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Research Article

Green Metrics Evaluation on The Cannizzaro Reaction of *p*-Anisaldehyde and Benzaldehyde Under Solvent-Free Conditions

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Abstract

This research aimed to evaluate the Cannizzaro reaction employing *p*-anisaldehyde and benzaldehyde under solvent-free conditions, highlighting environmentally responsible chemical processes. Using reflux and ultrasonication approaches with KOH as the reagent, the reaction's progress was observed through TLC, and the products were characterized by means of melting point analysis, FTIR, and GC/MS. A comprehensive environmental evaluation was performed by applying green metrics called the Environmental Assessment Tool for Organic Syntheses (EATOS) software, and the Andraos algorithm, accompanied by energy consumption calculations. An in-depth analysis of the green metrics outcomes was achieved within the context of present literature, allowing a measurement of the attained level of eco-friendliness. Experimental findings revealed optimal conditions for the Cannizzaro reaction concerning *p*-anisaldehyde at a temperature of 50 °C for 90 minutes, resulting in remarkable *p*-anisyl alcohol and *p*-anisic acid in 95.16% and 95.04% yields, respectively. Similarly, the reaction involving benzaldehyde reached its peak performance at 50 °C for 2 hours, yielding benzyl alcohol (96.17%) and benzoic acid (97.22%). The overall assessment of green metrics and energy consumption reliably affirmed that the solvent-free Cannizzaro reaction, particularly when utilizing ultrasonication, offers a substantially greener and more energy-efficient alternative compared to traditional methods.

Keywords: aldehyde, Cannizzaro, green metrics, ultrasonication

1. INTRODUCTION

Chemical synthesis has well-documented negative effects on the environment, i.e. ozone layer depletion and the generation of harmful organic pollutants.[1] To overcome these problems, the International Union of Pure and Applied Chemistry (IUPAC) arranged four conferences devoted to green chemistry. The result is vital arrangements endorsing the development of eco-friendly products and processes and the development of the use of renewable chemical sources.[2] This has directed to cutting-edge waste disposal approaches, and thoughtful chemical and solvent practices to guarantee that chemical reactions leave a minimal footmark on the environment and human health. Remarkably, the espousal of water as a solvent in organic synthesis is a prominent improvement in green chemistry.[3] However, the reaction without solvent is preferable, as simpler, more efficient, and environmentally benign,[4] which thus, could be applied in the Cannizzaro reaction.

The Cannizzaro reaction is a chemical process characterized by the base-induced disproportionation of an aldehyde that lacks a hydrogen atom in the α position [5]. This third-order kinetic reaction is disclosed in two distinctive steps. The initial step involves a nucleophilic acyl substitution on an aldehyde, where the leaving group simultaneously participates in an attack on another aldehyde in the subsequent step. The ensuing step features the exchange of a proton between the acid and alkoxide ions formed during the reaction. Importantly, the rate-determining step occurs during the hydride transfer from the intermediate to the electron-deficient carbonyl

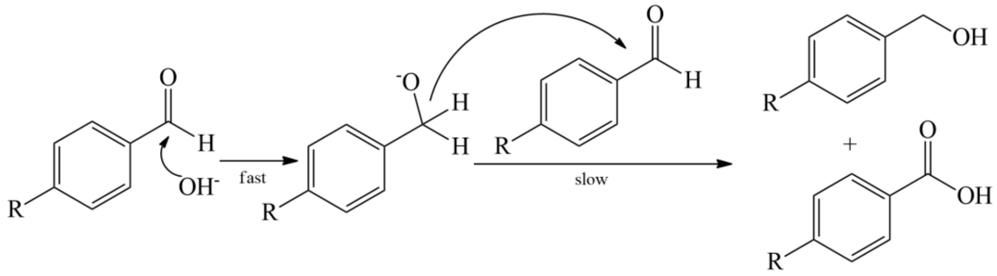


Figure 1. Reaction Scheme of the Cannizzaro Reaction

carbon atom of another aldehyde molecule. This pivotal step governs the overall speed of the Cannizzaro reaction, underscoring its significance in understanding the kinetics of this chemical transformation (**Figure 1**).[6] The Cannizzaro reaction can be performed using strong bases such as NaOH, KOH, LiOH, and Mg-Al hydrotalcite.[7,8] The method can be done with reflux,[9] microwave irradiation,[10] and grinding.[11] Some of these methods have limitations, for example, the grinding method, where small amounts of sample might be lost during processing, and since it is done by hand, the energy cannot be quantified. Thus, the reaction time and the yield of the product might be different depending on the grinding power.[4] In the case of reflux, the limitation of the Cannizzaro reaction is generally carried out in a hazardous organic solvent with a relatively long reaction time. The Cannizzaro reaction involving benzaldehyde and a KOH base in water was reported by Furniss et al. at room temperature for 24 hours.[12] The Cannizzaro reaction of *p*-anisaldehyde was reported by Kusumaningsih et al. using KOH in water at room temperature for 24 hours.[9] Unfortunately, the reaction did not produce the expected *p*-anisyl alcohol, and only a small amount of *p*-anisic acid (<10%) was obtained. Likewise, microwave irradiation has drawbacks concerning its maximum power and the temperature sensor i.e., infrared sensor, which is susceptible to poor measurements. In addition, prolonged exposure to microwaves can cause damage to body tissues and cells.[13] Based on these weaknesses, in this study, the ultrasonication method was chosen for the Cannizzaro reaction.

The ultrasonication method uses ultrasonic irradiation which produces a cavitation effect thereby increasing the reaction rate compared to conventional procedures which usually require a longer reaction time.[14] Ultrasonic waves provide mechanical energy for homogenizing reactants as well as providing heat energy for the reaction to take place. In addition, these ultrasonic irradiations dominate the tensile forces at high-intensity sound waves, resulting in the creation of cavitation bubbles that grow from coalescing and crushing during the compression phase resulting in the formation of a hot area and helping in mass transfer.[15] This cycle begins with the appearance of bubbles with a diameter of about 100 μm which are getting bigger and the frequency of the bubbles decreases because they carry energy.[16] This energy can be utilized in the Cannizzaro reaction. Research on the ultrasound Cannizzaro reaction has been reported.[17] Unfortunately, some of the reported Cannizzaro reactions have not been evaluated for the impact of the chemical reaction on the environment, energy consumption, as well as assessing the level of greenness.

In the extension of former research efforts intensive on green metrics assessment,[18,19] this research studies the environmental footprint of Cannizzaro reactions involving benzaldehyde and *p*-anisaldehyde. The Environmental Assessment Tool for Organic Syntheses (EATOS) software and the Andraos algorithm were employed to assess the effectiveness and environmental sustainability of these chemical reactions. Moreover, the investigation of energy efficiency by quantifying the energy consumed during the Cannizzaro reaction process was performed, accounting for electrical power and reaction time.

2. RESEARCH METHODS

Materials

The materials used in this study were commercial products from Merck, including *p*-anisaldehyde (98%), benzaldehyde (99%), KOH, HCl, Na_2SO_4 anhydrous, dichloromethane, *n*-hexane (99%), ethyl acetate (99.5%), acetone (99.8%), $KMnO_4$, NaOH and K_2CO_3.

Equipment

Various analytical techniques were employed in this research. Thin-layer chromatography (TLC) utilized silica gel plates (0.2 mm thick, Merck), and stains were identified under a UV lamp (λ=365 nm). Melting points were determined using a Stuart melting point determination tool. Gas Chromatography / Mass Spectrometry (GC/MS) spectra were recorded with a Shimadzu QP-2010S spectrometer under the following conditions: electron impact (EI) ionization at 70 eV, HP-5MS 30-meter column, helium as the carrier gas, column temperature at 70 °C, injector temperature at 300 °C, gas flow rate of 35.6 mL/min, pressure set at 30 kPa, column rate of 0.65 mL/min, split injection type, pressure-based rate controller, linear velocity of 29.6 cm/second, purge flow at 3.0 mL/min, and a split ratio of 49.0. Infrared (IR) spectra were recorded using a Shimadzu FTIR-PRESTIGE 21 spectrophotometer. Ultrasonication was performed with a Baku BK-2000 ultrasonic cleaning bath operating at a frequency of 40 kHz and a power of 120 W.

Experimental

Ultrasonication

In a beaker, 0.54 g (0.01 mol) of powdered KOH was combined with 0.850 g (0.00625 mol) of *p*-anisaldehyde and subjected to ultrasonication at varying durations (15, 30, 45, 60, 75, and 90 minutes) and temperatures (room temperature and 50 °C). After cooling, 2.5 mL of water was added, followed by extraction with dichloromethane (2 x 2 mL). The water layer was then acidified with 3M HCl. The resulting white precipitate underwent a melting point test. Concurrently, the dichloromethane layer was mixed with anhydrous Na_2SO_4 and evaporated to yield a second product. Both products underwent identification using FTIR and GC/MS. The same experimental procedure was replicated with benzaldehyde (0.00625 mol; 0.663 g) under varying ultrasonication durations (30, 60, 90, and 120 minutes) and temperature conditions (room temperature and 50˚C). All of the isolated carboxylic acid and alcohol products were determined for their yields.

Reflux

Powdered KOH 0.54 g (0.01 mol) was mixed with 0.850 g (0.00625 mol) *p*-anisaldehyde in a two-neck flask and refluxed with varying temperatures (room temperature and 50˚C) and times (1, 2, 3, 4 and 4.5 hours). After cooling, 2.5 mL water was added, extracted with dichloromethane (2 x 2 mL), and the water layer was acidified with 3M HCl. The separated white precipitate underwent a melting point test. The dichloromethane layer was dried over anhydrous Na_2SO_4 and evaporated to obtain the second product. All of the products were then characterized by means of FTIR and GC/MS. The identical procedure was employed for benzaldehyde (0.00625 mol; 0.663 g) with ultrasonication durations of 1, 2, 3, 4, and 5 hours, encompassing temperature variations at both room temperature and 50 °C. Yields were determined for all the isolated carboxylic acid and alcohol products.

3. RESULTS AND DISCUSSION

Cannizzaro Reaction using Ultrasonication Method

This study investigated the Cannizzaro reaction of aldehydes (*p*-anisaldehyde and benzaldehyde) using basic KOH under solvent-free ultrasonic conditions. The reaction was performed at room temperature and 50 ℃ and the progress of the reactions was monitored using TLC with *n*-hexane:ethyl acetate (7:3) as the eluent. Visible starting material spots persisted for 90 minutes (*p*-anisaldehyde) and 2 hours (benzaldehyde). Contrastingly, at 50 ℃, complete reactions occurred in 90 minutes (*p*-anisaldehyde) and 2 hours in the case of benzaldehyde. Compared to reflux under the same conditions, room temperature reactions took longer reaction time i.e. 4.5 hours for *p*-anisaldehyde and 5 hours in case of benzaldehyde. However, at 50 ℃, reactions were completed within 4.5 hours (p-anisaldehyde) and 5 hours (benzaldehyde). This showcases ultrasonication's efficiency over reflux, attributed to its cavitation effect induced by ultrasonic or acoustic waves causing bubble formation and bursting in liquids. The presence of ultrasonic waves will increase the number of active cavitation bubbles which will increase the efficiency of the reaction by increasing the reaction rate, speeding up the reaction,[18] and increasing the local temperature and pressure of the liquid [20,21]. Therefore, the Cannizzaro reaction using the ultrasonic method is faster than the reflux method. The Cannizzaro reaction of *p*-anisaldehyde produced *p*-anisyl alcohol (95.16% as yellowish liquid) and *p*-anisic acid (95.04% as white solid). Benzaldehyde generated benzyl alcohol (96.17% as yellowish liquid) and benzoic acid (97.22% as white solid). The acid products were identified through melting point tests: *p*-anisic acid melted at 184-185 °C and benzoic acid at 121-123 °C, aligning with literature values[22] and the melting point of benzoic acid is 122.4 °C.[23]

Identification by FTIR and GC/MS was carried out on the Cannizzaro reaction product. The FTIR results for *p*-anisyl alcohol and *p*-anisic acid are shown in **Figure 2a**. The *p*-anisyl alcohol FTIR spectra show a strong absorption at 3393 cm^{-1} with a broad peak indicating that there is a hydroxyl group (-OH). Absorption at 3004 cm^{-1} showed the aromatic C-H strain, and absorption at 2943 cm^{-1} and 2840 cm^{-1} showed the Csp^3-H stretch of the methyl group. Absorption at 1610 cm^{-1} and 1513 cm^{-1} shows the double bond stretching (C=C) from the aromatic core. The presence of a methylene group is shown in the absorption with a vibrational frequency of 1460 cm^{-1}. Strong absorption at 821 cm^{-1} indicates that the aromatic group has a substituent in the para position. Based on the identified functional groups, it is very supportive of the functional group of the *p*-anisyl alcohol compound. The FTIR results for benzyl alcohol and benzoic acid are shown in **Figure 2b**. Based on the benzyl alcohol FTIR spectral analysis, it shows that there is no strong absorption around 1700 cm^{-1} which indicates there is no carbonyl group,[24] this is the characteristic of the conversion of benzaldehyde to benzyl alcohol. Strong absorption was found at around 3404 cm^{-1} indicating the presence of the -OH hydroxyl group. Absorption that appears at a vibrational frequency of 1601 cm^{-1} and around 1553 cm^{-1} indicates the presence of double bond stretching (C=C) from the aromatic core. At 3030 cm^{-1} the absorption shows stretching of the aromatic C-H bonds. In addition, there is also a methylene group indicated by absorption at 1453 cm^{-1}. Based on the spectra, it shows the absorption of benzyl alcohol.

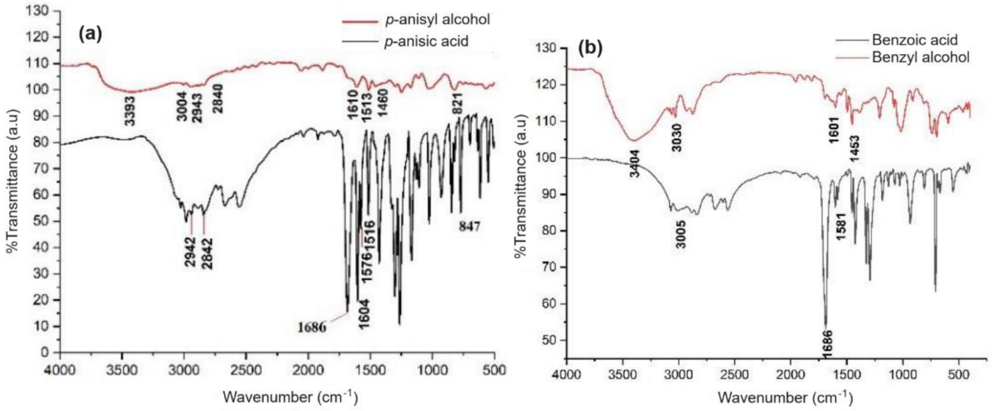
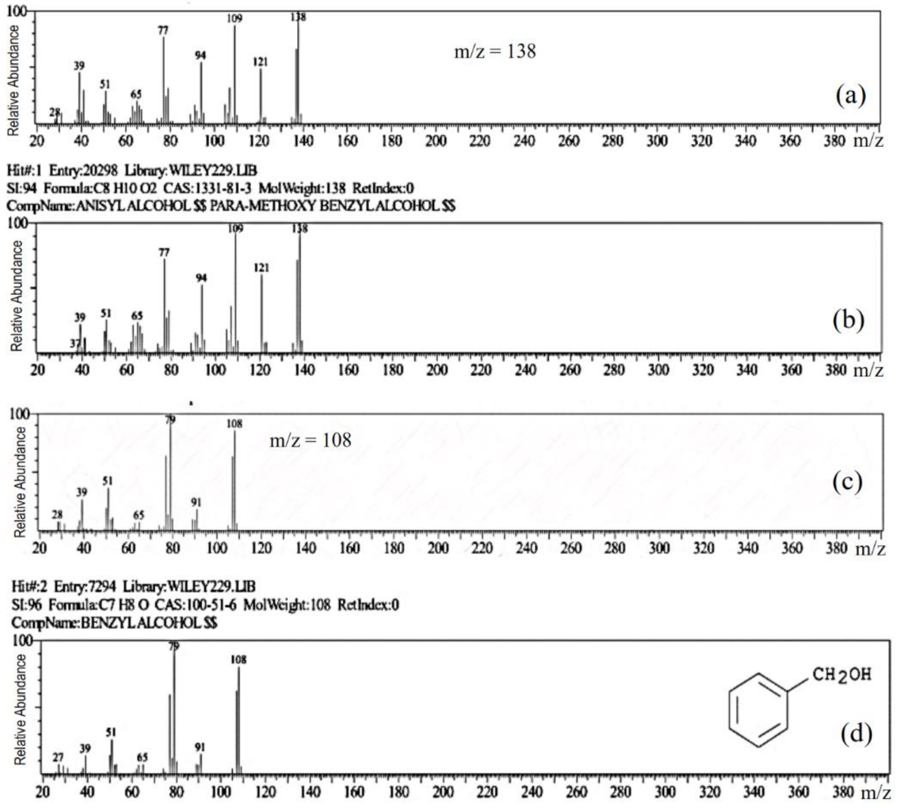


Figure 2. FTIR spectra of p-anisyl alcohol and p-anisic acid from the p-anisaldehyde Cannizzaro reaction (a), benzyl alcohol and benzoic acid from the benzaldehyde (b) (KBr plate)



Hit#:1 Entry:20298 Library:WILEY229.LIB
SI:94 Formula:C8 H10 O2 CAS:1331-81-3 MolWeight:138 RetIndex:0
CompName:ANISYL ALCOHOL $$ PARA-METHOXY BENZYL ALCOHOL $$

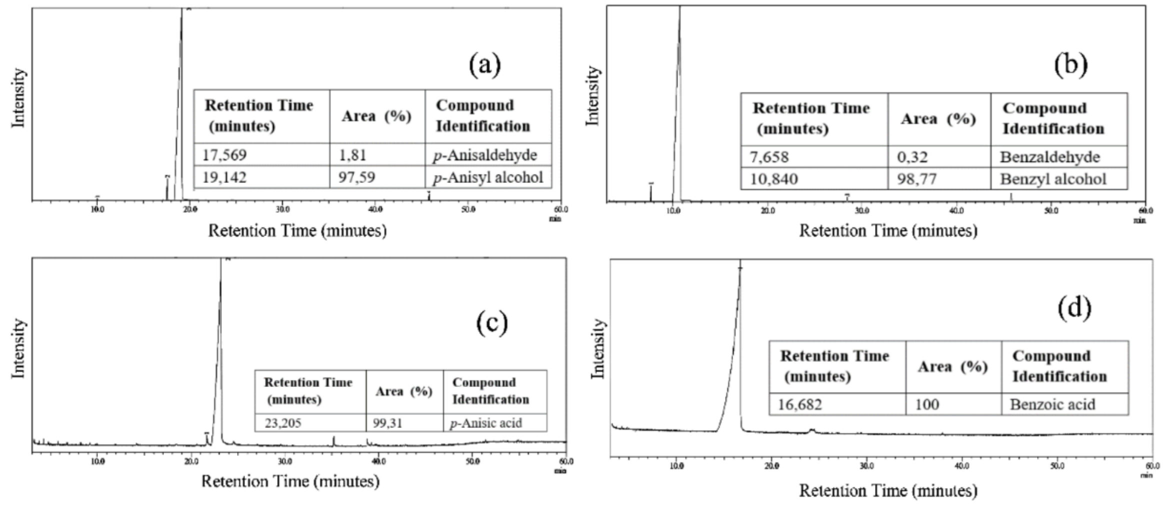
Hit#:2 Entry:7294 Library:WILEY229.LIB
SI:96 Formula:C7 H8 O CAS:100-51-6 MolWeight:108 RetIndex:0
CompName:BENZYL ALCOHOL $$

Figure 3. Mass Spectra of p-anisyl alcohol of Cannizzaro reaction (a), p-anisyl alcohol standard (b) benzyl alcohol of Cannizzaro reaction (c), and benzyl alcohol standard (d). The standard is according to the Wiley229 library.

The FTIR results of the *p*-anisic acid compound are shown in **Figure 2a.** In the spectra, there is strong absorption at 1686 cm^{-1} which shows a typical absorption of C=O stretching conjugated to aromatic compounds. Wide absorption in the region between 3300-2500 cm^{-1}, indicating O-H stretching vibrations of carboxylic acid products forming dimers.[25] Absorption at 1604 cm^{-1}, 1576 cm^{-1}, and 1516 cm^{-1} showed double bond strain (C=C) from the aromatic core. Absorption of 847 cm^{-1} indicates that the aromatic core is substituted in the para position. Then at 2842 cm^{-1} and 2942 cm^{-1}, absorption showed Csp^3-H stretching absorption.[25] Based on the absorption, there is a carbonyl group, a wide O-H absorption, and an aromatic core substituted at the para position, so it is very supportive of the functional group of the compound *p*-anisic acid. Meanwhile, the FTIR results for benzoic acid are shown in **Figure 2b**. The strong absorption at 1686 cm^{-1} shown by the FTIR spectra identified a typical C=O stretching absorption conjugated with aromatic compounds. The FTIR spectra did not show any OH absorption bands in the 3750-3000 cm^{-1} region but showed a wide absorption at 3200-2500 cm^{-1} resulting from the dimerization of carboxylic acids.[26] The absorption at 1581 cm^{-1} indicates the C=C double bond from the aromatic core. The aromatic C-H strain is indicated by the presence of absorption at a vibrational frequency of 3005 cm^{-1}. The compounds analyzed contain carbonyl groups, broad OH absorption, and an aromatic core. These functional groups correspond to the functional groups of benzoic acid compounds.

The FTIR identification is supported by the GC/MS identification. The chromatogram of *p*-anisyl alcohol showed that there was a main peak at a retention time of 19.142 minutes **(Figure 4a)** which was identified as a compound of *p*-anisyl alcohol. Likewise, the chromatogram of benzyl alcohol shows a dominant peak at a retention time of 10.84 minutes **(Figure 4b)**. The mass spectra of *p*-anisyl alcohol (**Figure 3a)** show the presence of a molecular ion at m/z 138 corresponding to the molecular weight of *p*-anisyl alcohol and similar to the mass spectra of the standard compound *p*-anisyl alcohol **(Figure 3b)** with the similarity index value of 94%. As for benzyl alcohol (**Figure 3c)**, the molecular ion at m/z 108 shows the molecular weight of benzyl alcohol. The similarity index of benzyl alcohol to the standard compound benzyl alcohol **(Figure 3d)** is 95%.

The GC/MS identification was also carried out on carboxylic acid products. The *p*-anisic acid chromatogram shows that there is a main peak with a retention time of 23.205 minutes **(Figure 4c)**. Meanwhile, there was one peak with a retention time of 16.68 minutes for benzoic acid **(Figure 4d)**. The mass spectra of *p*-anisic acid (**Figure 5a)** are similar to those of the standard compound *p*-anisic acid **(Figure 5b)** with a similarity index value of 93 and showing a molecular ion at m/z 152. The mass spectra of benzoic acid (**Figure 5c)** are similar to standard benzoic acid compounds **(Figure 5d)** with a similarity index of 96% and molecular ion at m/z 122.



(a)

Retention Time (minutes)	Area (%)	Compound Identification
17,569	1,81	*p*-Anisaldehyde
19,142	97,59	*p*-Anisyl alcohol

(b)

Retention Time (minutes)	Area (%)	Compound Identification
7,658	0,32	Benzaldehyde
10,840	98,77	Benzyl alcohol

(c)

Retention Time (minutes)	Area (%)	Compound Identification
23,205	99,31	*p*-Anisic acid

(d)

Retention Time (minutes)	Area (%)	Compound Identification
16,682	100	Benzoic acid

Figure 4. Chromatogram of p-Anisyl alcohol (a), Benzyl alcohol (b), p-Anisic acid (c), and Benzoic acid (d)

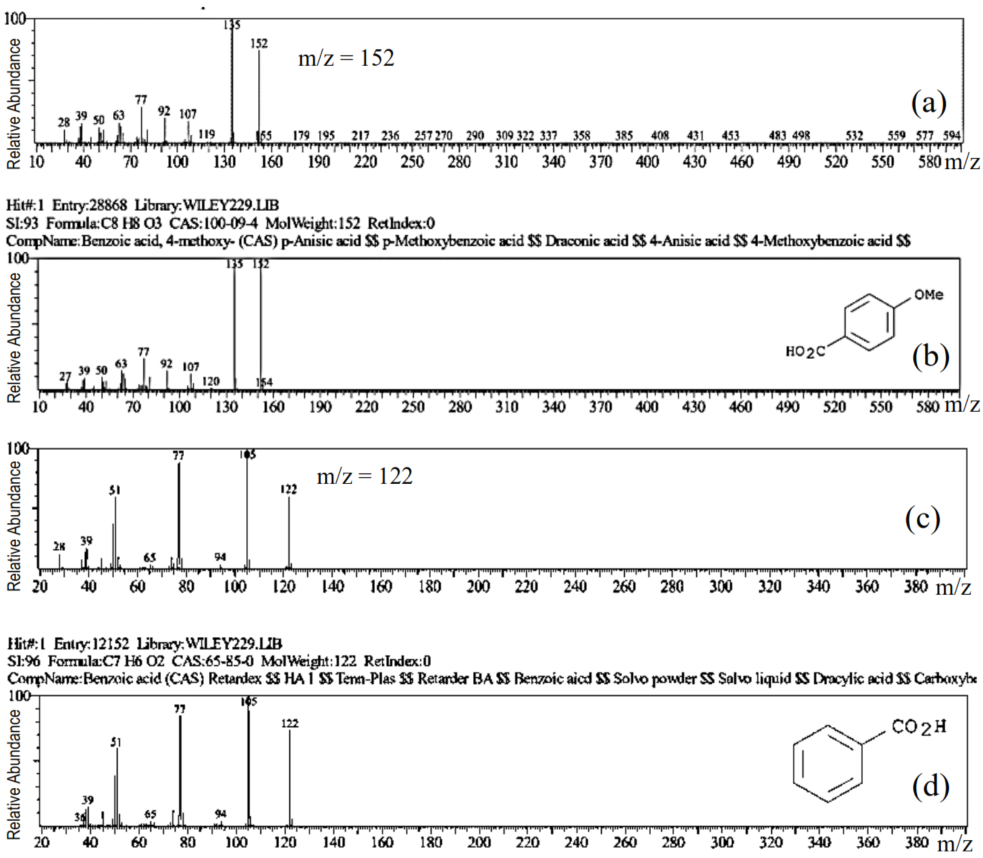


Figure 5. Mass Spectra of p-anisic acid of Cannizzaro reaction (a), p-anisic acid standard (b), benzoic acid of Cannizzaro reaction (c), and benzoic acid standard (d)

Energy Comparison

The ultrasonication method and the reflux method use different tools with different power levels. These differences lead to differences in energy consumption during the reaction. Therefore, energy calculations can be carried out to determine the level of research energy efficiency. This is intended to apply the principles of green chemistry with minimal energy use to avoid environmental and economic impacts. The energy calculation results from the ultrasonication method and the reflux method are shown in **Table 1**.

Table 1. is the result of the energy calculation of the ultrasonication and reflux method which is obtained from the formula of the equation that has been reported by [30] on research by [21]. According to **Table 1.** it can be seen that the ultrasonication method is more efficient than the reflux method with large energy consumption.

It is worth to note that the difference in *p*-anisaldehyde yields between ultrasonic and reflux methods (95% vs. 83%) implies that the ultrasonic approach may offer more efficient conditions for the Cannizzaro reaction with *p*-anisaldehyde compared to reflux. Moreover, the methoxy group on *p*-anisaldehyde, serving as an electron-donating group, influences the electrophilicity of the aldehyde carbonyl group through resonance, rendering it challenging for $^{-}$OH to initiate an attack. This phenomenon is suspected under reflux conditions but not observed during ultrasonication, attributed to the influence of cavitation effects. However, the analogous yields obtained for benzaldehyde in both methods (96-97% vs. 95-94%) suggest that the impact of the ultrasonic method might be less significant for benzaldehyde.

Green Metrics Measurements

The greenness of the reaction is important to know in a chemical reaction process. EATOS software can be used to determine the effect of all substances in the reaction. The parameters in the EATOS software are mass index (S^{-1}), environmental factor (E Factor), environmental index input (EI_{in}), and environmental index output (EI_{out}). S^{-1} and EI_{in} values are presented in **Figure 6**.

Table 1. Energy comparison ultrasonication method and reflux method

Aldehyde	Parameter	Ultrasonication	Reflux
p-anisaldehyde	Equipment	Ultrasonicator	Hot plate and water pump
	Moles	0.00625	0.00625
	Yield (%)	*p*-anisyl alcohol: 95.16 *p*-anisic acid: 95.04	*p*-anisyl alcohol: 82.28 *p*-anisic acid: 83.55
	P (kW)	0.22	Hot plate=0.8, Water pump=0.06
	t (h)	1.5	4.5
	E (kW h)	0.33	3.87
	E (kW h/mol)	55.48	752.55
Benzaldehyde	Equipment	Ultrasonicator	Hot plate dan water pump
	Moles	0.00625	0.00625
	Yield (%)	Benzyl alcohol: 96.17 Benzoic acid: 97.22	Benzyl alcohol: 94.12 Benzoic acid: 95.91
	P (kW)	0.22	Hot plate=0.8, Water pump=0.06
	t (h)	1.5	5
	E (kW h)	0.44	4.3
	E (kW h/mol)	70.4	730.98

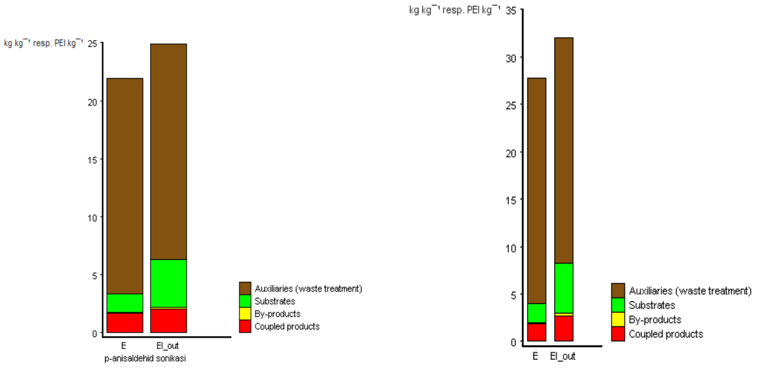
(a) (b)

Figure 6. Results of measuring S^{-1} and EI_{in} values from the optimum conditions of the Cannizzaro *p*-anisaldehyde (a) and benzaldehyde (b) reactions using the EATOS software

The S^{-1} value of the Cannizzaro *p*-anisaldehyde reaction without solvent was 22.83 Kg/Kg of product, while it showed a value of 28.66 Kg/Kg of product for benzaldehyde. This value is dominated by dichloromethane and water as the solvent for separation. The measurement of the EI_{in} value by combining the S^{-1} and Q values is related to the price and risk of the nature of the substances involved. The EI_{in} value interprets the potential environmental impact of the raw materials used, namely substrates and auxiliary materials.[28] The EI_{in} value for the Cannizzaro reaction *p*-anisaldehyde was 32.93 PEI/Kg, while for benzaldehyde it was 28.66 PEI/Kg. Green metric measurements using the EATOS software also produce E factor and EI_{out} values shown in **Figure 7**. which refer to the amount of waste and its properties produced during the reaction process.[29]

The EI_{out} measurement interprets the properties of the waste generated and its impact. EI_{out} is obtained by combining the E Factor and Q values (toxicity values) based on the calculations shown by EATOS. In this study, the EI_{out} value for *p*-anisaldehyde was 24.74 PEI/Kg, while the value for benzaldehyde was 31.66 PEI/Kg. This relatively high value is due to dichloromethane and water for product separation. The Q value of KOH has a role in the environmental impact value. KOH has a specific impact with a value of Q = 4. This shows that KOH has a toxicity effect of 4 on humans and the environment. E Factor value interprets the amount of waste.[29] In this study, the *p*-anisaldehyde E Factor value was 21.77 Kg/Kg of product, which was dominated by dichloromethane and water in the reaction product separation process. Whereas Benzaldehyde was 27.58 Kg/Kg of the product. The E Factor value on the substrate is due to the excess substrate (KOH and HCl).

Green metric measurements are also carried out using the Andraos algorithm with five parameters. Atom Economy (AE) shows the ratio of product molecular weight to the number of reactant molecules. Reaction Mass Efficiency (RME) shows the ratio of the mass of the product to the total mass of the reactants, solvents, and auxiliaries used in the reaction. Rxn Yield shows the yield resulting from the reaction. The Stoichiometry Factor describes the total amount of excess reagent used in a particular chemical reaction to the stoichiometrically balanced amount. Material Recovery Parameter (MRP) describes the consumption of solvents and auxiliaries used in reactions that can be recovered through recycling.[30] The results of the green metric measurements of the solvent-free Cannizzaro reaction with the Andraos algorithm are shown in **Table 2.**



(a) (b)

Figure 7. The results of measuring the E Factor and EI_{out} values of the optimum conditions for the reaction of Cannizzaro *p*-anisaldehyde (a) and benzaldehyde (b) using the EATOS

Table 2. Green Metric Measurement Results for the Cannizzaro Reaction Solvents-free Using the Andraos Algorithm

Aldehyde	AE	RME	Rxn Yield	1/SF	MRP
p-Anisaldehyde	1	0.099	0.469	0.755	0.278
Benzaldehyde	1	0.088	0.487	0.705	0.257
Ideal	1	1	1	1	1

Table 3. List of Cannizzaro p-Anisaldehyde Reactions from Various Literature

Code	Substrate (moles)	Catalyst (g)	Solvent (mL)	Yield^a	Yield^b	Reference
A	*p*-anisaldehyde (0.006), KOH (0.009)	-	-	83.55 %	82.28%	Reflux (This study)
B	*p*-anisaldehyde (0.006), KOH (0.009)	-	-	95.04 %	95.16%	Ultrasonication (This study)
C	*p*-anisaldehyde (0.002), NaOH (0.01)	Al_2O_3	water (0,2)	98%	98%	[10]
D	*p*-anisaldehyde (0.002), KOH (0.01)	-	water (10)	7.33%	-	[9]

Yield^a for *p*-anisic acid and Yield^b for *p*-anisyl alcohol

The results of green metric measurements for the Cannizzaro reaction without solvent using the Andraos algorithm show an ideal AE value, a relatively high 1/SF value, and relatively low Rxn Yield, MRP, and RME values. The AE value shows that almost all of the reactants are utilized to become products. The 1/SF value is close to ideal due to the excess moles of the substrate, namely KOH so that the reaction equilibrium goes towards the products. The low MRP value is due to the use of auxiliary materials. A low Rxn Yield value is obtained, because stoichiometrically the reactants used have a coefficient of 2 for the oxidation and reduction reactions to produce both products, while the resulting products each have a coefficient of 1. The RME value is the numerical result of the other four variables. The low RME value is due to the other four factors which are not ideal.

Comparison of the Green Metric between Ultrasonic Methods and Other Methods

The results of this study were compared with studies of the Cannizzaro reaction from other literature. A list of Cannizzaro's reactions to *p*-anisaldehyde as a comparison from various literature can be seen in **Table 3**.

Calculations using EATOS have specific parameters to compare these reactions, including the bases used, catalysts, solvents, and yields regardless of other factors such as additives, price, and material quality factor (Q). Therefore, without considering the material quality factor in the environment, only a comparison of the E Factor and S^{-1} values is obtained. A Comparison of the results of measuring the values of E factor and S^{-1} from this study with various other methods using the EATOS software is shown in **Figure 8.**

Based on **Figure 8,** it can be seen that the highest E Factor values (Kg/Kg product) and S^{-1} (Kg/Kg product) are highest in method D, due to high solvent usage. Then it was followed by research C. In this study, method B had the lowest E Factor and S^{-1} values. Compared to method A, values were similar, but method A had a higher E Factor and S^{-1} due to lower yield. Method C had a high yield but elevated E Factor and S^{-1} due to excessive catalyst and solvent use. Contrasting method B with D, B showed a lower E Factor and S^{-1}. The high value of S^{-1} in method D was due to abundant substrate and solvent, while the high E Factor stemmed from low yield and lack of alcohol products. Low E Factor in D was from high yield and minimal excess substrate, and low S^{-1} was due to limited substrate. Apart from EATOS, calculations using the Andraos algorithm were also carried out. Calculation results are shown in **Table 4**.

Based on **Table 4**, it can be seen that all methods (A, B, C, and D) have the same AE value. This is because it uses the assumption of the same reaction so that it is easy to compare. Method B has a superior Rxn Yield value when compared to the other three methods, because of the high yield obtained and also the production of KCl. Based on **Table 4**, it can also be seen in the value of 1/SF and MRP, Methods A and B have the same value due to the use of the same amount of substrate. However, both are superior when compared to method D. As for the comparison between methods A and B, method B has a higher Rxn Yield value than method A because the yield value of method B is higher than method A. The RME value of method B is the highest. This shows that the mass percentage of the reactants remaining in the product is small when compared to the others. The results of the Cannizzaro reaction to benzaldehyde were also compared with other methods, and are presented in **Table 5**.

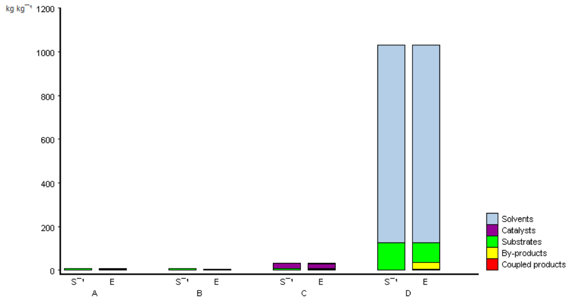


Figure 8. The results of measuring the E Factor and S^{-1} values from the optimum conditions for the Cannizzaro p-anisaldehyde reaction using the ultrasonication method and various other methods using the EATOS software.

Table 4. Green Metrics Measurement Results of the Cannizzaro *p*-Anisaldehyde Reaction Various Literature Using the Andraos Algorithm

Parameter	Method (A)	Method (B)	Method (C)	Method (D)
AE	1	1	1	1
Rxn Yield	0.421	0.469	0.398	0.055
1/SF	0.755	0.755	0.791	0.525
MRP	0.278	0.278	0.074	0.072
RME	0.089	0.099	0.023	0.002

Table 5. List of Cannizzaro Benzaldehyde Reactions from Various Literature

Code	Substrate (moles)	Catalyst (g)	Solvent (mL)	Yield[a]	Yield[b]	Reference
A	Benzaldehyde (0.002), NaOH (0.01)	Al_2O_3 (3)	Water (0.2)	97%	97%	[10]
B	Benzaldehyde (0.03), KOH (0.06)	-	Water (3.6)	61.4%	55.4%	[31]
C	Benzaldehyde (0.006), KOH (0.009)	-	-	95.91%	94.12%	Reflux (This study)
D	Benzaldehyde (0.006), KOH (0.009)	-	-	97.22%	96.17%	Ultrasonication (This study)

Yield[a] for benzoic acid and Yield[b] for benzyl alcohol

Table 6. Green Metrics Measurement Results for the Reaction of Cannizzaro Benzaldehyde Various Literature Using the Andraos Algorithm

Parameter	Method (A)	Method (B)	Method (C)	Method (D)
AE	1	1	1	1
Rxn Yield	0.872	0.224	0.463	0.487
1/SF	0.307	0.696	0.705	0.705
MRP	0.370	0.828	1	1
RME	0.099	0.129	0.326	0.343

Parameters compared were the use of solvents, reaction methods, and yields produced. So what can be compared is the value of S^{-1} and factor E. The results of the Cannizzaro benzaldehyde reaction with various methods are presented in **Figure 9**. The use of an Al_2O_3 catalyst in reaction A has a high impact on the environment. Reaction B showed the presence of by-products caused by the low yield produced from reaction B. In addition, the use of a solvent in reaction B increases the value of S^{-1} and E Factor. Solvent usage affects reaction greenness. Based on the effect caused by the presence of solvent, the reaction without solvent was carried out in this study indicated by reactions C and D. Reaction C closely resembled D, differing only in product quantities due to similar ingredients. The high S^{-1} and E Factor values are due to the high substrate used. Reaction D showed low S^{-1} and E Factor values affected by the high ratio of products to reactants. Notably, the ultrasonication method without solvents in the Cannizzaro benzaldehyde reaction displayed the highest greenness compared to other approaches.

Andraos algorithm was used to consider the amount of material based on other parameters. Green metric calculations with the Andraos algorithm for the Cannizzaro benzaldehyde reaction from various literature are shown in **Table 6**.

The AE values of all reactions show almost ideal values indicating that almost all of the reactants are used as products. The RME value in reaction A shows the lowest value due to the low ratio of product to substrate. The use of solvents and catalysts in reaction A affects the RME value.

The 1/SF value which is not ideal is due to the presence of a material (base) that exceeds the stoichiometry. In reaction A, the base NaOH was used with a greater mole ratio than the use of KOH in reactions B, C, and D so that the value of 1/SF in reaction A is smaller. High MRP values in reactions B, C, and D indicate the use of materials that can be recovered by recycling less than in reaction A which uses a catalyst.

4. CONCLUSIONS

Based on the results and discussion, it can be concluded that the Cannizzaro reaction on *p*-anisaldehyde produced 95.16% *p*-anisyl alcohol and 95.04% *p*-anisic acid. Meanwhile, benzaldehyde produces 96.17% benzyl alcohol and 97.22% benzoic acid. Energy consumption investigation preferred the ultrasonic technique because of its shorter reaction times. Green metrics evaluations displayed the ultrasonic method's superior environmental performance, highlighting the importance of green chemistry principles in enhancing eco-friendly and efficient Cannizzaro reactions.

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