Bioenergy potential and thermochemical characterization of lignocellulosic biomass residues available in Pakistan

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Abstract−We evaluated the thermochemical properties and suitability of a variety of lignocellulosic biomass residues in Pakistan for energy production. Proximate, ultimate and calorific value analyses were performed to know the energy perspective, whereas thermogravimetric analysis was used to study the decomposition behavior of biomass samples under pyrolysis conditions. The moisture content, volatile matter, fixed carbon and ash content in the biomass samples were found within the range of 4.38-5.69%, 63.25-80.53%, 7.97-23.13%, and 7.12-14.35%, respectively. The range of carbon, hydrogen, and oxygen content was reported as 35.83-47.23%, 5.2-6.56%, and 45.6-58.55%, respectively. Lower values of sulfur and nitrogen content amongst the samples indicated that the biomass was environmentally friendly in terms of energy production. The heating value of the biomass was reported in the range of 15.20-18.44 MJ/kg. Fourier transform infrared spectroscopy showed the existence of hydroxyl, aldehydes, ketones, aromatic compounds, carbonyl compounds, ether, and halogen groups. Orange leaf biomass indicated a greater potential in producing bio-oil, whereas the horticulture biomass and mango leaves may have greater potential for biochar.

Keywords: Bioenergy, Lignocellulosic Biomass, Thermochemical Characterization, Proximate Analysis, Pyrolysis

INTRODUCTION

Increase in population and economic activities have led to an increase in energy demand, especially in developing countries. People largely depend on fossil fuels to fulfil their energy needs, which results in considerable environmental issues [1-3]. The burning of fossil fuels generates greenhouse gases (GHGs), such as carbon dioxide and carbon monoxide, which contribute significantly towards global warming [4-6]. To diminish the amount of hazardous gases being emitted, carbon from the atmosphere may be captured and stored, but this is expensive, requiring major investments for CO_2 absorption and transportation [7]. Alternatives to mitigating fossil fuel burning could be expanding the capacity of energy produced from renewable sources [8,9]. In this regard, biomass utilization is a promising option as it is easily and abundantly available, a cheap alternative and eco-friendly source of energy with lower GHG emissions as compared to fossil fuel burning [10,11]. In addition, biomass grows rapidly and is considered as the third-largest source of energy in the world after coal and oil. Further-

more, it contains a negligible amount of sulfur and nitrogen, hence decreases certain environmental issues such as acid rains [12]. Due to being a cost effective alternative and with lower environmental emissions, biomass is an important fuel source. For the above-mentioned attributes, the global scientific community is focusing research on the efficient utilization of biomass energy as an alternative renewable energy source [13,14]. Amongst biomass, lignocellulosic biomass is considered as a paramount source of energy production [15]. Different forms of energy such as biofuels, biochar and biogas can be produced from biomass, which can be further converted to other useful products such as bioethanol, syngas, bio hydrogen, ethanol, methanol and methane [16,17].

Pakistan is a well-established agricultural country with its economy mainly dependent on agricultural products, hence generates a large amount of agricultural residues, such as leaves, stems, and seed pods, which can be potentially employed for energy generation. Presently, a large number of crop residues, such as wheat straw, rice husks, sunflower stems, garden biomass wastes, and date, mango, and orange tree biomass are burned every year in Pakistan to prepare the land for re-cultivation [18]. According to the World Meteorological Organization in 2016, concentrations of CO_2 are at their highest compared to the past 800,000 years [19]. Before the advent of modern technology, populations primarily gener-

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ated energy through the combustion of biomass in the form of wood [20]. Burning of biomass directly for energy is an inefficient process that results in emissions of contaminants, primarily carbon monoxide, polyaromatic hydrocarbons, formaldehyde and other hazardous gases. These emissions may cause a multitude of diseases, including asthma, tuberculosis, and other respiratory diseases [21-23]. In contrast, a considerable number of agricultural residues can be utilized as feedstock of energy conversion processes for energy production, thus, providing the additional benefits of environmental safety [18]. Lignocellulosic biomass is a favorable source of energy with environmentally sound prospects. Presently, approximately 18% of the energy is obtained from renewable sources globally, such as biomass, wind, and solar [24,25]. Rapidly growing energy demand, lack of awareness and ineffectual energy policies have pushed Pakistan to a situation of severe energy deficiency and economic challenges, resulting in the wastage of agricultural residues by burning. Renewable energy sources are widely available in Pakistan which can be managed appropriately to fulfil national energy requirements without importing energy resources, such as oil and coal, from other countries. In Pakistan, energy demand is continuously increasing annually by more than 9%, which is predicted to increase eight-fold until 2030 and 20-fold until 2050 [26]. At present, approximately 27% of the energy demand in Pakistan is being met through biomass sources, such as agricultural waste and wood [27]. According to a prediction, in 2050 Pakistan will be the fourth largest country in the world in terms of population, with 62% of the population linked with agriculture for its livelihood [28].

Energy from biomass can be obtained by using different biochemical and thermochemical techniques like combustion, liquefaction, gasification, anaerobic digestion, pyrolysis and fermentation. The selection of technology depends upon the type and quality of the biomass and the form of energy required [29]. Among these options, pyrolysis is one of the most well adopted technologies as it can produce energy in solid (Biochar), liquid (bio-oil) and gaseous form as well by using a variety of feedstock materials [30]. The present study explored the potential and suitability of various lignocellulosic biomass residues, including mango leaves, orange tree leaves, date tree leaves, horticulture biomass, and sunflower biomass via thermochemical characterization for energy generation in Pakistan.

EXPERIMENTAL

1. Sample Collection and Preparation

The lignocellulosic biomass samples used in this study include residues from date leaves, mango leaves, orange leaves, sunflower and horticulture biomass which were collected from Shahdara Lahore, Pakistan. In total, 3-5 kg of each biomass sample was collected and sun dried for approximately two weeks to eliminate extrinsic moisture. The air-dried biomass specimens were then chopped and ground using a hammer mill, resulting in a fine powder which was sieved to obtain uniform particle size of less than 250 μm. These samples were stored in airtight plastic bags to avoid contamination and cross mixing of the samples. The biomass residues were given short names for the ease of reporting in the study as mango leaves (ML), orange leaves (OL), date leaves (DL), horticulture biomass (GB), and sunflower biomass (SB).

2. Methodology of Characterization

A schematic diagram of the characterization methodology used in the present study is shown in Fig. 1 with details explained in the coming subsections.
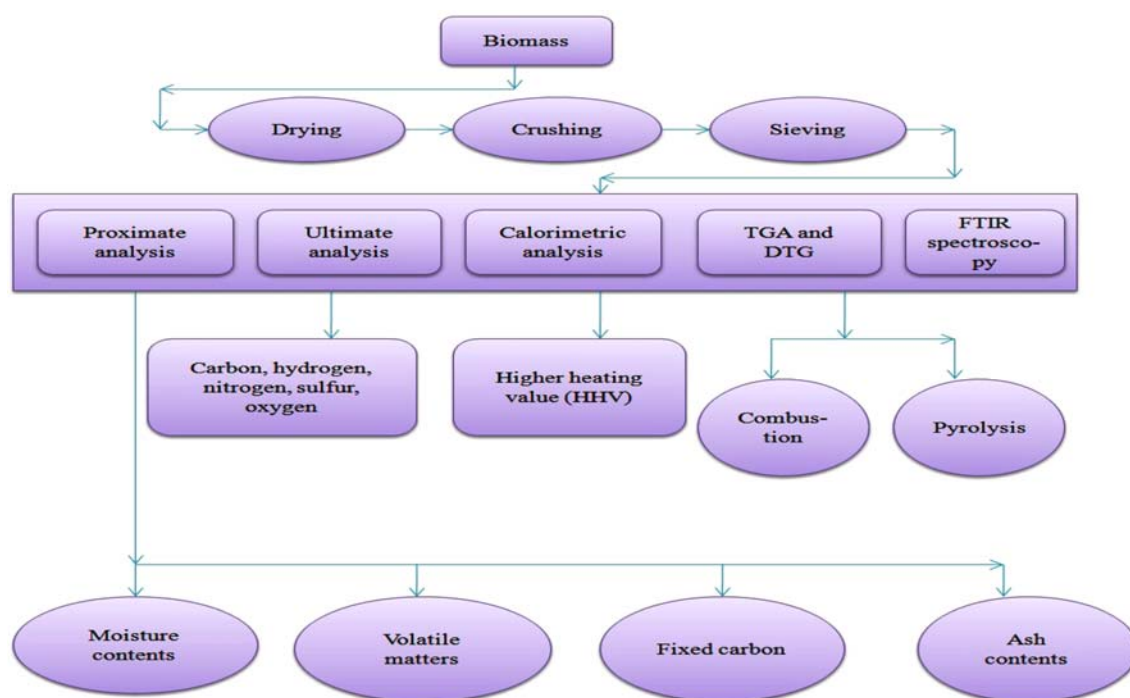

Fig. 1. The schematic diagram for the characterization of biomass residues.

2-1. Proximate Analysis

Proximate analysis helped to determine the moisture content (MC), volatile matter (VM), ash content, and fixed carbon (FC) in the biomass samples. The moisture content investigation of the biomass samples followed the procedure ASTM D3173. Precisely 1.0 g of each sample was retrieved and placed into a crucible, which was then inserted into an oven maintained at 105 °C for 2 h. Ash content refers to the amount of solids remaining after the burning of biomass. Ash content of the biomass samples was studied by following the ASTM E 1755 procedure. The volatile matter consisted of hydrocarbons, CO, CO_2, and tars. Biomass with high levels of VM is readily combusted and rapidly decomposed during the pyrolysis process. The VM present in the samples was determined using the ASTM D 3175-07. The fixed carbon is the amount of solid residue remaining after biomass burning and removal of volatile matters (VM). FC was determined by subtracting the sum of the moisture content, ash content and the volatile matter content from 100, as shown as follows in Eq. (1).

$$FC (wt\%) = 100 - (MC + VM + Ash) \qquad (1)$$

2-2. Ultimate Analysis

The ultimate analysis determined the percentage of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) present in the sample. The ultimate analysis was performed using the CHNS analyzer, model LECO SC144-DR (USA). The oxygen content of the biomass samples was calculated by subtracting the sum of all the elements from 100 as given in Eq. (2).

$$Oxygen (wt\%) = 100 - (C + H + N + S) \qquad (2)$$

2-3. Higher Heating Value (HHV)

The higher heating values (HHV) of the biomass samples were determined using the bomb calorimeter, model Parr 6200 (USA) by following ASTM-D-5865-07a standard [31]. In each experimental run, 1.0 g of biomass sample was used; the crucible containing nickel ignition wire and a thread remained in contact with the biomass sample placed in the bomb calorimeter. The highly purified oxygen was used to maintain the pressure in the bomb calorimeter in the range of 20-30 atm. The calorimeter was placed in a bucket filled with distilled water and ignition was provided for twenty minutes. The biomass sample in the bomb was completely burned, which increased the temperature of the bucket, as precisely recorded using an electronic thermometer. The temperature values were then used to determine the heating values of the biomass samples.

2-4. Fourier Transform Infrared (FTIR) Spectroscopy

Functional groups in the biomass samples were identified via FTIR spectroscopy using the equipment model Nicolet iS10 Mid Infrared (Thermo Fisher Scientific, Austria). The experiments were conducted within the range of 650 cm^{-1}-3,700 cm^{-1} and reported as a percentage of transmittance.

2-5. Thermogravimetric Analysis (TGA and DTG)

Thermogravimetric analysis of the biomass samples involved using the equipment model LECO TGA-701 (USA) and was performed under the pyrolysis environment employing 5.0 mg of each biomass sample under continuous flow of 99.99% pure Nitrogen gas at a flow rate of 85 ml/min, and heating rate of 30 °C/min within

Table 1. Proximate analysis of the biomass residues

Biomass samples	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)
OL	4.39	78.8	9.37	7.44
SB	5.51	63.25	23.13	8.11
ML	5.69	64.65	18.03	11.63
DL	4.38	80.53	7.97	7.12
GB	5.21	68.36	12.08	14.35

temperature range of 50 °C-900 °C for all biomass samples.

RESULTS AND DISCUSSION

1. Proximate Analysis

The proximate analysis of all biomass samples along with the higher heating values used in the study is shown in Table 1 and explained comprehensively in the subsections below.

1-1. Moisture Content (MC)

The percentage of water content present in the biomass is an important factor for the selection of biomass for as a feedstock for the conversion process. In general, high MC affects the quality of the biofuels. The increase in MC lowers the heating value of the fuels. The MC in the biomass residues is given in Table 1. The MC was reported in the range of 4.38-5.69 wt %. All values were reported to be lower than 10%, indicating that biomass residues are suitable to be used as feedstock for the pyrolysis process [32]. The lowest MC was reported from the DL (4.38%). The highest MC was reported from the ML biomass (5.69%) followed by the SB biomass (5.51%). Greenhalf et al. reported the MC for switch grass as 4.61%, and for reed canary grass as 4.96%, hence quite comparable with the MC percentage reported for the OL and DB reported in the current study [33]. Garcia et al. reported MC as 9.2% for the orange biomass, which is higher than the value reported in the present study [34]. The difference in the values of MC in the biomass samples used in the current study and the previously reported studies could be due to the difference in the growing conditions and the location of the source of the biomass.

1-2. Volatile Matter (VM)

Volatile matter is the portion of biomass released when it is exposed to a high temperature. Hence, biomass with high VM content has a tendency to easily combust and decompose during the thermochemical process, preferably producing higher percentage of bio-oil during the pyrolysis process [35]. The VM obtained in the present study was reported in the range of 63.25%-80.53%. The lowest VM level was found for the SB residues (63.25%), while the highest VM content was reported for the DL residues (80.53%) followed by OL (78.8%), as presented in Table 1. Greenhalf et al. reported VM content for switch grass and reed canary grass as 83.23% and 77.45%, respectively, which is higher than the values reported in the present study [33]. Garcia et al. reported 73.2% VM in orange tree biomass, which is lower than the values of VM reported in the current study [34].

1-3. Ash Contents

Ash content in the biomass is mainly comprised of the salts and

minerals of silica, aluminium, iron and calcium and small amount of sodium, potassium, phosphorous and chlorine [36]. The quantity of ash varies in different biomasses between 1-40% [34]. Biomass with higher ash content produces more char residues during the pyrolysis process [35]. In this study, the ash content in the biomass samples was found in the range of 7.12%-14.35%. DL biomass residue was reported to have the minimum ash content as 7.12%, followed by ML residue reported as 11.63%, while GB was reported to have the highest percentage of ash content as 14.35%, as reported in Table 1. In the current study, all biomasses had lower and medium ash content. Garcia et al. reported 38% and 15.4% ash content in GB and orange trees, respectively, which is higher than the values reported in this study [34]. Akhtar et al. reported 9.46% ash in mango biomass, which could be compared with that of SB (8.11%) reported in the current study [37].

1-4. Fixed Carbon

Fixed carbon content is the part of the biomass left after the volatile matters are expelled and by subtracting the percentage of moisture and ash content from the biomass sample. Carbon is the major component in the biomass with some other minor components like hydrogen, oxygen, nitrogen and sulfur [36]. In the present study, the FC components were reported in the range of 7.97%-23.13%, as shown in Table 1. Lower FC was reported in the DL residue biomass (7.97%), and the highest value of FC was reported in the SB residues (23.13%), followed by MLs (18.03%), as reported in Table 1. Garcia et al. reported the value of 11.45% FC in orange biomass, which is comparable to the values obtained for the GB (12.08%) residues in the current study [34]. Akhtar et al. reported 7.71% FC in mango biomass, which is also comparable with the 7.97% of FC reported in DL residues in the current study [37].

2. Ultimate Analysis

The ultimate analysis of the biomass samples used in the study is shown in Table 2. While the van Krevelen diagram for the biomass residues showing the plots between the O/C and H/C molar ratios is in Fig. 2. The carbon content in the biomass samples was reported in the range of 35.83%-47.23% with the highest carbon content (47.23%) reported in the DL followed by OL (44.01%). While, the lowest value of carbon content (35.83%) was reported for the SB residues, as shown in Table 2. The hydrogen content reported in the present study was in the range of 5.2%-6.5%. The lowest hydrogen content (5.2%) was obtained for SB, while the highest value of hydrogen content (6.56%) was reported from the DL biomass followed by OL (6.26%). Ahmed et al. reported 7.77% hydrogen content in *Acacia holosericea* phyllodes, which is higher
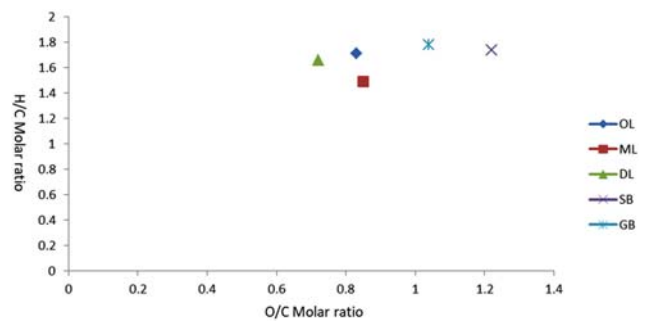

Fig. 2. Van Krevelen diagram of the biomass samples.

than the values obtained in the current study [35]. Nitrogen values obtained for the present study were found in the range of 0.1%-0.39%. The highest nitrogen content (0.39%) was obtained in OL followed by ML (0.36%). The lowest value of nitrogen content (0.16%) was reported in SB residues. Bakar et al. reported a value of 0.665% nitrogen in Brunei rice husks, which is well comparable with the values reported in the current study [38]. Sulfur content reported in the current study was within the range of 0.22%-0.47%. The highest sulfur content was obtained in GB (0.47%) followed by DLs (0.38%) and the lowest in the ML (0.22 %) residues as shown in Table 2. Danish et al. reported 0.05% sulfur in corn leaves, which is lower than the values of the current study [39]. Garcia et al. reported 0.21% sulfur in orange trees, which is comparable with the values for MLs (0.22%), SB (0.26%), and OLs (0.28%) reported in this study [34]. The oxygen content reported in the present study was within the range of 45.6-58.55%. The highest oxygen content was obtained for the SB (58.55%) followed by GB (54.47%). The lowest oxygen content was found in DL (45.6%) as presented in Table 2. Danish et al. reported 65.71% oxygen in rice straw, which is higher than the values of the current study [39].

3. Higher Heating Values

The heating value of biomass represents the quantity of energy released when a specific amount of biomass is completely burned in the presence of oxygen. The comparison of the higher heating values for the biomass residue samples used in the study is shown in Fig. 3. In the current study, the reported range for HHV lies in the within 15.20-18.44 MJ/kg for all the biomass samples. It can be seen that DL has the highest value of HHV (18.44 MJ/kg) followed by the OL (17.90 MJ/kg) biomass. SB have the lowest HHV (15.20 MJ/kg) among the biomass samples, as reported in Table 1. Greenhalf et al. reported heating values of 19.64 and 19.12 MJ/kg

Table 2. Ultimate analysis of the biomass samples used

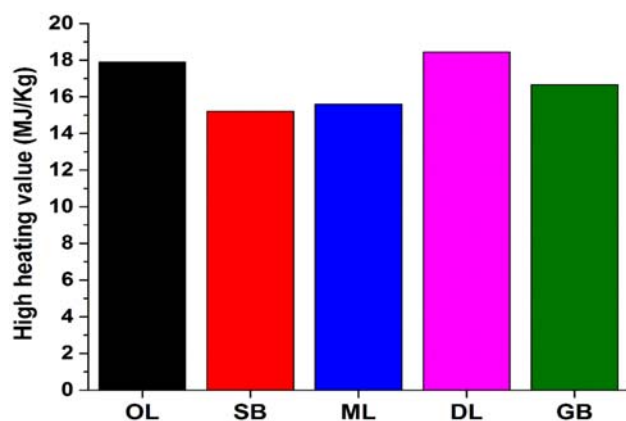| Biomass sample	Carbon (wt%)	Hydrogen (wt%)	Nitrogen (wt%)	Sulfur (wt%)	Oxygen (wt%)	O/C	H/C	Empirical formulae
OL	44.01	6.26	0.39	0.28	49.06	0.84	1.71	$CH_{1.71}N_{0.03}O_{0.84}$
SB	35.83	5.2	0.16	0.26	58.55	1.23	1.74	$CH_{1.74}N_{0.01}O_{1.23}$
ML	43.84	5.45	0.36	0.22	50.13	0.86	1.49	$CH_{1.49}N_{0.03}O_{0.86}$
DL	47.23	6.56	0.23	0.38	45.6	0.72	1.67	$CH_{1.67}N_{0.02}O_{0.72}$
GB	39.01	5.8	0.25	0.47	54.47	1.05	1.78	$CH_{1.78}N_{0.02}O_{1.05}$

Fig. 3. Comparison of the higher heating values (HHV) of the biomass residue samples used in the study.

Fig. 4. Thermogravimetric (TGA) curves of the biomass samples under pyrolytic degradation conditions.

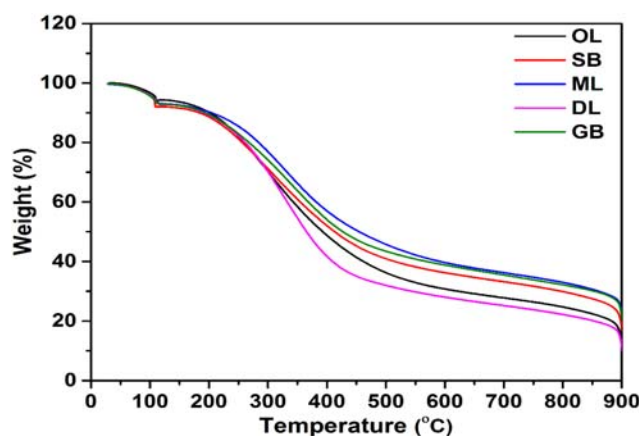Fig. 5. Derivative thermogravimetric (DTG) curves of the biomass samples under pyrolytic degradation conditions.

for the switch grass and reed canary grass, respectively, which are comparable with the values reported in the current study [33]. Garcia et al. reported a heating value of 16.17 MJ/kg for the orange biomass, which is comparable with the values reported for the ML biomass (16.03 MJ/kg) and the DL (16.39 MJ/kg) in the current study [34].

4. Thermogravimetric Analysis (TGA and DTG)

Pyrolytic degradation behavior of the biomass samples under pyrolysis was investigated with the help of thermogravimetric analysis. The thermogravimetric and its derivative (TGA and DTG) curves obtained for the biomass samples are shown in Fig.
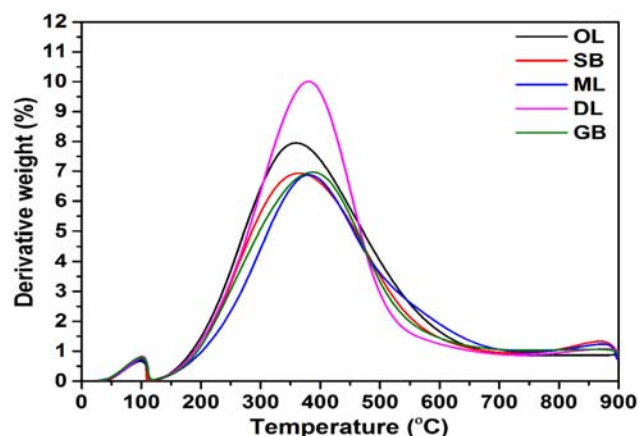
4 and 5, respectively. The degradation of biomass under pyrolysis conditions took place in three major stages, which includes the removal of moisture and the light volatile matter present in the biomass, followed by the decomposition of cellulose and hemicellulose components and, finally, the decomposition of lignin components present in biomass. The first two major stages of biomass decomposition were further divided into the two subzones to represent the decomposition of biomass components [40]. The temperature range for the zone 1 under stage I corresponding to the removal of moisture was found to be in the range of 105 °C-110 °C, corresponding to the loss of 4.38%-5.69% weight due to the removal of moisture present in biomass samples. Values reported for the removal of moisture in this study are comparable with the results reported in previous studies. Akhtar et al. reported the loss of weight occurring in the leaf litter of *Mangifera indica Populus deltoides*, and *Polyalthia longifolia* at temperatures lower than 100 °C, which was followed by the removal of MC at 100 °C-130 °C, the removal of volatile compounds at 130-250 °C, and the degradation of hemicellulose at 250 °C-350 °C, whereas at 350 °C-500 °C, cellulose degraded and the degradation of lignin took place at temperatures higher than 500 °C [37]. Hidayat et al. reported that in *Imperata cylindrica* the removal of water took place at 40 °C-105 °C, and major degradation of lignocellulosic biomass and the removal of volatile compounds occurred at 105 °C-500 °C [41]. In zone 2 of stage I, weight loss was observed at 147 °C-197 °C which can be attributed to the removal of light volatile matter (1.28%-3.72%) present in the biomass samples [37].

Table 3. Temperature ranges for major decomposition stages and zones in TGA and DTG analysis

Biomass sample	Stage I (°C)		Stage II (°C)		Stage III (°C)	Peak temp (°C)
	Zone 1	Zone 2	Zone 1	Zone 2		
DL	30-105	105-188	188-290	290-491	491-900	290-397
GB	30-106	106-197	197-301	301-409	409-900	301-409
ML	30-110	110-172	172-269	269-471	471-900	269-375
OL	30-109	109-147	147-232	232-443	443-900	232-338
SB	30-108	108-139	139-217	217-430	430-900	217-326

Table 4. Weight loss in different stages and zones in TGA and DTG analysis

Biomass sample	Stage I		Stage II		Stage III (wt%)	Char residue (wt%)
	Zone 1 (wt%)	Zone 2 (wt%)	Zone 1 (wt%)	Zone 2 (wt%)		
DL	4.38	3.72	9.92	42.05	19.94	19.99
GB	5.21	3.22	16.43	25.24	27.54	22.36
ML	5.69	1.85	6.8	38.04	23.35	24.27
OL	4.39	1.28	5.31	48.21	27.73	13.08
SB	5.51	2.42	2.63	43.7	27.1	18.64

Table 5. Functional group analysis by FTIR spectroscopy

Wavenumber rang (cm^{-1})	DL	GB	ML	OL	SB	Functional groups
3,200-3,600	3,283.07	-	3,280.33	3,294.95	3,291.61	O-H
2,900-3,000	2,917.09	2,916.84	2,916.68	2,917.73	2,919.00	C-H aliphatic group
	2,849.04	2,849.01	2,848.93	2,849.60	2,850.31	CH$_3$
1,625-1,750	1,732.48	-	-	1,726.90	-	C=O (ketones)
1,575-1,675	1,632.55	1,624.11	1,614.15	1,603.83	1,606.18	C=C
1,500-1,600	1,516.81	-	-	1,516.36	-	Aromatic ring stretch in lignin
1,405-1,445	1,435.80	-	1,444.67	-	-	Deformation bendingof CH (alkane group)
1,346-1,384	-	1,374.97	-	1,369.86	1,375.17	C-H deformation in cellulose and hemicellulose
1,150-1,270	1,240.14	-	-	1,254.18	1,234.54	C-O-C (ester carbonyl)
1,000-1,300	1,035.25	1,029.69	1,030.84	1,015.45	1,015.68	C-O (alcohols, carbonyl, ether and ester)

Stage II represents the decomposition of lignocellulosic components in the biomass including the hemicellulose and cellulose components. In zone 1 of stage II, SB, OL, and ML decomposed in the range of 139 °C-269 °C, resulting in weight loss of around 2.63%-6.8%. The temperature ranges for the biomass degradation stages and the corresponding weight loss are provided in Tables 3 and 4. DL and GB exhibited decomposition in the range of 188°C-301 °C, resulting in the weight loss of around 9.92%-16.43%. In zone 2 of stage II, DL and ML biomass showed a decomposition in the temperature range of 269 °C-491 °C, which led to a weight loss of 38.04%-42.05%, respectively. SB and OL decomposed in the range of 217 °C-443 °C, resulting in weight loss of 43.7%-48.21%. GB decomposed in the temperature range of 301 °C-409 °C, resulting in a weight loss of 25.24%. The stage III of biomass decomposition for all the biomass samples was observed up to 900 °C, which resulted from the slow and continuous breakdown of lignin components of the biomass. The OL, SB, and DL biomass residues exhibited residual char in the range of 13.0%-19.99% while the GB and ML biomass showed comparatively higher yields of char residues in the range as 22.36%-24.27%, respectively, as shown in Table 4. The higher yields of residual char were regarded as a result of the presence of higher percentage of ash in these biomass samples compared to the other samples studied [42,43].

5. FTIR Spectroscopy

FTIR spectroscopy was used to study the functional groups present in the biomass samples. FTIR peaks corresponding to functional groups are presented in Table 5, while the FTIR spectra for all the samples are given in Figs. 6-10. All the biomass samples showed prominent spectra for the O-H group, appearing in the range of 3,280.33-3,294.95 cm^{-1}. The aliphatic C-H group was
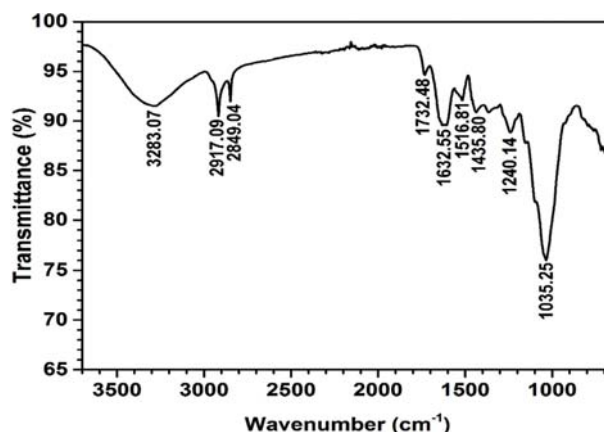
Fig. 6. FTIR spectrum of the date leaves (DL) biomass.
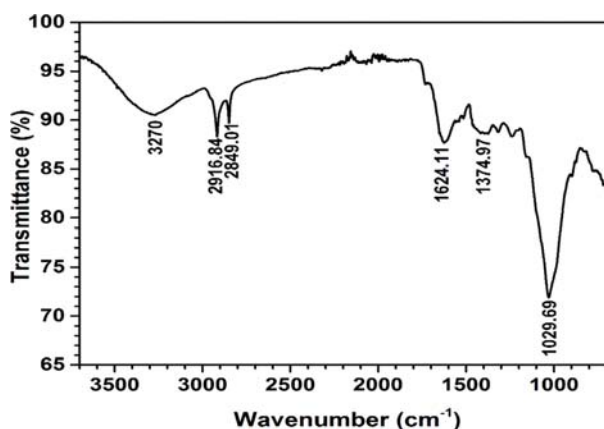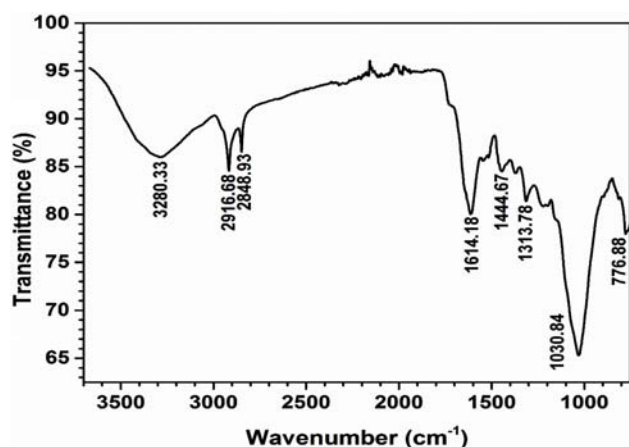

Fig. 7. FTIR spectrum of horticulture (GB) biomass.
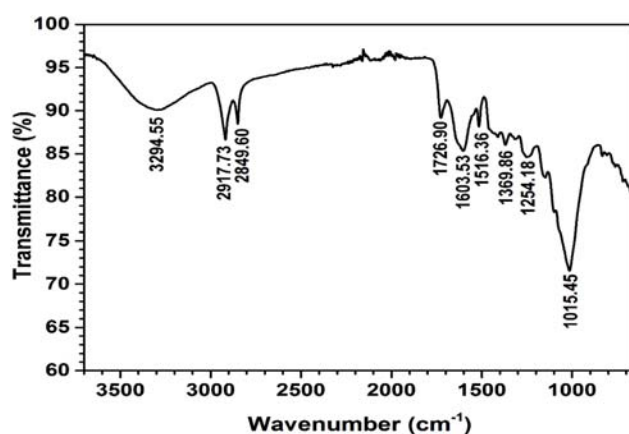
Fig. 8. FTIR spectrum of mango leaves (ML) biomass.

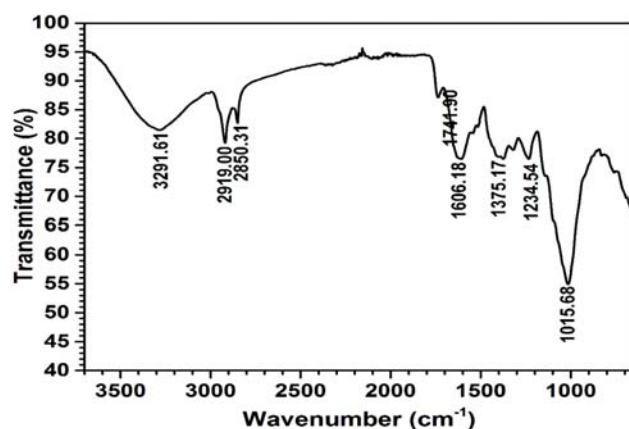**Fig. 9. FTIR spectrum of orange leaves (OL) biomass.**

Fig. 10. FTIR spectrum of sunflower (SB) biomass.

observed in the range of 2,916.68-2,919 cm^{-1} in the spectra of all the biomass samples. The peaks observed within the range of 2,848-2,850.31 cm^{-1} indicated the presence of a CH$_3$ group [44]. Additionally, C=O stretching was observed in the range of 1,726-1,732 cm^{-1} in DL and OL [45]. Aromatic C=C was observed in all the biomass samples in the range of 1,603-1,632 cm^{-1} [46]. The deformation bending of C-H (alkane group) was observed only in DL and

ML in the range of 1,435-1,444.67 cm^{-1} [46]. The C-H deformation in cellulose and hemicellulose was also observed in the range of 1,369-1,375.17 cm^{-1} in GB, OL, and SB residue biomass [37]. C-O-C (ester group) was observed in the range of 1,234-1,254.18 cm^{-1} for all biomasses except in the GB and ML. A peak appearing in the range 1,015-1,035.25 cm^{-1} ascribed to C-O group can be observed for all the biomass samples which represent the presence of alcohol, carbonyl, ester, and ether. Peaks observed in the range of 512-416.97 cm^{-1} represent the presence of aromatic compounds [47].

CONCLUSION

The current study assessed the thermochemical characterization and potential of a variety of biomass residual specimens, including date leaves, orange leaves, mango leaves, biomass, and sunflower biomass available in Pakistan for utilization as energy resource. The lignocellulosic biomass residues indicated suitability as feedstock of the pyrolysis process to produce bio-oil, biochar and gaseous products. The bio-oil can be upgraded to have improved biofuel properties for use as a liquid oil in internal combustion engines. Biochar can be used for multiple value-added applications, including for the synthesis of carbon black, as catalyst, soil conditioning, and as fertilizer. Orange leaves biomass indicated a better potential for producing bio-oil for the reason of having more volatile matter in these biomass which resulted in the higher weight loss during the stage II decomposition, compared to others reported in this study.

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