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Interpretation of Fourier Transform Infrared Spectra (FTIR): A Practical Approach in the Polymer/Plastic Thermal Decomposition

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ABSTRACT

Fourier transform infrared (FTIR) is one of the tools to represent molecular structure based on atomic vibration. It can denote a specific property of the chemical bond and molecular structure in the material, especially when analyzing specimens relating to plastics, polymers, and organic components. The FTIR peaks and spectrum act as a fingerprint of a specific molecular structure and chemical bonding, which need a sufficient reference database to distinguish them. This paper is to address issues of the need for a reference database of FTIR. This paper exhibits step-by-step information on how to read and interpret the FTIR spectra and identify a molecule's backbone with its functional groups. Practical examples from the analysis of several plastics/polymers and the thermally decomposing plastics/polymers were included to help and guide the reader to comprehend the basic concept of FTIR spectra.

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1. INTRODUCTION

Fourier Transform Infrared (FTIR) is one of the tools for the simultaneous and quantitative identification of molecular structure (Al-Alawi *et al*., 2004). The FTIR releases peaks and spectra that can act as a fingerprint of a specific molecular structure and chemical bonding. To understand the FTIR results, a reference database is required. Some papers regarding FTIR analysis are available (Nandiyanto *et al*., 2019; Sukamto & Rahmat, 2023; Obinna, 2022; Valand *et al*., 2020; Magalhães *et al*., 2021; Ellis & Goodacre, 2006; Coates, 2000), However, until now, the database itself is limited, while it is a crucial aspect for understanding easily the FTIR results.

The purpose of this study is to address issues of the need for a reference database of FTIR spectra. As a continuation of our previous study (Nandiyanto *et al*., 2019) regarding the interpretation of FTIR data, this study presents more comprehensive strategies for understanding FTIR data. This paper exhibits step-by-step information on how to read and interpret the FTIR spectra and to identify a molecule's backbone or the functional groups connected inside the material, including the type of functional groups, including distinguishing linear/ branched or saturation/unsaturation/ aromatic chains and rings in the chemical structure. As practical examples of how to read the FTIR spectra, this paper took FTIR analysis data from several polymers (*i.e.* polycarbonate, polyvinyl chloride, polyacrylic, and nylon polypropylene). The heated plastics or polymers were also added to understand how to distinguish several data in FTIR results. In addition, the analysis of burned plastics can give additional ideas since wastes containing plastics/polymers are usually burned recently since plastic does not decompose naturally, while its burning process creates environmental and health issues (Verma *et al*., 2016). Thus, this paper brings dual impacts for readers: comprehending the way how to interpret FTIR data to get the chemical structure inside the analyzed specimen and understanding the impact of burning plastic/polymer on its chemical structure.

2. METHOD

This study prepared a database of the FTIR spectra. To make the reader easily understand, the collected database was summarized and explained in a step-by-step interpretation. This paper was completed by analyzing some polymer specimens (i.e. polycarbonate, polyvinyl chloride, polyacrylic, and nylon polypropylene) using the FTIR analysis equipment (FTIR-4600, Jasco Corp., Japan). All specimens (sizes of 1.00 x 1.00 x 0.5 cm for length, width, and thickness, respectively) were obtained from a local market in Indonesia. We also analyzed the burned specimens (*i.e.* polycarbonate was heated using an electrical furnace at 100, 200, 300, and 400°C for 30 min in the atmospheric condition).

3. RESULTS AND DISCUSSION

3.1. Database FTIR Spectrum

To understand the FTIR spectrum, understanding zones (see **Figure 1**) and database (see **Tables 1-4**) is important. Four zones are available, in which zones I (single bone), II (triple bond), III (double bond), and IV (fingerprint) are in the wavenumber region of 2500-4000, 2000-2500, 1500-2500, and less than 1500 cm^{-1}, respectively.

To interpret the FTIR spectrum, two ways can be done: (i) depicting the spectrum from 4000 to 500 cm^{-1} (**Figure 1(a)**) and depicting the spectrum from 500 to 4000 cm^{-1} (**Figure 1(b)**). However, to make it simpler in understanding the FTIR spectrum, this report focused only on depicting the spectrum arranged from 500 to 4000 cm^{-1} (**Figure 1(b)**). Five steps should be done:

(i) Step 1: Identify the overall FTIR peaks of the specimen. Distinguish the zones (see **Figure 1(b)**) and make sure to identify

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the wavenumber arrangement (from 500 to 4000 cm^{-1}).

(ii) Step 2: Identify the peak at the single bond region in the 2500-4000 cm^{-1} region for **zone I**. Check the existing peaks and compared them with the reference database (see **Table 1**).

(iii) Step 3: Identify the peak at the triple bond region in the 2000-2500 cm^{-1} region for **zone II**. Check the existing peaks and compared them with the reference database (see **Table 2**).

(iv) Step 4: Identify the peak at the double bond region in the 1500-2500 cm^{-1} region for **zone III**. Check the existing peaks and compared them with the reference database (see **Table 3**).

(v) Step 5: Identify the peaks of ethanol FTIR which are in the range of the fingerprint region for **zone IV** (less than 1500 cm^{-1}). Check the existing peaks and compared them with the reference database (see **Table 4**).

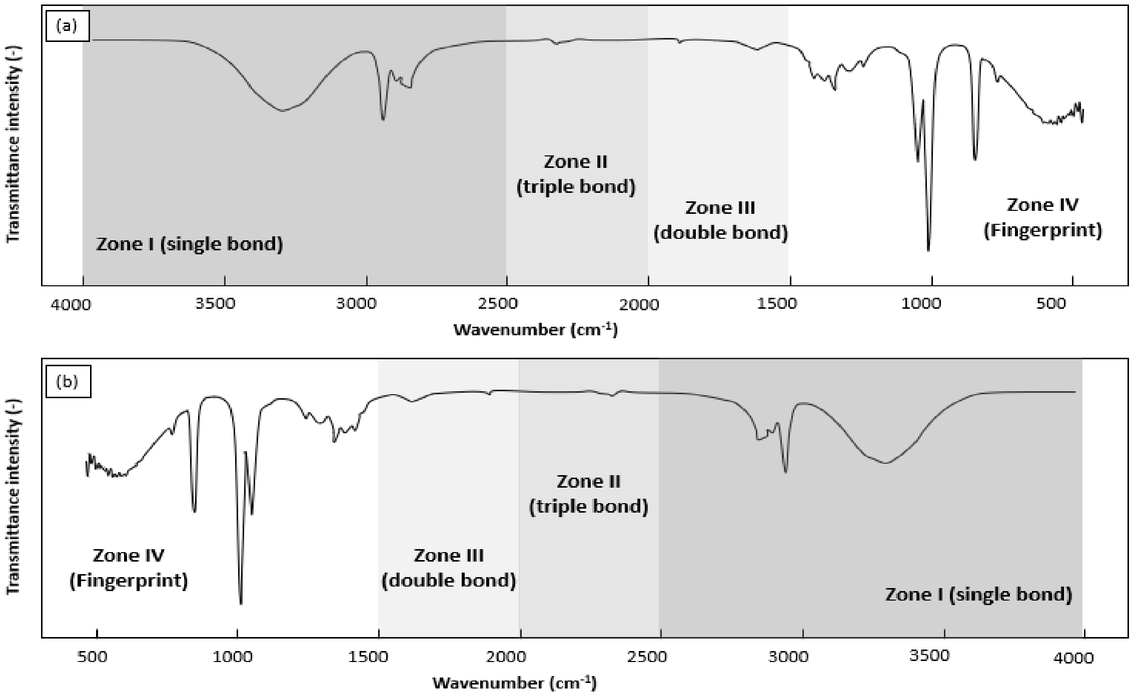

Figure 1. FTIR spectrum in sequences of 4000-500 (a) and 500-4000 cm^{-1} (b).

Table 1. Single bond area (3250-3650 cm^{-1}), adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
Hydrogen bond in H_2O/-OH/NH_3/-NH_2	3250-3650 (broad) *Followed by* 600–800 1000–1200 1300–1600,
Hydrogen bond in alcohol/phenol	3550-3670 (sharp)
Unsaturated/aromatic compound olefinic at 3010-3040 cm^{-1}	> 3000 (sharp)
Aliphatic compound long-chain linear aliphatic at 2860-2935 cm^{-1}	< 3000 (sharp) Followed by 720-1470
Aldehyde	2700-2800
C-H bond	> 3000

Table 2. Triple bond area (2000-2500 cm^{-1}), adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
Triple bond of $C\equiv C$	2200 *Followed by* 600-800 1000-1200 1300-1600
Cyclic (C-C)	2350 (dual peaks)
Graphite	
Alcohol	2350 (not strong)

Table 3. Double bond area (1500-2000 cm^{-1}), adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
Triple bond of $C\equiv C$	2200 *Followed by* 600-800 1000-1200 1300-1600
Carbonyl C=C	1650-1850
Active carbonyl (e.g. anhydrides, halide acids, or halogenated carbonyl)	>1775
Ring-carbonyl carbons (e.g. lactone, or organics carbonate).	
Simple carbonyl (e.g. ketones, aldehyde, ester, carbonyl)	1700-1750
Amide/carboxylate	< 1700
Double bond carbon (C=C): olefinic compounds	1650
Unsaturated bond (e.g. double and triple bond)	1620-1670
Double bonds (C=C): aromatic compounds	1600-1650 (sharp)
Aromatic ring (C-H)	1495-1615 Followed by 670-850 (probably)* 3000-3150 (C-H stretching)

Table 4. The functional group in FTIR peaks, adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
1. Saturated Aliphatic (alkene/alkyl)	
a) Methyl ($-CH_3$)	
gem-Dimethyl or ‘‘iso’’- (doublet)	1380-1385/1365–1370
Trimethyl or ‘‘tert-butyl’’ (multiplet)	1385–1395/1365
Methyl C-H asym./sym. Bend	1430–1470/1370–1380
Methyl C-H asym./sym. Stretch	2950–2970/2860–2880
b) Methylene ($>CH_2$)	
Methylene $—(CH_2)_n—$ rocking ($n \geq 3$)	720–750
Cyclohexane ring vibrations	1000–1055/925-1005
Methylene C-H bend	1445–1485
Methylene C-H asym./sym. Stretch	2915–2935/2845–2865
c) Methyne ($>CH-$)	
Skeletal C-C vibrations	700–1300
Methyne C-H bend	1330–1350
Methyne C-H stretch	2880–2900
d) Special methyl ($-CH_3$) frequencies	
Methylamino, $N-CH_3$, C-H stretch	2780–2820
Methoxy, methyl ether $O-CH_3$, C-H stretch	2815–2850

Table 4 (Continue). The functional group in FTIR peaks, adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
2. Olefinic (alkene)	
cis-C-H out-of-plane bend	700 (broad)
Vinylidene C-H out-of-plane bend	885–895
trans-C-H out-of-plane bend	960–970
Vinyl C-H out-of-plane bend	985–995/890-915
Vinylidene C-H in-plane bend	1290-1310
Vinyl C-H in-plane bend	1410-1420
Conjugated C=C	1600
Alkenyl C=C stretch	1620-1680
Aryl-substituted C=C	1625
Medial, cis- or trans-C-H stretch	3010–3040
Pendant (vinylidene) C-H stretch	3075–3095
Terminal (vinyl) C-H stretch	3075–3095
	3010–3040
3. Aromatic ring (aryl)	
Aromatic C-H out-of-plane bend	670-900 (several)
C-H 1,2-Disubstitution (ortho)	735–770
C-H Monosubstitution (phenyl)	730–770 and 690-710
C-H 1,3-Disubstitution (meta)	750-810 and 860-900
C-H 1,4-Disubstitution (para)	800–860
Aromatic C-H in-plane bend	950-1225 (several)
C=C-C Aromatic ring stretch	1580-1615
	1450-1510
Aromatic combination bands	1660-2000 (several)
Aromatic C-H stretch	3070-3130
4. Acetylenic (alkyne)	
Alkyne C-H bend	630 (typical)
Alkyne C-H bend	610–680
C≡C Terminal alkyne (monosubstituted)	2100–2140
C≡C Medial alkyne (disubstituted)	2190-2260
Alkyne C-H stretch	3310-3320
5. Aliphatic organohalogen compound	
Aliphatic iodo compounds, C-I stretch	500-600
Aliphatic bromo compounds, C-Br stretch	600-700
Aliphatic chloro compounds, C-Cl stretch	700-800
Aliphatic fluoro compounds, C-F stretch	1000-1150
6. Alcohol and hydroxy compound	
Alcohol, OH out-of-plane bend	590-720
Primary alcohol, C-O stretch	~1050
Secondary alcohol, C-O stretch	~1100
Tertiary alcohol, C-O stretch	~1150
Phenol, C-O stretch	~1200
Primary or secondary, OH in-plane bend	1260-1350
Phenol or tertiary alcohol, OH bend	1310-1410
Tertiary alcohol, OH stretch	3540-3620
Secondary alcohol, OH stretch	3620-3635
Normal ‘‘polymeric’’ OH stretch	3200-3400
Hydroxy group, H-bonded OH stretch	3200-3570 (broad)
Dimeric OH stretch	3450-3550

Table 4 (Continue). The functional group in FTIR peaks, adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
Internally bonded OH stretch	3540-3570
Phenols, OH stretch	3530-3640
Primary alcohol, OH stretch	3630-3645
Nonbonded hydroxy group, OH stretch	3645–3600 (narrow)
7. Ether and oxy compound	
Peroxides, C-O-O- stretch	820-890$^{1)}$
Alkyl-substituted ether, C-O stretch	1050-1150
Cyclic ethers, large rings, C-O stretch	1070-1140
Epoxy and oxirane rings	~1250/800–890$^{1)}$
Methoxy, C-H stretch (CH_3-O-)	2810–2820
a) Primary amino	
Primary amine, CN stretch	1020–1090
Primary amine, NH bend	1590-1650
Aliphatic primary amine, NH stretch	3380-3400/3325-3345
Aromatic primary amine, NH stretch	3460-3510/3380-3415
b) Secondary amino	
Secondary amine, CN stretch	1130-1190
Secondary amine, >N-H bend	1550-1650
Aliphatic secondary amine, >N-H stretch	3310-3360
Imino compounds, =N-H stretch	3320-3350
Heterocyclic amine, >N-H stretch	3430-3490
Aromatic secondary amine, >N-H stretch	~3450
c) Tertiary amino	
Tertiary amine, CN stretch	1150-1210
d) Aromatic amino	
Aromatic primary amine, CN stretch	1250-1340
Aromatic secondary amine, CN stretch	1280-1350
Aromatic tertiary amine, CN stretch	1310-1360
8. Carbonyl compound	
Carboxylate (carboxylic acid salt)	1550-1610/1300-1420
Amide	1630-1680
Quinone or conjugated ketone	1675-1690/(1600-1650)$^{2)}$
Carboxylic acid	1700-1725
Ketone	1705-1725
Aldehyde	1725-1740/(2700-2800)$^{3)}$
Ester	1725-1750
Six-membered ring lactone	1735
Alkyl carbonate	1740-1760
Acid (acyl) halide	1770-1815
Aryl carbonate	1775-1820
Transition metal carbonyls	1800-2100
Five-membered ring anhydride	1820-1870/1775-1800
9. Nitrogen multiple and cumulated double-bond compound	
Open-chain azo (-N=N-)	1575-1630
Open-chain imino (-C=N-)	1590-1690
Isothiocyanate (-NCS)	1990-2150
Thiocyanate (-SCN)	2140-2175
Aromatic cyanide/nitrile	2220-2240
Cyanate (-OCN and C-OCN stretch)	2240-2260/1080-1190
Isocyanate (-N=C=O asym. stretch)	2240-2276

Table 4 (Continue). The functional group in FTIR peaks, adapted from Nandiyanto *et al.* (2019).

Functional group/assignment	Wavenumber (cm^{-1})
Aliphatic cyanide/nitrile	2240-2280
11. Nitrogen multiple and cumulated double-bond compound	
Open-chain azo (-N=N-)	1575-1630
Open-chain imino (-C=N-)	1590-1690
Isothiocyanate (-NCS)	1990-2150
Thiocyanate (-SCN)	2140-2175
Aromatic cyanide/nitrile	2220-2240
Cyanate (-OCN and C-OCN stretch)	2240-2260/1080-1190
Isocyanate (-N=C=O asym. stretch)	2240-2276
Aliphatic cyanide/nitrile	2240-2280
12. Simple hetero-oxy compounds	
a) Nitrogen-oxy compounds	
Aromatic nitro compounds	1485-1555/(1320-1355) 4)
Aliphatic nitro compounds	1540-1560/(1350-1380) 4)
Organic nitrates	1620-1640/(1270-1285) 4)
b) Phosphorus-oxy compounds	
Aliphatic phosphates (P-O-C stretch)	990-1050
Aromatic phosphates (P-O-C stretch)	1190-1240/850-995
Organic phosphates (P=O stretch)	1250-1350
c) Sulfur-oxy compounds	
Dialkyl/aryl sulfones	1300-1335/(1170–1135)4)
Sulfonates	13401365/(1100-1200)4)
Organic sulfates	1370-1420/(1180-1200)4)
d) Silicon-oxy compounds	
Organic siloxane or silicone (Si-O-Si)	1075-1095/1020-1055
Organic siloxane or silicone (Si-O-C)	1080-1110
13. Thiols and thio-substituted compounds	
Aryl disulfides (S-S stretch)	430-500
Polysulfides (S-S stretch)	470-500
Disulfides (C-S stretch)	570-705
Disulfides (S-S stretch)	600-620
Thioethers, CH_3-S-(C-S stretch)	630-660
Aryl thioethers, ø-S (C-S stretch)	670-715
Thiol or thioether, CH_2-S-(C-S stretch)	685-710
Thiols (S-H stretch)	2550-2600
14. Common inorganic ions	
Silicate ion	900-1100
Phosphate ion	1000-1100
Sulfate ion	1080-1130/(680–610)5)
Nitrate ion	1350-1380/(840–815)5)
Carbonate ion	1410-1490/(880–860)5)
Cyanide ion, thiocyanate ion, and related ions	2000-2200
Ammonium ion	3030-3300/(1390-1430)5)

Note: 1)Normally, it is very weak in the infrared but more characteristic in the Raman spectrum; 2)Lower frequency band because of the conjugated double bond; 3)Higher frequency band characteristic of aldehydes, related with the terminal aldehydic C-H stretch; 4)Asymmetric/symmetric XO_2 stretch (NO_2 and SO_2); 5)Normally, the first peak is intense and broad, and the second has weak to medium intensity and narrow. Both often exist as multiple-band structures, and they may be used to characterize individual compounds.

3.2. Application to Understanding the Chemical Structure of Ethanol

Figure 2 shows the FTIR spectra of ethanol. The steps for the interpretation are:

(i) Step 1: Identify the overall FTIR peak of the ethanol specimen and distinguish zones.

(ii) Step 2: Identify the peak at the single bond region in the 2500-4000 cm^{-1} region for **zone I** (see **Table 1**). Here, several peaks are identified, including:

- The presence of a narrow peak in the area around 2832.51 cm^{-1} with a stretching vibration type indicates C-H bonds in aldehydes (CH_2 group).
- Narrow peak in the 2943.42 and 2975.29 cm^{-1} regions with a stretching vibration type showing C-H bonds in the CH_3 group.
- Broad and strong peaks in the 3000-3500 cm^{-1} region indicate the presence of OH hydroxyl groups.

(iii) Step 3: Identify the peak at the triple bond region in the 2000-2500 cm^{-1} region for **zone II** (**Table 2**). Small peaks were detected at about 2350 cm^{-1}, showing the bond for C-C in alcohol.

(iv) Step 4: Identify the peak at the double bond region in the 1500-2500 cm^{-1} region for **zone III** (see **Table 3**). In this area, the FTIR spectra did not show any peak, confirming no double bonds in ethanol.

(v) Step 5: Identify the peaks of ethanol FTIR which are in the range of the fingerprint region for **zone IV** (600-1500 cm^{-1}) (see **Table 4**). Several peaks were obtained, including:

- A sharp and narrow peak with a bending vibration type in the 880.52 cm^{-1} regions indicate the presence of C-H bonds in aromatic functional groups.
- A sharp and narrow peak with a stretching vibration type in the area 1024.22-1087.87 cm^{-1} with a stretching vibration type related to C-O absorption in secondary alcohol
- The narrow peak in the region of 1350-1449.57 cm^{-1} with a stretching vibration type indicates the presence of -C-H bonds.

Based on the interpretation results, the specimen has a C-H, -C-H, C-O, C-C, and O-H bond structure. The FTIR results agree with the ethanol structure (as shown in the insert chemical structure in **Figure 2**).

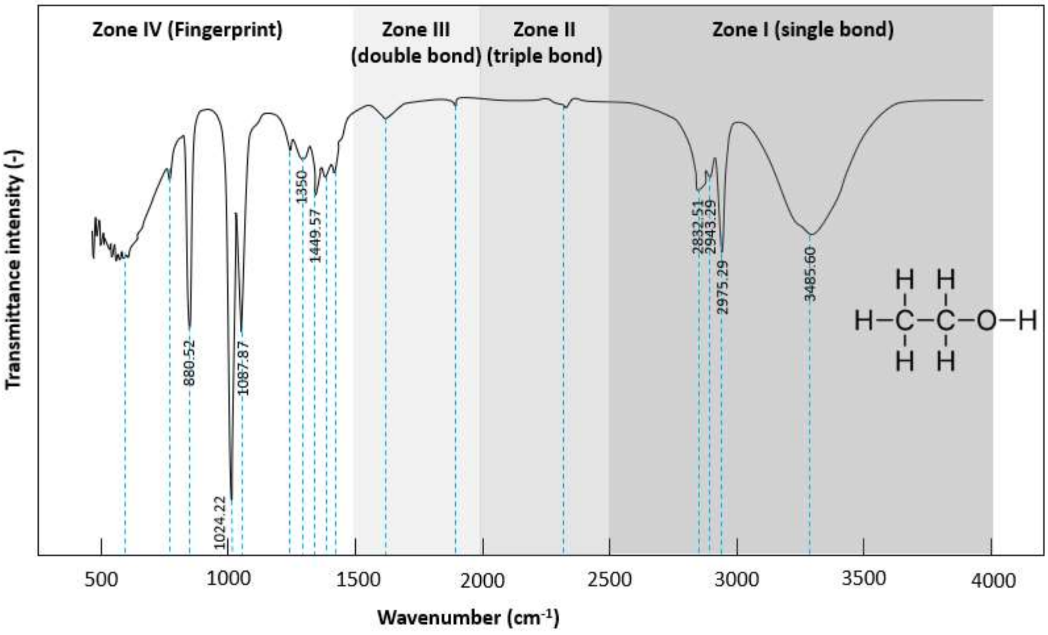

Figure 2. FTIR spectrum of ethanol.

3.3. Application to Understanding the Chemical Structure of Polyacrylic

Figure 3 shows the FTIR spectrum of polyacrylic. Here are step-by-step instructions for interpreting the data:

(i) Step 1: Identify the overall spectra of acrylic and distinguish the zones.

(ii) Step 2: Observe the peak in the single bond region in the 2500-4000 cm^{-1} for **zone I** (see **Table 1**). There are two bands in the range 2874-2996 cm^{-1}, indicating absorption from stretching vibrations of C-H bonds.

(iii) Step 3: Observe the peak in the triple bond zone in the 2000-2500 cm^{-1} for **zone II** (see **Table 2**). We found a small intensity at 2350 cm^{-1}, informing some C-C bonds.

(iv) Step 4: Observe the band in the double bond zone in 1500-2000 cm^{-1} for **zone III** (see **Table 3**). A sharp and intense band was found at 1736.88 cm^{-1}, associated with the stretching vibration of the carbonyl group (C=O).

(v) Step 5: Observe the band in the fingerprint zone in 500-1500 cm^{-1} for **zone IV** (see **Table 4**). In the fingerprint zone, several peaks appear, including:

- The sharp and intense band at 759.89 cm^{-1} is associated with the methylene $-(CH_2)n-$ rocking vibration where n≥3.
- The band at 700-1397.19 cm^{-1} is associated with skeletal C-C vibrations.
- The peak at 1165.58-1397.19 cm^{-1} is related to the ester group stretching vibration (C-O-C).
- The band appears at 1453.53 cm^{-1} is the bending vibration band of methyl ($-CH_3$).

Based on the FTIR results, acrylic has a bond structure of C-H, CH_2, C=O, $(-CH_2)n-$, C-C, C-O-C, and $-CH_3$ that agree with the acrylic structure (as shown in the insert chemical structure in **Figure 3**).

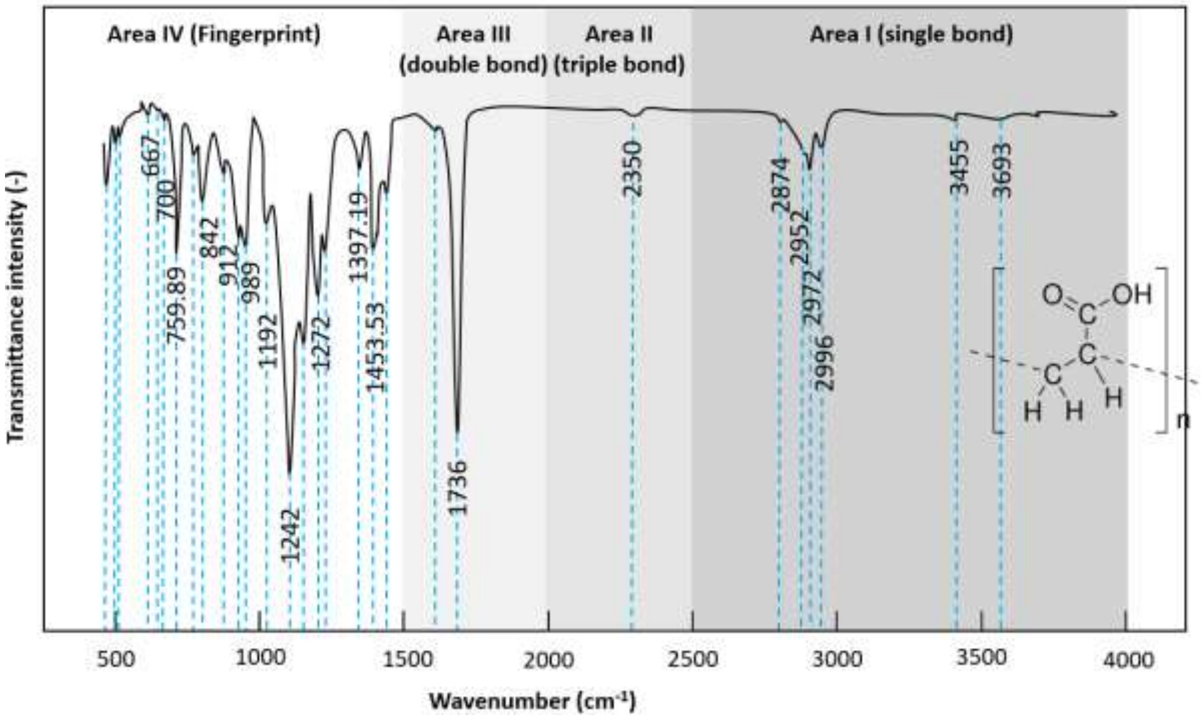

Figure 3. FTIR spectrum of polyacrylic.

3.4. Application to Understanding the Chemical Structure of Polyvinyl Chloride

Figure 4 shows the FTIR spectrum of polyvinyl chloride. The interpretation of the FTIR spectrum is as follows:

(i) Step 1: Identify the overall spectra of polyvinyl chloride and its zones.

(ii) Step 2: Identify the peaks in **zone I** at 2500-4000 cm^{-1}. Compared to the database in **Table 1**, several peaks were identified, including:

- The presence of peaks in the area of 2800-3000 cm^{-1} is associated with the presence of C-H bonds.
- Peaks in the area around 3500-3700 cm^{-1} indicate the presence of O-H bonds.

(iii) Step 3: Observe the peaks in **zone II** (triple bond) at 2000-2500 cm^{-1}. A peak at around 2350 cm^{-1} was identified indicating the presence of the C-H group.

(iv) Step 4: Identify the peaks in **zone III** (double bond) at around 1500-2000 cm^{-1}. In **zone III**, no absorption band is detected, which means that the specimen does not have a double bond.

(v) Step 5: Observe the peak in **zone IV** (fingerprint) around 500-1500 cm^{-1}. Several peaks appeared, including:

- The peaks around 700-800 cm^{-1} (see **Table 4**) are the absorption from the stretching of the C-Cl bond.
- The peak in the region of 1000-1100 cm^{-1} is related to aliphatic bending absorption bonds (C-C).

The FTIR spectra are confirmed to have structures from the C-H, C-C, and C-Cl structures with linear backbone. This predicted chemical bonding is in good agreement with the chemical structure results shown in the insert image in **Figure 4**.

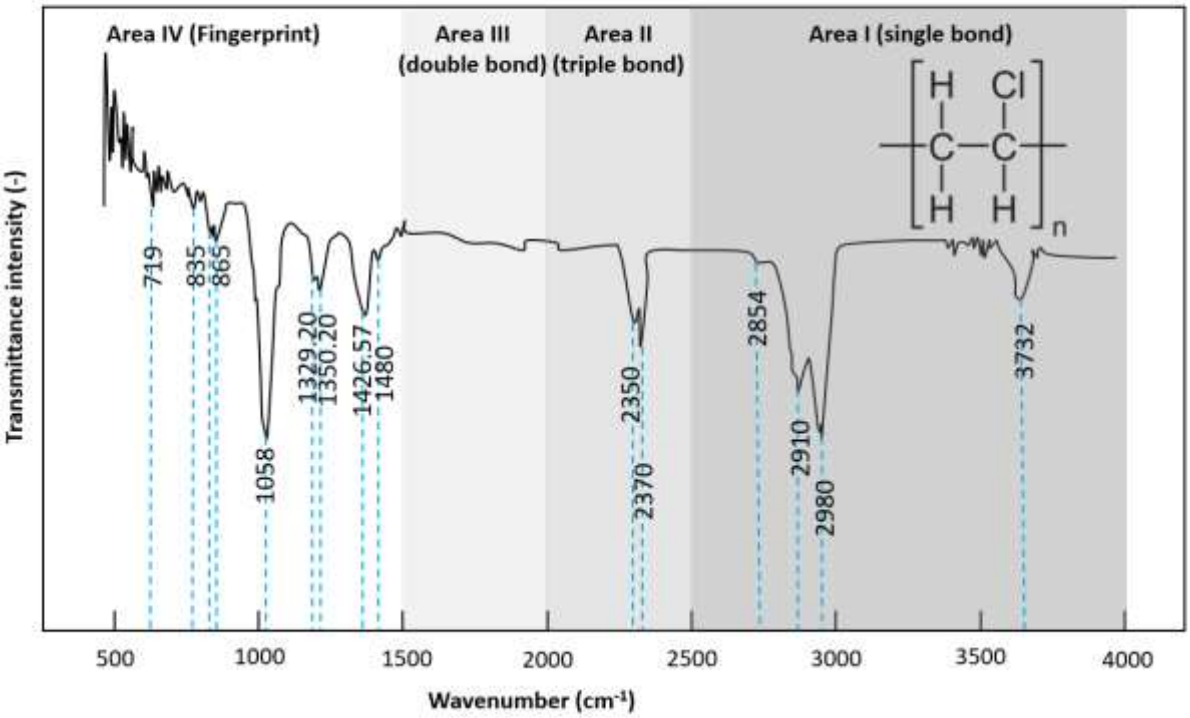

Figure 4. FTIR spectrum of polyvinyl chloride.

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3.5. Application to Understanding the Chemical Structure of Polycarbonate

Figure 5 shows the FTIR spectrum of polycarbonate. The interpretation is:

(i) Step 1: Identify the overall FTIR peaks of the specimens and their zones.

(ii) Step 2: Identify the peak at the single bond region in the 2500-4000 cm^{-1} region for **zone I** (**Table 1**). Several peaks are identified:
- The presence of a narrow peak in the area around 2832.51 cm^{-1} with a stretching vibration type indicates C-H bonds in aldehydes.
- A narrow peak in the 2943.42 cm^{-1} regions with a stretching vibration type showing C-H bonds in the CH_3 group.
- The sharp peak at 2975.29 cm^{-1} region (stretching vibration type and the vibration of C-H in the CH_3 group).

(iii) Step 3: Identify the peak at the triple bond region in the 2000-2500 cm^{-1} region for **zone II** (see **Table 2**). The peaks at 2350 cm^{-1} with small intensities were obtained, confirming the C-C bond.

(iv) Step 4: Identify the peak at the double bond region in the 1500-2500 cm^{-1} region (**zone III; Table 3**). The peak at 1750 cm^{-1} was detected, confirming the carbonyl bond (C=C).

(v) Step 5: Identify the peaks of ethanol FTIR which are in the range of the fingerprint region for **zone IV** (600-1500 cm^{-1}) (see **Table 4**). Several peaks were detected:
- The peaks observed at 1066, 1242, and 1272 cm^{-1} are related to the C_{sp2}-O stretching bonds.
- The peak at 1386 cm^{-1} indicates the presence of C_{sp3}-H bending vibrations.
- The peak in the range 1442-1457 cm^{-1} is the presence of C=C stretching.
- The peaks in the 1636 and 1484 cm^{-1} regions also indicate the presence of another C=C stretching due to the aromatic ring carbon.
- The peak at 1728 cm^{-1} corresponds to the C=O bond.
- The peaks that appear at 2844 and 2950 cm^{-1} indicate the presence of C_{sp3}-H bonds. Meanwhile, a peak at 2996 cm^{-1} indicates the presence of C_{sp2}-H bonds.
- Furthermore, the 500-1000 cm^{-1} region is the fingerprint associated with the C-C stretching bond.

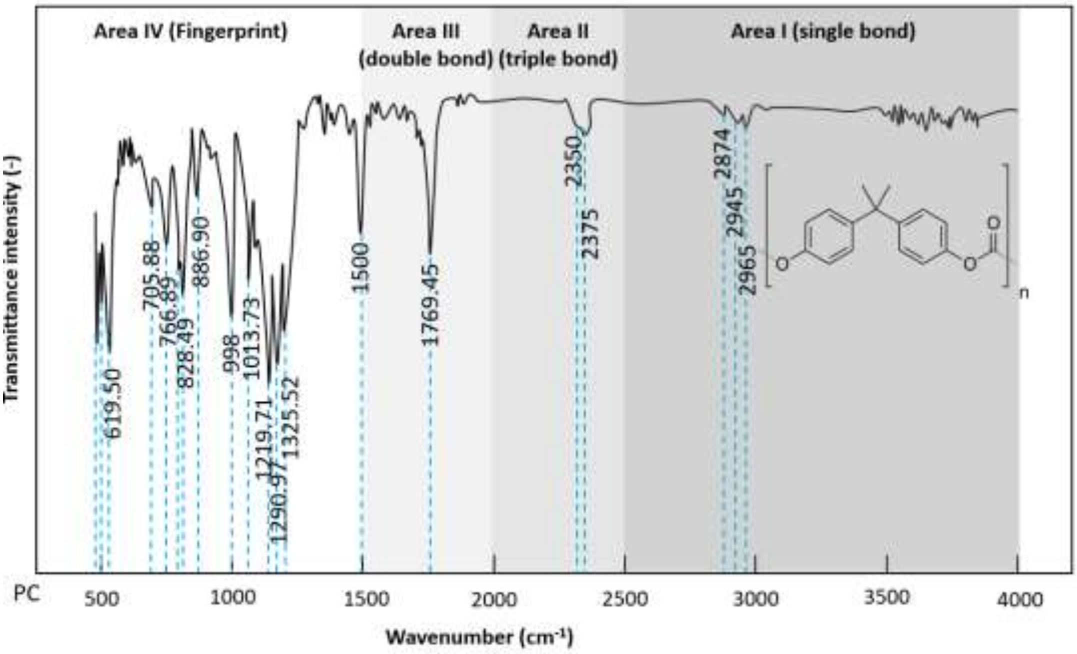

Figure 5. FTIR spectrum of polycarbonate.

Based on the interpretation results, the FTIR spectra of polycarbonate are confirmed to have absorption from the C-H, C-C, C=O, and C-O structures, as well as the aromatic ring with C=C structure. These predicted chemical bonding results are in good agreement with the chemical structure results shown in the insert image in **Figure 5**.

3.6. Application to Understanding the Chemical Structure of Nylon Polyethylene

Figure 6 shows the FTIR spectrum of polyvinyl chloride. The interpretation of the FTIR spectrum of polyvinyl chloride is as follows:

(i) Step 1: Identify the overall spectra of polyvinyl chloride and its zones.

(ii) Step 2: Identify the peaks in zone I at 2500-4000 cm^{-1}. Compared to the database in **Table 1**, several peaks were identified, including:
  - Peaks in the area around 3000-3500 cm^{-1} indicate the presence of the N-H stretch.
  - The presence of peaks in the area of 2800-3000 cm^{-1} is associated with the presence of C-H bonds.

(iii) Step 3: Observe the absorption band in **zone II** (triple bond) at 2000-2500 cm^{-1}. In **zone II**, a peak around 2350 cm^{-1} was identified indicating the presence of the C-H group.

(iv) Step 4: Identify the absorption band in **zone III** (double bond) around 1500-2000 cm^{-1}. In **zone III**, no absorption band is detected, meaning that the specimen does not have a double bond.

(v) Step 5: Observe the peak in zone IV (fingerprint) around 500-1500 cm^{-1}. Several peaks appeared, including:
  - The peak around ~750 cm^{-1} (**Table 4**) is the absorption from the rocking of the C=O bond.
  - The peak in the region of 953 cm^{-1} is related to aliphatic bending absorption bonds (C-C).
  - The peak in the region of ~1150 cm^{-1} is related to stretching the C-N bond.

Based on the interpretation results, the FTIR spectrum of nylon polyethylene (see **Figure 6**) contains N-H, C-H, C-C, C-N, and C=O groups. The results correspond to the chemical structure depicted in the insert image in **Figure 6**.

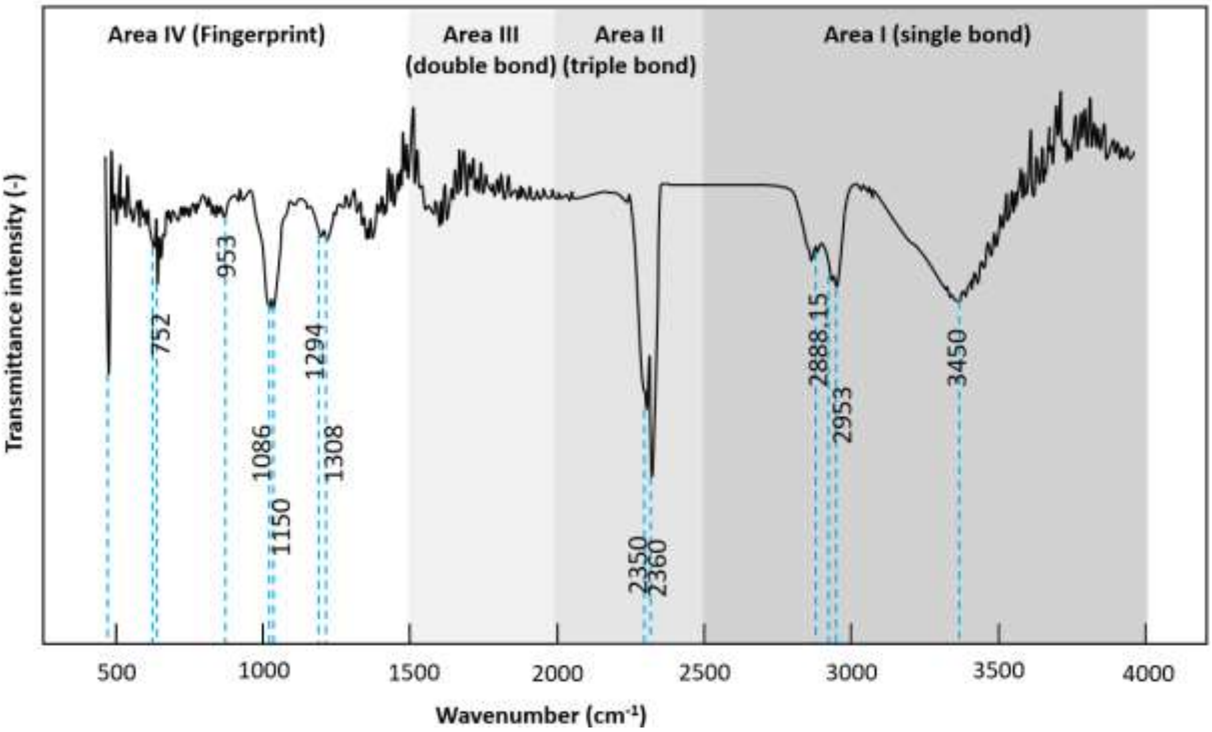

Figure 6. FTIR spectrum of nylon polyethylene.

3.7. Application to Understanding the Chemical Structure Transformation in the Heat Decomposition of Plastic (Polycarbonate)

Figure 7 depicts the FTIR spectra of polycarbonate after thermal treatment at temperatures of 100, 200, 300, and 450°C. Similar to previous sections, the reading process can be done using several steps. However, in this section, we explained how to distinguish the data. The different peaks were detected (see the red-dashed area). The specimens heated at 100 and 200°C have an identical FTIR spectrum to the initial polycarbonate (similar to **Figure 5**). Minor changes are observed during the thermal treatment process at 100 and 200°C. Significant changes occur when the thermal treatment temperature exceeds 200°C. The heating process at higher than 200°C allowed the change in the chemical structure in the specimen. The main peaks in zone IV (fingerprint) disappeared, and new peaks in **zone III** (triple bond) appeared.

The new peaks based on **Table 2** relate to the C-C bond in the graphite pattern. Peak attenuation is observed in the carbonyl and carbon regions. The presence of peak attenuation indicates that the thermal treatment alters the chemical structure of the polymer. Based on the FTIR results, the changing chemical structure can be obtained, and the predicted chemical structures are shown in the inserted images in **Figure 7**. In addition, the burning process can convert plastics/polymers into smaller molecular structures (such as carbon) and some gases (Nandiyanto, 2018; Nandiyanto *et al*., 2020). Indeed, the types of gases must be considered.

4. CONCLUSION

This report is to address the issue of the need for a reference database of FTIR, presenting step-by-step information on how to read and interpret the FTIR spectra, identifying a molecule's backbone and the functional groups connected inside the material. Practical examples in the case of plastic/polymer decomposition were included to help and guide the reader to comprehend the basic concept of FTIR spectra. This paper can be used as a reference for understanding FTIR data.

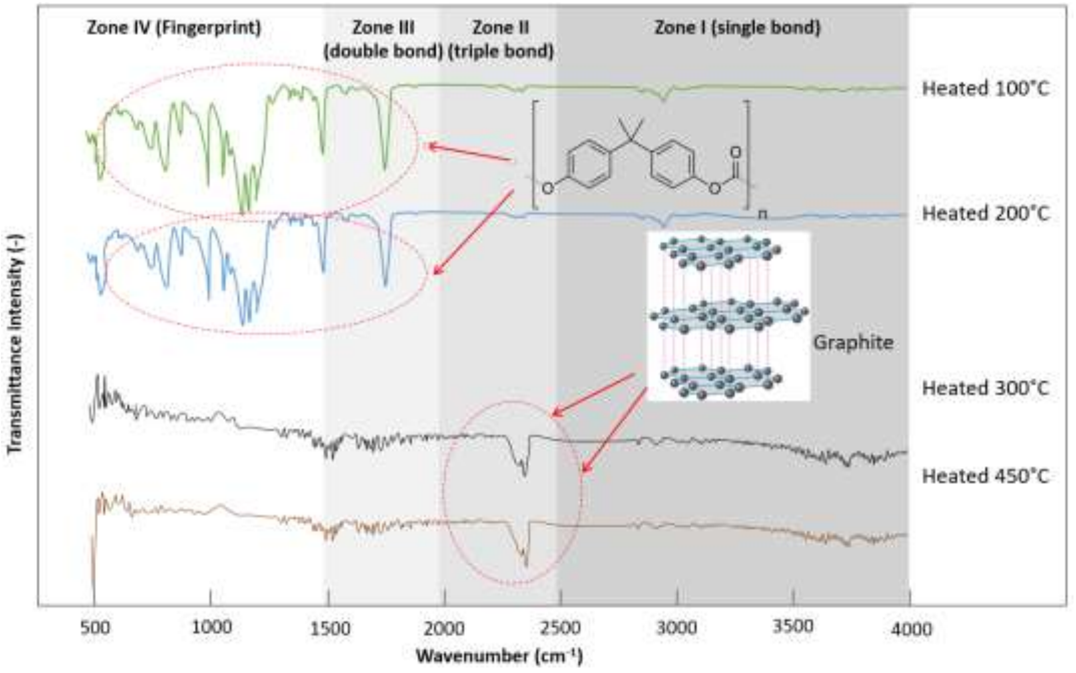

Figure 7. FTIR spectrum of polycarbonate heated at various temperatures.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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