (Supporting Information)), which is higher than that reported earlier for the reaction using benzene as solvent.¹⁰ Formation of 3-hydroxy-2-methylpentanal (2, RT11.2 (Supporting Information)) was also noted as an intermediate product, according to Scheme 1A. At lower resin concentration (0.2 g/mL), propanal conversion was only 80% and maximum selectivity for the product 3 was 50% at 2 h reaction time, while at higher resin concentration (0.6 g/mL), although the propanal consumption was complete, only 30% ended in product 3 after 30 min reaction. Much higher levels of product 2 were detected (up to 20%) when using 0.2 g/mL of the resin as compared to 1–2% for the higher resin concentrations. As seen in Figure 1, the concentration of 3 decreased on prolonged reaction to give additional reaction products, which were not detected by HPLC and hence were not aldehyde compounds and are proposed as polyol, acetal, and hemi-acetal compounds later in this paper.

The effect of reaction temperature (20, 35, and 50 °C) was evaluated using 0.4 g/mL of Amberlite IRA-401. The optimum temperature with respect to propanal conversion and selectivity for product 3 was 35 °C as shown above. Although the reaction rate increased at higher reaction temperature, the selectivity was extremely low while lower reaction temperature showed lower reaction rate (after initial 20 min) and increasing selectivity with the course of the reaction (Figure 2).

The possibility of the product 3 reacting with the starting aldehyde (1) as second aldol condensation (pathway A) was further investigated. Only two small peaks appeared at RT14 on the HPLC chromatograms, which were predicted as isomers of β -hydroxyaldehyde product (4) by LC-MS (Supporting Information). In the presence of strong base, Cannizzaro reaction from 3 could take place to produce an alcoholic compound

Scheme 1. Possible Reaction Pathway during Self- and Cross-Aldol Condensation of Propanal and Formaldehyde in Aqueous Medium



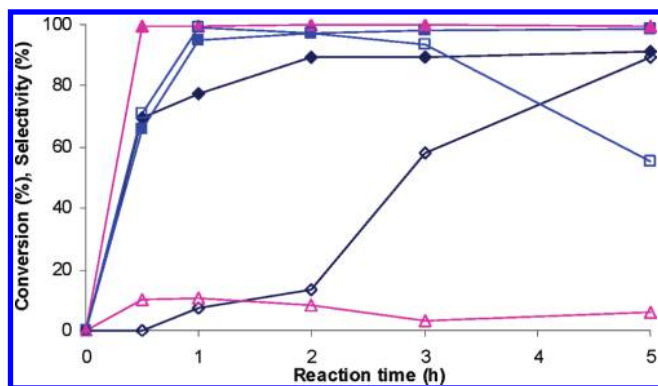


Figure 2. Effect of reaction temperature on self-aldol condensation of propanal using 0.4 g/mL of Amberlite IRA-401. The temperatures used were 20 °C (diamond), 35 °C (square), and 50 °C (triangle). Percent conversion of propanal is shown as filled symbols, and selectivity for production of 2-methyl-2-pentenal is shown as empty symbols.

Table 1. Molecular Masses of Aldehyde Products Derivatized by DNPH

products	mass	
	calculated	measured ^a
1	238.20	237.17
2	296.28	295.23
3	278.26	277.21
4	336.34	335.27
5	210.15	209.12
6	268.23	267.19
7	250.21	249.17
8	298.25	297.12

^a The molecular masses were measured as negative mode by electrospray ionization mass spectrometry.

(mono-ol).¹³ However, as in the present system, the final reaction pH was around 5, this possibility was ruled out. On the other hand, hydration and/or hemiacetalization of **3** could take place in the acidic aqueous medium.

1.2. Self-Aldol Condensation of Propanal Using Weak Anion-Exchange Resin. Using a weak anion-exchange resin as the catalyst gave different results under similar reaction conditions as above. The conversion of propanal was only around 70%, and the selectivity for 2-methyl-2-pentenal (**3**) was very low as only a trace amount was detected by HPLC (data not shown). Even the other major peaks were not detected on the HPLC chromatogram. This was explained as the differences of reaction rates between aldol condensation and hydration reaction. During the time taken to reach 70% conversion (7 h), the resulting product (**3**) could be quickly converted further to other products. The intermediate (**2**) was maintained at a slightly higher content than with strong anion exchanger, while there was no peak of a second aldol condensation product.

2. Cross-Aldol Condensation of Propanal and Formaldehyde. **2.1. Strong Anion-Exchange Resin as a Catalyst for Cross-Aldol Condensation between Propanal and Formaldehyde.** In the reaction between propanal and formaldehyde, both self- and cross-aldol condensation reactions are possible (Scheme 1). HPLC chromatograms of the samples taken from the initial

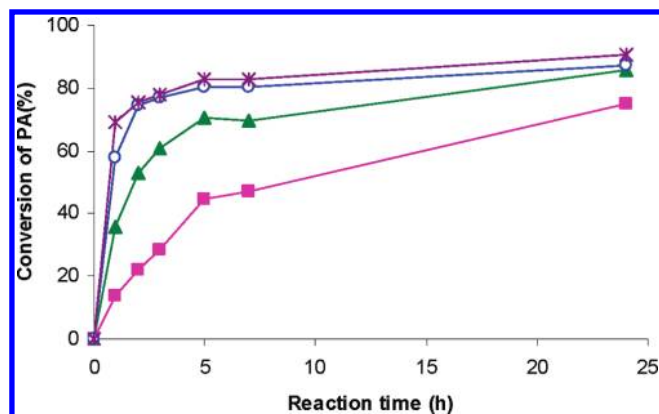


Figure 3. Effect of the amount of strong anion-exchange resin, Amberlite IRA-401 on cross-aldol condensation of propanal with formaldehyde at 35 °C. The resin was used at a concentration of 0.4 g/mL (■), 0.8 g/mL (▲), 1.2 g/mL (○) and 1.6 g/mL (*), respectively.

stage of the reaction between propanal and formaldehyde, using Amberlite IRA-401 as catalyst, included two peaks of the starting materials at RT9.5 and RT12.6 and a new peak at RT 6.2 corresponding to 2,2-bishydroxymethylpropanal as the main product (**8**) resulting from first and second cross-aldol condensation (Table 1, Scheme 1B, Supporting Information). The product peak at RT 8.7 (**6**) is the intermediate, 3-hydroxy-2-methylpropanal formed after first cross-condensation, which is transformed to **8** by a second aldol condensation on one hand and, on the other, undergoes dehydration to product **7**, with methacrolein appearing at RT13.8. A small amount of the product **3** from self-condensation of propanal was also seen at RT16.2 (Supporting Information, Pathway A). Figure 3 shows the profiles of propanal conversion obtained at different amounts of the ion-exchange resin. Larger amount of resin, 1.2–1.6 g/mL, was required for the highest reaction rate that was slower than that of self-aldol condensation. The maximum conversion of propanal obtained was about 83% after 5 h and 91% after 24 h at 35 °C (Figure 3).

Figure 4 shows the conversion of propanal and formaldehyde with time along with the formation of different products in the reaction catalyzed by 1.2 g/mL of resin. The selectivity of conversion of propanal to particular aldehyde products was estimated from the area of each peak in HPLC. From the product profiles observed in Figure 4, it seems that all of the possible reactions took place to give corresponding products within 1 h from the start of the reaction. The products (**2** and **3**) from self-aldol condensation (pathway A) and the product **7** from pathway B involving first cross-condensation followed by dehydration reaction were maintained at the same low level during the entire reaction time. Pathway B was the main reaction giving primarily **8** within 3 h, while the intermediate **6** was increased until 1 h and then decreased within a few hours to a basal level. Product **8** reached highest level at 4–7 h, after which it started to gradually decrease, which may correspond to conversion to other reaction products.

When following the consumption of the starting materials, it was observed that the conversion rate of propanal was slightly higher in the initial stage perhaps due to self-condensation reaction (Scheme 1A). However, the conversion of formaldehyde was continuously increased and reached 94.5%, while conversion of propanal was 87.4% at 24 h. The higher conversion

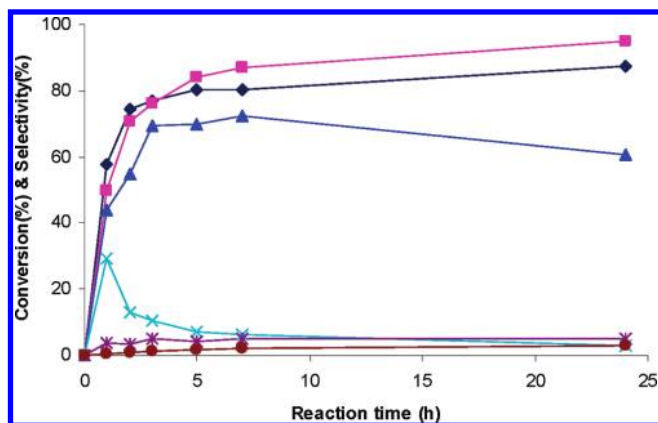


Figure 4. Cross-aldol condensation of propanal with formaldehyde catalyzed by 1.2 g/mL of Amberlite IRA-401 at 35 °C. The various symbols show conversion of propanal (◆) and formaldehyde (■), and selectivity for formation of 3 (●), 6 (×), 7 (*), and 8 (▲).

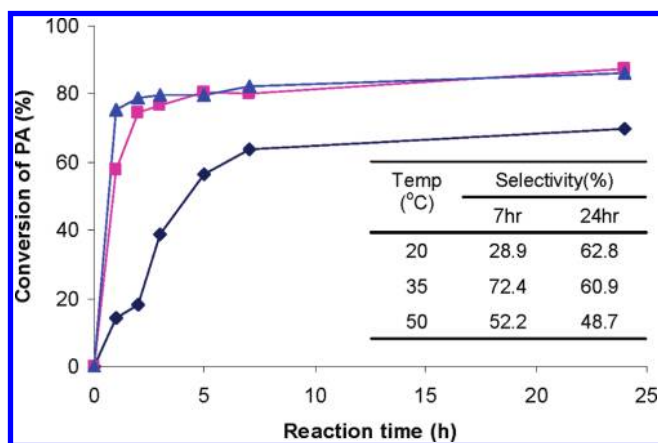


Figure 5. Effect of reaction temperature on cross-aldol condensation of propanal with formaldehyde using 1.2 g/mL Amberlite IRA-401 at 20 °C (◆), 35 °C (■), and 50 °C (▲). The inset table shows selectivity for product 8 after 7 and 24 h reaction.

from use of an excess amount of formaldehyde explained the second aldol condensation of 6 to produce 8.

Figure 5 shows the effect of reaction temperature (20, 35, and 50 °C) on the reaction using 1.2 g/mL of Amberlite IRA-401. The reaction progressed to over 75% conversion within 2 h at 35 and 50 °C, while the rate at 20 °C was significantly low. Selectivity for 8 was the highest (72.4%) at 35 °C at 7 h of reaction but decreased with time as described above.

2.2. Ratio of Propanal and Formaldehyde in Cross-Aldol Condensation Using Strong Anion-Exchange Resin. Propanal was reacted with different concentrations of formaldehyde (0, 0.57, 1.14, and 1.71 equiv). Although the highest rate was obtained in the reaction without formaldehyde, that is, self-aldol condensation, all reactions reached about 80% conversion within 7 h (Figure 6A). Selectivity for 8 was 72.6, 65.9, and 32.8% at FA/PA ratios of 1.14, 1.71, and 0.57, respectively (Figure 6B). Considering reaction rates at ratios 1.14 and 1.71 to be similar (Figure 6A), some different tendencies were seen with respect to selectivity for 8 and 6 (Figure 6B,C). Reaction intermediate 6 was quickly made in the initial stage, reaching the highest level at the highest ratio of FA/PA, and then decreased rapidly due to its

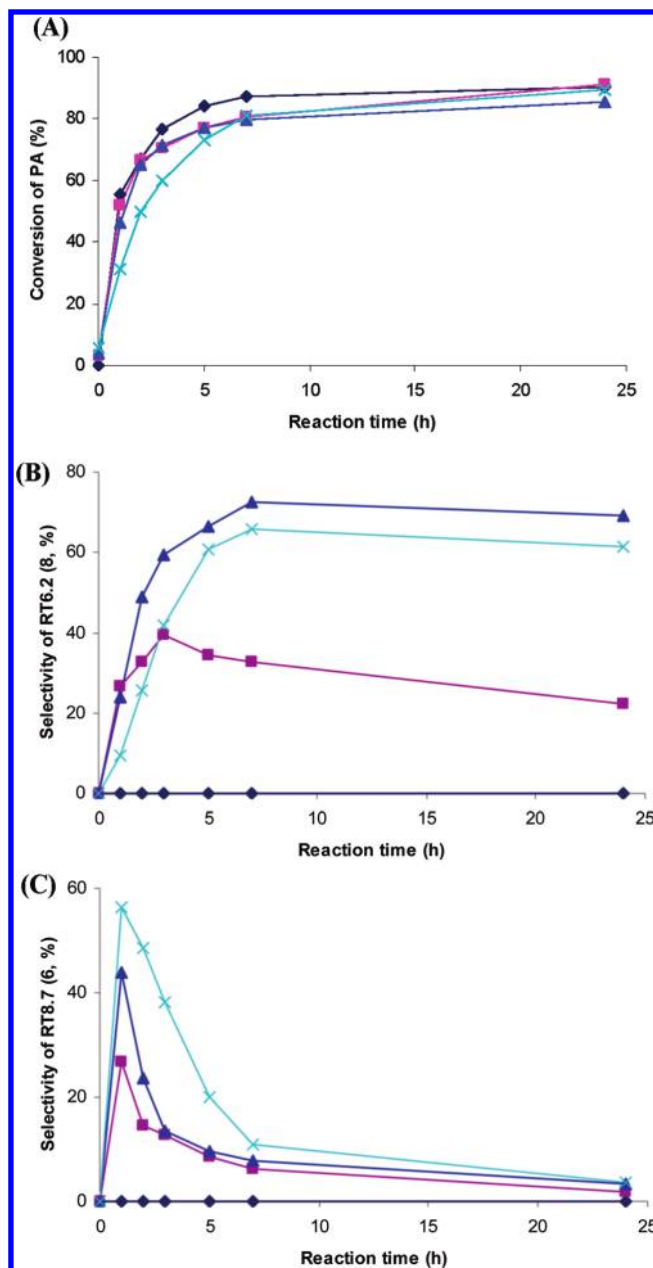


Figure 6. Conversion of propanal (A) and selectivity for product 8 (B), and product 6 (C) during cross-aldol condensation with formaldehyde at various ratios of formaldehyde (FA) and propanal (PA) using 1.2 g/mL of Amberlite IRA-401 at 35 °C. FA/PA ratios were 0:1 (◆), 0.57:1 (■), 1.14:1 (▲), and 1.71:1 (×).

conversion to 8. The sum of 6 and 8 was increased with increasing amount of FA as a result of increase in first and second cross-aldol condensations. On the other hand, the amount of 2 and 3 was decreased to 9.9, 2.2, and 0.8% for FA/PA ratios of 0.57, 1.14, and 1.71, respectively.

2.3. Cross-Aldol Condensation of Propanal with Formaldehyde Using Weak Anion-Exchange Resin. The use of weak anion-exchange resin for the reaction between propanal and formaldehyde gave 3-hydroxy-2-methylpropanal (6) as the main product (Figure 7). The highest selectivity for product 6 was 70.9% at 2 h reaction time (when the conversion of PA was about 50%) and decreased with time to about 60% at 24 h when the

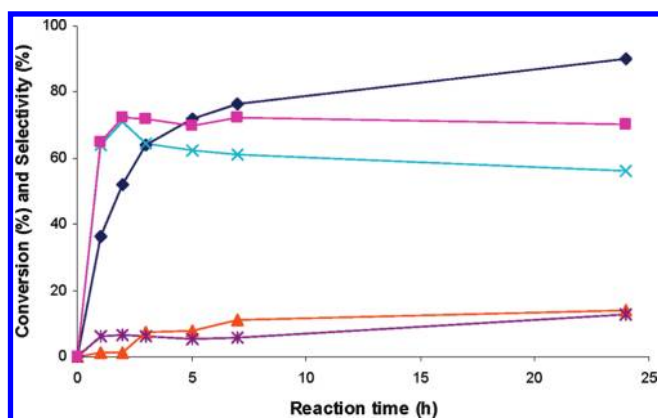


Figure 7. Conversion of propanal (◆) and selectivity for 6 (×), 7 (*), 8 (▲), 6 and 8 (■) during cross-aldol condensation using weak anion-exchange resin (Amberlite IRA-45, 1.2 g/mL) at 35 °C.

conversion had reached 89.9%. Both 7 and 8 were maintained at similar low levels throughout the reaction. The combined selectivity for 6 and 8 was maintained over 70%. The self-condensation products (2 and 3) were not detected by HPLC. It can thus be inferred that the reaction progressed quickly to produce the main product (6), part of which was slowly converted to 7 and 8, and then may be further converted to hydrated products.

The extent of PA conversion and selectivity for different products (6, 7, and 8) obtained at different times with different amounts of weak anion-exchange resin are summarized in Table 2. The reaction (runs 1 and 2) at low temperature and high amount of resin gave lower yield and selectivity. The maximal conversion of about 90% was obtained in the reaction at 35 °C, 24 h, and 0.8 g/mL resin, with 6 being the major product while 7 and 8 were formed in almost equal amounts. The rate of second aldol condensation using weak exchanger was slower than that with the strong exchanger, which could be due to weak association of the resin with α -carbon to give low rate dissociation of H^+ by its counteranion, and the longer lifetime of 6 results in increased formation of 7/8.

3. End Products of Pathways of Self- and Cross-Aldol Condensation of Propanal with Formaldehyde Catalyzed by Anion-Exchange Resins in Aqueous Media. Garland et al. have earlier demonstrated by FT-IR and 1H NMR that the products resulting from acid-catalyzed reaction of hexanal on sulfuric acid particles were both aldol condensation and hemiacetal products.¹⁷ It seems that the aldehyde products formed by aldol condensation in aqueous media catalyzed by the ion-exchange resins also undergo further reaction to give alcoholic, hemiacetal, and acetal moieties. The reaction mixtures with anion-exchange resins were allowed to stand at room temperature for 2 weeks. The solutions were then filtered, and the filter rinsed with acetonitrile and pooled with filtered solution, which was dried to give clean liquid with high viscosity. The samples were then subjected to FT-IR and 1H and ^{13}C NMR analyses.

Very similar results from self- and cross-aldol reactions using strong and weak anion-exchange resin were obtained (Supporting Information). The FT-IR spectrum showed a strong band in the OH stretching region of 3000–3500 cm^{-1} ascribed to alcoholic compounds, while very weak or no band for the band stretching of carbonyl and water was seen at around 1700 and 1650 cm^{-1} , respectively, suggesting the absence of carbonyl

Table 2. Conversion and Selectivity of Cross-Aldol Condensation Using Weak Anion-Exchange Resin under Varying Reaction Conditions

run	reaction condition			conversion (PA, %)	selectivity (%)		
	temp (°C)	resin/PA ratio	time (h)		6	7	8
1	20	1.2	7	72.0	51.1	2.8	4.9
2	20	1.2	24	84.6	56.5	3.5	6.4
3	35	0.4	7	45.4	79.6	11.2	8.9
4	35	0.8	7	76.3	55.6	5.9	6.5
5	35	0.8	24	89.9	56.2	12.8	14.2
6	35	1.2	5	81.2	55.3	5.2	7.6
7	35	1.2	7	89.8	49.8	5.5	11.3
8	35	1.2	24	95.8	42.1	11.6	11.4

compounds in the sample. The chemical shifts on 1H NMR at 2.07, 2.50, and 3.33 ppm under DMSO- d_6 were assigned to the remaining solvents of acetonitrile, DMSO, and water according to the work of Gottlieb et al.¹⁸ The protons attached to heteroatoms such as oxygen and a particular functional group such as aldehyde and acetal show different chemical shifts on 1H NMR (Supporting Information). The weak intensity of aldehyde at around 9.5 ppm showed that remaining aldehyde was very little in comparison to the protons of aliphatic carbon at around 0.5–1.0 ppm. Resulting alcohol, vinyl, hemiacetal, and acetal products appeared at the chemical shift region of 3.0–7.0 ppm. ^{13}C NMR spectrum showed multiple peaks in the 80–110 ppm region, also indicating hydration and/or hemiacetalization of aldehyde, but the hydration could also take place on the β -carbon of α,β -unsaturated aldehyde such as 3 and 7.

Hence, the pathways of self- and cross-aldol condensation are followed by further reaction such as hydration, hemiacetalization, and acetalization. The equilibrium between an aldehyde and its hydrate is quickly established, resulting in higher molecular dimers, trimers, and polymers.^{14–17,19}

CONCLUSION

The work reported in this paper shows that aldol condensation using ion-exchange resin as heterogeneous catalyst in aqueous media can provide an alternative green approach for new C–C bond formation. While self-aldol condensation using strong anion-exchange resin is extremely efficient, providing high yields of the product rapidly, cross-aldol condensation is more complex involving more than one condensation reactions. The desired products of cross-aldol condensation can, however, be obtained by proper selection of weak or strong catalyst and other reaction conditions. The aqueous conditions promote the formation of other reaction products on prolonged incubation, hence termination of the reaction at a proper time is important for obtaining high product yields. Low temperature and absence of organic solvents provide extremely energy-efficient and eco-friendly process conditions as compared to the other methods reported so far. Recycling of the ion-exchange resin was, however, limited to a few cycles, perhaps due to deactivation of the resin in the aqueous medium.²⁰ Conditions for improved recycling need to be investigated to make the process economically viable.

EXPERIMENTAL SECTION

Materials. Propanal (97%), 2,4-dinitrophenylhydrazine (99%, DNPH), 2-methyl-2-pentenal (97%), and methacrolein (95%) were purchased from Sigma-Aldrich (St. Louis, MO). Formaldehyde (37%, aqueous solution in 10% methanol) and acetonitrile (HPLC grade) were purchased from Merck (Germany). All chemicals were used without further treatment. Amberlite IRA-401 (strong anion-exchange resin with quaternary amino groups) and Amberlite IRA-45 (weak anion-exchange resin with primary, secondary, and tertiary amino groups), based on styrene-divinylbenzene matrix, were purchased from BDH Chemicals (Poole, England).

General Reaction Procedure. For the self-condensation reaction, 64.8 mmol (4.5 mL) propanal was mixed with 60 mL of deionized water on a magnetic stirrer for 30 min at room temperature in a 250 mL flask attached with a water condenser. The reaction was started by adding strong anion-exchange resin (Amberlite IRA-401) or weak anion-exchange resin (Amberlite IRA-45), which were preactivated by treatment with 10% sodium hydroxide, followed by washing with deionized water to pH 7.5–8.0.

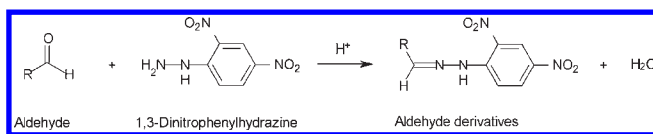
As a general method of cross-aldol condensation, 65 mmol (4.5 mL) propanal and 74 mmol (6 mL) formaldehyde (37%, aqueous solution) were mixed with 54 mL of deionized water under the same conditions as above. The reaction was started by addition of strong or weak anion-exchange resin.

Effects of the amount of ion-exchange resin, ratio of propanal and formaldehyde, and temperature on reaction yield and product selectivity were investigated. The reaction temperature was controlled by using a water bath. Aliquots were taken at different time intervals to analyze the contents of the substrates and products. Blank reactions without using ion-exchange resin were also run, which did not show any substrate conversion.

Analyses Using HPLC, LC-MS, FT-IR, and ^1H and ^{13}C NMR. Quantitative analyses of the substrates and products were performed using high-performance liquid chromatography (Jasco, Tokyo, Japan) on a RP-18 column (4.6 \times 250 mm, pore diameter 5 μm , Merck, Germany). The column was eluted by a gradient of solvent A (30% acetonitrile/water) and B (100% acetonitrile) starting from 90 vol A/10 vol B to 10 vol A/90 vol B for 15 min, and then 10 vol A/90 vol B for 5 min at a flow rate of 1.0 mL/min. All samples were derivatized with DNPH for detection by UV detector (Scheme 2).²¹ One hundred microliter samples diluted 40 times were reacted with 50 μL of 0.1 M DNPH stock solution (prepared in a solvent system composed of 1:1 2 N HCl/acetonitrile) at room temperature for 20 min, followed by two extractions using 250 μL of ethyl acetate. One hundred microliters of the extract solution was dried and dissolved in 0.5 mL of acetonitrile for injection into HPLC. Elution was monitored at 356 nm, λ_{max} of derivatized propanal.²² The selectivity was estimated by comparing the peak area of the products on the chromatogram. The concentrations of propanal and formaldehyde in the samples taken during the reaction were calculated from their respective standard curves prepared in the range of 0.05 to 2.0 mg/mL. The percent conversion of the substrates was then calculated by comparison with the respective concentration at time zero.

The derivatized aldehyde compounds were also elucidated by electrospray ionization mass spectrometry using a QSTAR hybrid Pulsar instrument (Applied Biosystems, CA, USA) equipped with series 200 liquid chromatography system

Scheme 2. Formation of Aldehyde Derivatives by 1,3-Dinitrophenylhydrazine (DNPH)



(Perkin-Elmer, Norwalk, CT) and spiking method using standard materials. Elucidations of product structure were performed using FT-IR (Bruker, ALPHA-P, Germany) and ^1H and ^{13}C NMR (Bruker, UltraShield Plus 400, Germany).

ASSOCIATED CONTENT

S Supporting Information. Additional figures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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