

Article Home Trash Biomass Valorization by Catalytic Pyrolysis

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Abstract: With the increase in population, large amounts of food waste are produced worldwide every day. These leftovers can be used as a source of lignocellulosic waste, oils, and polysaccharides for renewable fuels. In a fixed bed reactor, low-temperature catalytic pyrolysis was investigated using biomass gathered from domestic garbage. Thermogravimetry, under N₂ flow, was used to assess the pyrolysis behavior of tea and coffee grounds, white potato, sweet potato, banana peels, walnut, almonds, and hazelnut shells. A mixture of biomass was also evaluated by thermogravimetry. Waste inorganic materials (marble, limestone, dolomite, bauxite, and spent Fluid Catalytic Cracking (FCC) catalyst) were used as catalysts (16.7% wt.) in the pyrolysis studies at 400 °C in a fixed bed reactor. Yields of bio-oil in the 22–36% wt. range were attained. All of the catalysts promoted gasification and a decrease in the bio-oil carboxylic acids content. The marble dust catalyst increased the bio-oil volatility. The results show that it is possible to valorize lignocellulosic household waste by pyrolysis using inorganic waste materials as catalysts.

Keywords: renewable energy; food waste; waste management; pyrolysis; inorganic waste catalysts

1. Introduction

Developed societies with high incomes generate huge amounts of solid waste (Figure 1), including food waste (around 44% [1]).

In Europe, food waste production is estimated at 174 kg/person/year, corresponding to 170 Mtons of CO_2 emissions [2]. Conventional incineration and landfilling processes have many environmental drawbacks, which has encouraged research in the field of converting food waste into valuable products through various processes, such as thermochemical conversion [3]. The conversion of food waste into liquid and/or gaseous fuels is an attractive route because it allows for the management of this waste and consequently reduces its environmental impact and contributes to reducing dependence upon fossil fuels [4]. Pyrolysis is among the current techniques to convert food waste into energy, and it allows up to 80% energy recovery from waste [4] because all the pyrolysis products, including bio-char, bio-oil, and pyro gas, have interesting heat values [5]. There are several types of pyrolysis depending on the conditions under which they occur (Table 1). By conducting pyrolysis under different conditions, temperatures, atmospheres, and even reactor types, different distributions of solid, liquid, and gaseous products can be obtained [6]. The characteristics of the fed biomass [7] (sugars, starch, oils, proteins, lignocellulosic composition, ashes, and moisture) play a key role in the distribution of the pyrolysis products, and most researchers report the existence of synergistic effects when co-pyrolysis of different biomasses, including food wastes [8], lignocellulosic wastes, and plastics [9], is performed. The moisture of food waste is considered a constraint for the valorization of these residues via the pyrolysis process because their drying requires a large amount of energy [8]. However, as recently mentioned, for microalgal biomass [10], the heat for drying food waste



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can be obtained by burning the biochar generated through the pyrolysis process itself. Hydrothermal carbonization of food waste overcomes the moisture drawback, allowing for the production of hydrochar with valuable characteristics [11].

Figure 1. World solid residues trends. Data from The World Bank [1] under the Creative Commons Attribution 4.0 International License (CC BY 4.0).

Туре	Main Features	Major Product
Slow	Slow heating rate < 1 °C/min 400 °C–500 °C	Biochar
Fast	High heating rate 600 °C–1000 °C	Bio-oil
Catalytic	300 °C–600 °C	Biochar or bio-oil depending on the used catalyst
Microwave assisted	400 °C–800 °C	Syngas and bio-oil
Hydropyrolysis	300 °C–450 °C Hydrogen instead of nitrogen	Bio-oil

Table 1. Pyrolysis types and main features (adapted from [4] Copyright Elsevier (2023)).

The use of catalysts allows the pyrolysis temperature to be reduced, with clear energy saving, and allows the desired pyrolysis product to be maximized. Several materials have been reported in the literature as catalysts for food waste pyrolysis: zeolites, ZrO_2 ceramic foams, KCl, Ni-MO/γ-alumina, Cu/Al₂O₃, Al₂O₃/Na₂CO₃, biochar, and Al-SBA-15, among other [6]. Recently, Rijo et al. [12] reported the use of sodium and calcium carbonate commercial materials as efficient catalysts for coffee and tea ground catalytic pyrolysis. The authors observed improved gasification reactions when pyrolysis was conducted using alkali carbonate catalysts. Waste materials, such as cenospheres (Si-rich material from fly ashes), showed a high ability to decrease the bio-oil acidity during catalytic pyrolysis of almonds shells [13]. Catalysts can also be used for postproduction biooil upgrading, thereby preventing the catalyst from being mixed with the produced biochar. Low-value inorganic materials, such as dolomite and bauxite, were used in bio-oil upgrade processes. Dolomite promotes cracking, thereby increasing the H_2 and hydrocarbons in the gas product, whereas red mud promoted decarboxylation and the formation of alkanes and alkenes [14]. The catalysts used in the pyrolysis of lignocellulosic biomass and food waste are similar. Zeolite materials, mostly ZSM-5, are the most commonly used in wood pyrolysis

because they have high acidity and porosity, which gives them shape selectivity [15]. In a review, Kim et al. [6] underlined the fact that catalysts in food waste pyrolysis are used to increase the bio-oil yield and aromatics content. The HZSM-5 catalyst is the most widely used for such purposes. The authors point out the limited number of publications in the field of catalytic pyrolysis of food waste, highlighting the need for further studies on the design of efficient catalysts and the optimization of the process to maximize the yields of high-value pyrolysis products. In this context, food waste catalytic pyrolysis was studied using inorganic residues as catalysts. Despite the separation of plastics, paper, metal, and glass, household garbage has a complex composition, making selective pyrolysis of lignocellulosic waste unfeasible. However, the domestic garbage bin contains significant volumes of garden debris, paper, and cardboard, predominantly cellulose, implying that the lignocellulosic biomass pyrolysis data provided here are indicatory of household waste.

2. Experimental Section

2.1. Materials

Biomass from a household waste bin was collected for the catalytic pyrolysis study. Banana peels, white and sweet potato peels, almond, walnut, and hazelnut shells, and coffee and tea grounds were dried overnight at 60 °C (dry atmosphere), reduced to powder in a blade mill, and sieved. The granulometric fractions above 750 μ m were rejected. Commercial samples of hemicellulose, Whatman filter paper (100% cellulose), and starch were used as the standard for thermogravimetry tests. A mixture of biomass (BMIX) was prepared following the existing proportions (before drying) in the household waste container. The catalytic pyrolysis tests were carried out using the BMIX.

The solids used as catalysts come from industrial ore residues: marble, bauxite, dolomite, and limestone. A spent fluid catalytic cracking catalyst (FCC) was also used as pyrolysis catalysts. The materials were ground and sieved, and the fraction below 750 μ m was used in the catalytic tests.

2.2. Methods

The powdered biomasses were characterized by thermogravimetry analysis under inert gas flow (nitrogen) to simulate pyrolysis. The thermograms were acquired on a Netzsch STA 490 PC thermobalance using a heating rate of 20 °C/min with 60–100 mg of powder (<750 μ m) placed in an alumina crucible. The thermogravimetric tests were carried out from 30 °C to 1100 °C using N₂ (18 L/h) to guarantee an inert atmosphere in the sample neighboring. The mass loss rate (DTG) was processed by applying the equipment software (Pegasus). The thermograms of the reference materials were collected and compared with the results of the biomass mixture.

The pyrolysis bench scale experiments were carried out in a fixed bed reactor, shown in Figure 2, at 400 °C. The pyrolysis temperature was selected from the thermal degradation profile of the biomass mixture.



Figure 2. Scheme of the fixed bed reactor used in the pyrolysis tests.

The fixed bed of the reactor, from the bottom to the top, was composed of the following layers: carborundum (SiC), which was used as an inert material; a small layer of glass wool; and then the biomass sample. For each pyrolysis test, 10 g of biomass was used. For catalytic pyrolysis experiments, 2 g (16.7% (wt.)) of the catalyst was used and mixed with the BMIX sample. Both the biomass and catalyst were grounded and sieved, and granulometric fractions above 750 μ m were discarded. A nitrogen flow of 300 mL/min for 15 min was required in these tests. At the end of the pyrolysis experiments, the gas phase was discarded and quantified by mass balance, and the solid (composed of biochar and catalyst) was removed from the reactor and weighed. The liquid product was obtained using a condensing system and by washing the inert SiC with acetone. The following step was to dry the liquid product in a rotavapor (at 80 °C and 120 mmHg for 1 h) to remove the acetone and the water formed during pyrolysis. The dried liquid phases, rich in organic compounds, were weighed to compute the bio-oil yields and characterized by ATR-FTIR spectroscopy. The spectra were recorded on FT-MIR equipment from BOMEN (FTLA2000-100, ABB) with a DTGS detector. The FTIR spectra were deconvoluted to identify and quantify the bio-oils' organic functional groups [13]. More information about this procedure can be found in the previous work [16-18]. Simulated distillation in a thermobalance was used to determine the bio-oils' volatility [19]. The thermograms were acquired at a 20 °C/min heating rate with 60 mg of bio-oil sample under nitrogen atmosphere. The volatile fraction considered was the mass fraction lost for temperatures below 350 °C, which corresponds to the distilled fractions of petroleum (light and medium distillate).

3. Results and Discussion

3.1. Thermogravimetry Analysis (TGA)

The biomasses were characterized by thermogravimetry analysis to evaluate the different steps that occur during thermal degradation in inert conditions (under N₂ flow). The thermal degradation profiles for the reference materials (Figure 3) were used as standards to identify the degradation processes of lignocellulosic waste. For all samples, the release of volatiles occurs in the temperature range reported in the literature for the thermal decomposition of lignocellulosic components of food waste (180–510 °C [20]). As expected [21], the thermograms show that the biomasses exhibit distinct thermal degradation processes that depend on their respective lignocellulosic compositions. Banana and potato peels show the highest values, at lower temperatures, for thermal decomposition because they have pectin and hemicellulose with smaller molecules than dried fruit shells or coffee and tea grounds. In fact, different hemicelluloses show distinct thermal degradation profiles [22]. Coffee ground is the biomass with the highest temperature decomposition process, corresponding to the thermal decomposition of oils [12]. For all of the biomasses, the temperature range of active pyrolysis [23] is below 425 °C.

The thermal degradation profile of BMIX (Figure 4) shows an active pyrolysis range for temperatures slightly lower than those of the individual biomasses, which can arise from synergy effects between the different components of biomasses. Other researchers [24,25] have claimed the existence of synergy effects during the co-pyrolysis of distinct biomasses, stating a significant decrease in the pyrolysis activation energy. For BMIX, a passive pyrolysis temperature range (400–600 °C) is visible [26]. Such a pyrolysis step can also be the result of interactions between the many components of co-pyrolyzed biomasses. The majority of researchers believe that the lignin is decomposing during this slow pyrolysis step, which results in the biochar formation [27]. Given the complexity of the pyrolyzed biomass, the passive pyrolysis step can also correspond to the charring of compounds volatilized during the active step.



Figure 3. Thermal degradation rate of individual biomasses and cellulose and starch references at 20 $^\circ\text{C}/\text{min}$ under N_2 flow.



Figure 4. TG of biomass and DTGs of biomass and standard samples at a 20 °C/min heating rate.

The thermal degradation profiles and the literature data led to the selection of 400 °C as the temperature for the pyrolysis tests. At this temperature, the cellulose, which is the component of the tested food scraps most resistant to thermal degradation (Figure 5), has already been completely devolatilized. Quing et al. [28] reported for food waste pyrolysis a maximum bio-oil yield for temperatures in the 400–600 °C range. Higher pyrolysis temperatures would favor pyrogas yield [29]. The researchers point out that in this temperature range, the bio-oil yield is almost invariant, so lower pyrolysis temperatures will correspond to energy savings.



Figure 5. Bio-oil and biochar yield versus maximum rate of thermal degradation.

3.2. Fixed Bed Reactor Experiments

3.2.1. Pyrolysis Yields

Each biomass, dried and powdered, was pyrolyzed at 400 °C. Data in Figure 5 show that the composition of the biomasses has a noticeable influence on the distribution of the pyrolysis products [30,31]. The biomasses with lignocellulosic waste that degrade at

higher temperatures, the dried fruit peels, are those with the highest bio-oil yield. The starch and pectins from potatoes and banana peels as they degrade at lower temperatures lead to charring reactions in consecutive processes after the volatilization that occurs in the first pyrolysis step. It was expected that the bio-oil yields would follow the inverse trend of pyrolysis difficulty of the different components reported in the literature [32] (lipid > lignin > starch > cellulose > protein > hemicellulose), but biomasses are complex, and the interactions between the different components lead to deviations from the expected behavior. The inorganic content of each biomass (ash) also contributes to these deviations. Biomass ash acts as pyrolysis catalysts [33] and alkali elements of ash promote biomass gasification [34]. Given the complexity of the effects of biomass composition on the distribution of the pyrolysis products, an attempt was made to correlate the liquid and solid yields with the maximum rate of thermal degradation. The results in Figure 5 show that increasing the maximum thermal degradation rate favors the bio-oil yield over the biochar yield. Such a result is in line with the fact accepted by all researchers in the field of pyrolysis that for fast pyrolysis, the majority product is the liquid product, while in slow pyrolysis, the formation of the solid product is favored [35]. Potato peel biomass does not follow this path, which may be due to the fact that it is mainly composed of starch.

Pyrolysis of the biomass mixture (BMIX, Figure 6) shows a bio-oil yield similar to that of tea grounds (19%) but with a significantly lower biochar yield (30% instead of 43%). This result is a consequence of the interaction (synergy) between the different components of the biomasses. Recently, Samar et al. [20] reported that pyrolysis of a mixture of three biomasses produced more hydrogen than pyrolysis of the separate biomasses, which was responsible for the lower biochar yield. Such an effect may be responsible for the decrease in biochar yield observed here.





All of the catalysts tested (Figure 7) allowed for gains in bio-oil yield, with marble dust being the most efficient catalyst. This catalyst allowed an increase from 19% to 36% in bio-oil yield, while dolomite and limestone led to bio-oil yields of 21.5% and 25.5%, respectively. Several researchers have previously reported the catalytic activity of dolomite in the pyrolysis of lignocellulosic waste. P. Wang and Y. Shen concluded that the dolomite had good performance in the cracking of large-molecular chemical structures to small-molecular compounds during the pyrolysis process [36]. Ly et al. studied the fast pyrolysis of tulip trees using dolomite as the fluidized-bed material, and the highest bio-oil yield (45%) was reached at 400 °C. Also, there was an increase in the H₂/CO ratio produced in the gas product [37].



Figure 7. Pyrolysis yields obtained using biomass mix with 16.7% (wt.) of catalysts at 400 °C.

Prabhakara et al. [38] studied the influence of dolomite on the fast pyrolysis behavior of beechwood at a temperature of 500 $^{\circ}$ C and reported an increase in the H₂ content in the gas phase produced. Data in Figure 7 show that limestone and marble were more effective than dolomite at improving the liquid product yields. According to the literature, Ca-based catalysts promote thermal cracking of tar, leading to the production of H_2 , CH_4 , and light hydrocarbons [39]. Researchers state that Ca catalysts derived from ore residues are as highly viable as pyrolysis catalysts because they are abundant materials in nature and, as such, economical [39]. The marble catalyst showed the lowest biochar yield, which may be due to the ability of Ca catalysts to promote the steam-gasification of char [40]. Because limestone and marble, which are mainly calcite, are different ores, the microelements of each one may have an important role in their catalytic behaviors. Also, the high crystallinity of marble catalyst may justify its good catalytic behavior. The FCC catalyst had a moderate effect in promoting the yield of the pyrolysis liquid product due to the fact that its porosity and acidity are not the cracks of the non-deactivated zeolites. These two characteristics, acidity and porosity, are critical to the performance of zeolites in large molecule cracking and aromatization reactions reported in the literature [41]. Moreover, the working temperature used is below the temperature range reported in the literature for the performance of zeolitic catalysts in lignocellulosic biomass pyrolysis.

3.2.2. Bio-Oil Characterization

The composition of the bio-oil produced via food waste pyrolysis differs significantly from that produced from lignocellulosic biomass [42]. The food waste contains in its composition, in addition to lignocellulosic waste, starch, proteins, and oils that generate, by pyrolysis, compounds different from those generated by lignocellulosic waste. According to Mengxia et al. [28], the bio-oil from food waste pyrolysis is composed of N-containing compounds, hydrocarbons, and carboxylic acids. Dried pyrolysis bio-oils were characterized by ATR-FTIR to infer information about their main functional groups (carboxylic, phenolic, ester, and ketone, among others) and, using simulated distillation, to study their volatility.

The bio-oils' FTIR spectra, in Figure 8, were analyzed considering the bands attribution collected from the literature (Appendix A, Table A1). For all of the spectra, the most intense IR bands are located in the 1750–1650 cm⁻¹ range belonging to C=O stretching from aldehyde, ketone, carboxylic acids, ester, and quinone groups, as these compounds are the main components of pyrolytic bio-oil derived from wood biomass [34]. Additionally, all of the spectra present a broad band in the range 3600-3050 cm⁻¹ attributable to OH groups of carboxylic acids, alcohols, and phenols [43] overlapped with -NH bands of nitrogen-containing compounds [44]. The limestone and marble catalysts, both composed mainly of calcium carbonate, show identical bio-oil FTIR spectra. Looking at the band in the 800–600 $\rm cm^{-1}$ range, it is observed that both catalysts show a slight decrease in the olefin content of the bio-oil. This reinforces what was observed in previous work, where the sodium carbonate catalyst increases the olefin content while calcium carbonate decreases it. The bio-oils produced by catalytic pyrolysis with bauxite and dolomite have a different spectrum than the other bio-oils. Bauxite, an Fe-rich Al-Si mineral, is expected to behave similarly to an Fe-modified zeolite, promoting the formation of hydrocarbons and BTX fraction [45] (from Table A1: $3000-2800 \text{ cm}^{-1}$ belonging to aliphatics; $3600-2800 \text{ cm}^{-1}$ belonging to -OH including phelonics). Dolomite catalyst is reported to promote deoxygenation reactions during biomass pyrolysis, improving simultaneously the content of phenols $(3600-2800 \text{ cm}^{-1})$ and methylated $(3000-2800 \text{ cm}^{-1})$ cyclopentanones $(1696 \text{ cm}^{-1}, \text{ and } 1640 \text{ cm}^{-1})$ [38].

Organic compounds containing OH and C=O functional groups are referred to as being primarily responsible for the high acidity, low heating value, and high instability during bio-oil storage [46], whereas aromatic compounds are highly desired [47]. Therefore, it is relevant to quantify the different compounds with carbonyl and aromatic groups. The FTIR bands in the range of 1750–1650 cm⁻¹ (Figure 8) were deconvoluted following the methodology of Lievens and co-workers [48] to infer the respective amounts of these components (Figure 9). The distribution of functional groups (Figure 9) of bio-oils from the pyrolysis of food residues confirms the claims of Mengxia et al. [28] that they are different from congeners derived from wood biomass. Under analogous conditions, Rego et al. [34] found that poplar-biomass-obtained bio-oils had mostly carboxylic acids, while those derived from food waste had similar amounts of cyclic esters, esters, and aldehydes along with carboxylic acids. This finding makes it possible to claim that food waste produces pyrolysis bio-oil with superior properties (less oxygen and lower acidity) than wood biomass.

The compositions of the bio-oils obtained from catalytic pyrolysis using marble and limestone as catalysts are very similar to each other. This result was expected because these ores are essentially composed of limestone, although marble contains some dolomite content. It can also be seen that pyrolysis of food waste using deactivated FCC obtained a bio-oil with very similar composition to the bio-oil obtained by uncatalytic pyrolysis. As mentioned in previous work, the FCC catalyst has a microporous structure due to the presence of HY and ZSM5 zeolites. The shape-selectivity of these zeolites promotes the diffusion of the small compounds into the zeolite channels. However, if there was no difference in both bio-oil compositions, this means that that the zeolite used, a deactivated FCC catalyst, had already lost an important part of its relevant characteristics for good performance in pyrolysis (porosity and acidity).



Figure 8. ATR-FTIR spectra of dried bio-oils obtained by fixed catalytic and non-catalytic pyrolysis.



Figure 9. Functional groups of the produced bio-oils assessed by deconvolution of ATR-FTIR spectra.

The compositions of the bio-oils obtained by the bauxite and dolomite catalysts are different from the other bio-oils. The spectra of these two bio-oils, in Figure 9, are distinct from the others; thus, it would be expected that their compositions would also be different. P. Wang and Y. Shen [36] reported that the presence of dolomite in cellulose pyrolysis improved the conversion of anhydro sugars to light oxygenates or gases production (CO₂, CO, and H₂). They also reported that the high catalytic activities of CaO and MgO in the dolomite could enhance the breakage of typical chemical bonds, such as the glucosidic bond, C-O, and C–C. Ly et al. [37] reported that the use of dolomite as a catalyst increased the content of aromatic compounds (C₅–C₁₁), such as the derivatives of furfural, ketones, and phenolic compounds, compared to those from the uncatalytic pyrolysis vapor by dehydration, instead of decarboxylation or decarbonylation [37]. Prabhakara et al. [38] reported that the dolomite in beechwood pyrolysis increase the yield of cresols and cyclopentanones, achieving values around 23.3% and 29.6%, respectively.

Figure 10 illustrates the simulated distillation curves of the bio-oils produced using thermogravimetric analysis. These curves provide insights into the volatility of the bio-oils. The volatile fraction computed as the mass loss above 325 °C [12] (Figure 11) shows that marble catalyst improves the bio-oil volatility, while the other catalysts reduced the bio-oil volatility. The marble catalyst behavior is compatible with the role of calcium catalysts reported in the literature: tar cracking [39]. The other calcium-based catalysts, limestone and dolomite, played a different role, from marble to bio-oil volatility, which may be due to the fact that they were able to break down smaller molecules, but the larger molecules promoted deactivation by coke deposition [39]. The same effect can be attributed to the spent FCC catalyst due to its reduced porosity. In such a condition, the spent FCC catalyst was only able to crack smaller molecules forming non-condensable gas products. The bauxite catalyst, an iron-rich material, had an almost null effect on the bio-oil volatility because it acts as a dehydration and decarboxylation catalyst and not as cracking catalyst [49].



Figure 10. Rate of simulated distillation of the bio-oils obtained in the catalytic and non-catalytic pyrolysis at 400 °C. Thermograms were acquired under N_2 flow and a heating rate of 20 °C/min.



Figure 11. Bio-oil volatile fraction (mass loss for temperatures lower than 325 °C) assessed by simulated distillation by thermogravimetry.

4. Conclusions

Lignocellulosic biomass from household waste, dried fruit shells, and potato and banana peels were valorized through pyrolysis at a low temperature (400 $^{\circ}$ C) and in a fixed bed reactor, using as catalysts (16.7% wt.) low-value mineral residues: bauxite, limestone, dolomite, and marble and a spent zeolitic catalyst from FCC. The pyrolysis of the biomass mixture shows the existence of synergy effects through interaction between the different lignocellulosic components. All catalysts had a positive effect on bio-oil yield at the expense of biochar and decreased the carboxylic acids content. The carbonate rock-based catalysts were the most efficient in reducing the acidity of the bio-oil, while the deactivated FCC catalyst was the least efficient. The effect of the zeolite catalyst on cracking/deoxygenation, as reported in the literature for zeolites, was minimal because the deactivated catalyst had

lost much of its porosity and acidity. The results show that low-value inorganic materials can be used in biomass pyrolysis, thereby allowing cost savings. Additionally, the Ca catalysts that remain in the produced biochar do not prevent its use in soil amendment, because Ca is a fundamental element as an inorganic fertilizer.

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Appendix A Bio-Oil Infrared Bands Attribution

Table A1. Bio-oil FTIR bands attribution from the literature (adapted from [12], copyright Elsevier (2023)).

Band Position (cm ⁻¹)	Functional Group	Band Assignment	
1767	C=O	Lactones	
1740	C=O	Unconjugated alkyl aldehydes and alkyl esters	
1713	C=O	Carboxylic acids (and fatty acids)	
1696	C=O	Unsaturated aldehydes, ketones	
1640	C=O	Hydroxyunsaturated ketones, aldehydes	
1600	C=C		
1575	C=C	A romatice with various types of substitution	
1517	C=C	Atomatics with various types of substitution	
1501	C=C		
3008	C=C	Symmetric stretching vibration of aromatics	
3000–2800	C-H	Aliphatics	
3650-3100	OH	Carboxylic acids, alcohols, and phenols	
1645	NH	Amines	
3363 (broad)	OH	Water, alcohols, organic acids	
5565 (b10au)	NH		
1659	C=C	Stretching vibration of carbon-carbon double bonds	
	C=O	Stretching vibration of carbonyl groups	
1455	CH_2, CH_3	Bending vibrations of aliphatic groups	
1406	C-H	Rocking vibrations of olefins	
1028	C–O	Stretching vibration of ester groups	
880	C-H	Out-of-plane deformation vibration of terminal olefins	
666 (broad)	CH ₂	Overlapping of the rocking vibration and the out-of-plane vibration of cis-disubstituted olefins	

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