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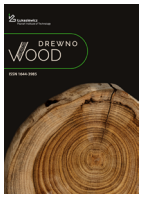

Investigation of Chemical and Thermal Properties of Giant Reed Harvested at Different Times

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Giant reed (*Arundo donax* L.), a perennial plant with a lignocellulosic structure, has become increasingly important in bioenergy production in recent years. Due to its wide natural and cultivated distribution worldwide, its high biomass yield, and a calorific value comparable to that of wood and other energy crops, giant reed represents a promising raw material for bioenergy production. For biomass production, it is essential in terms of raw material continuity that the product be harvested in a short time. Consequently, this study aimed to determine the chemical and thermal characteristics and calorific values of naturally grown giant reed obtained at different harvest times (6th month – late summer, 9th month – autumn, and 12th month – winter). The chemical properties were found to differ according to the harvest season. The thermal characters of samples were investigated by thermogravimetric analysis (TG) both in air and under an inert atmosphere. It was revealed that the thermal character of the giant reed was similar in autumn and winter harvest seasons. Fourier transform infrared (FTIR) analysis was performed to investigate the changes that may occur in the chemical structure of the giant reed during this six-month period. Higher heating values (HHV) of the giant reed harvested at different times were determined experimentally as 17,583 kJ/kg, 18,822 kJ/kg and 18,523 kJ/kg, respectively. The ash contents were determined as 5.72%, 4.59% and 4.48% for the same harvest periods.

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Introduction

The adverse environmental impacts, increasing carbon footprint and rising economic costs associated with the utilization of fossil-based fuels have prompted a pronounced shift in attention towards alternative energy sources, notably encompassing wood and energy crops (Hubbard, 2020; Leontopoulos & Arabatzis, 2021; Hefner et al., 2024). The carbon footprint is described as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann & Minx, 2008). Renewable energy sources are more effective than non-renewable sources in reducing carbon footprints (Jebli et al., 2016; Bhat, 2018). The use of biomass energy contributes to lowering carbon footprints by decreasing CO_2 emission levels (Dogan & Inglesi-Lotz, 2017; Sarkodie et al., 2019).

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One of several methodologies employed in the production of biomass energy is the process of direct combustion (Zhang et al., 2023).

Studies have been carried out to determine chemical characteristics and calorific values of woody plants, such as pine, fir, spruce, beech, poplar, willow, acacia, and eucalyptus, as well as energy crops like gorse, miscanthus, bamboo, sainfoin, sorghum, thistle, triticale, reed canary grass, gynerium, and giant reed (Ragland et al., 1991; Jasinskas et al., 2008; Mariani et al., 2010; Kumar et al., 2011; Carrol & Finnan, 2012; García et al., 2012; Aragón-Garita et al., 2016; Ahmed et al., 2018; Monedero et al., 2018; Zengin et al., 2020).

Based on their photosynthetic pathways, plants are categorized as C_3, C_4, or CAM (Crassulacean Acid Metabolism). C_3 plants, which represent about 85% of plant species, produce 3-phosphoglycerate (PGA) as the first stable carbon product. In this pathway, CO_2 is fixed by rubisco, which can also react with O_2, leading to photorespiration and reduced efficiency. C_3 plants are therefore better suited to temperate and humid climates. C_4 plants, adapted to hot and arid environments, initially fix CO_2 into oxaloacetate via PEP carboxylase, then deliver it to rubisco in bundle sheath cells, minimizing photorespiration and improving water-use efficiency. CAM plants, common in very dry areas, fix CO_2 at night and store it as malic acid, using it during the day with closed stomata – an adaptation that maximizes water conservation (Yamori et al., 2013; Kumar et al., 2017).

Giant reed (*Arundo donax* L.) is a perennial C_3 plant with a lignocellulosic structure, belonging to the subfamily Arundinoideae of the family Gramineae. It grows naturally under a wide range of ecological conditions. There is no complete consensus on its origin. While it is considered a plant of the Mediterranean zone, some ascribe it an East Asian origin. Although the giant reed has been growing naturally in Asia, America, and Africa for thousands of years, since the 19th century plantations have been established in America and Australia (Quinn & Holt, 2008; Arslan & Şahin, 2014; Arslan et al., 2021).

The giant reed has a large distribution area throughout the world and spreads naturally in the Aegean, Mediterranean, Marmara, and north-eastern Anatolia regions of Türkiye (Soyak, 2009; Arslan et al., 2012; Corno et al., 2014). The giant reed grows mainly in water-rich soils around rivers, lakes, and swamps, but can also grow in gravelly, sandy, clayey, and salty soils. Because the giant reed is an invasive species that easily grows over a wide ecological range, the way is paved for its rapid spread. Although it can grow up to 10 m under suitable conditions, it is generally 3–6 m in height and 1–4 cm in diameter, and is a suitable raw material source with many uses (Perdue, 1958; Gordon et al., 2011; Corno et al., 2014; Arslan et al., 2021).

The giant reed is used in the manufacture of wind instruments (Perdue, 1958; Koca, 2002; Odero et al., 2008; Gordon et al., 2011; Pilu et al., 2013), in the traditional treatment of urinary tract diseases and sweating, and in handicrafts such as macramé and weaving (Perdue, 1958; Bezirci, 2007; Guarrera, 2008; Gücel, 2010). In addition to its traditional uses, in the last quarter century, studies have focused on the utilization of giant reed in various industrial sectors. It is a very convenient raw material source for the production of pulp, paper, particleboard, fiberboard, and pellets (Altheimer, 1999; Shatalov et al., 2001; Dahl & Obernberger, 2004; Ghalehno et al., 2011; Ortunõ et al., 2011; Tenorio et al., 2015; Ramos, 2017; Ferrandez-García et al., 2020). Furthermore, giant reed is a suitable material for direct combustion and for bio-ethanol and bio-gas production (Angelini et al., 2009; Ragaglini, 2014; Salazar-Zeledon et al., 2015; Brusca et al., 2018). It is also a plant with potential for use in phytoremediation, a process in which plants are used to clean up contaminated soil, surface water, and even wastewaters, by removing or stabilizing hazardous substances such as heavy metals, pesticides, and petroleum compounds (Cervelli et al., 2016; Cristaldi et al., 2017; Cristaldi et al.,2020; Zeb et al., 2025).

Knowledge of the chemical structure of the giant reed is of great importance in assessing its potential for use in the production of composite board, pulp, and biomass energy. Chemical characteristics significant for biomass energy production can be examined under three subheadings: the basic chemical structure, structural analysis via Fourier-transform infrared (FTIR) spectroscopy, and thermal characteristics (Arslan et al., 2021).

The giant reed is an infertile plant that does not produce seeds and has an asexual vegetative reproduction system. In a temperate climate, the plant's life cycle begins with the sprouting of new reeds from the rhizomes. The giant reed, which grows very fast in spring, forms a significant amount of biomass and is included among the world's largest herbaceous plants. Although the plant continues to grow at the beginning of summer, the growth in this period is not as fast or effective as in the spring. Depending on the conditions, the giant reed blooms between August and October, and turns yellow as it enters the aging period at the end of November. However, the plant does not die, but maintains its vitality and enters a vegetation period again in February. It can be harvested within 6–12 months, that is, in late summer, autumn, or winter (Angelini et al., 2005; Bezirci, 2007; Odero et al., 2011; Corno et al., 2014; Salazar-Zeledon et al., 2015).

In the literature, studies can be found on the chemical structure (Neto et al., 1997; Shatalov & Pereira, 2013), thermal characteristics (Jeguirim & Trouvé, 2009; Fiore et al., 2014), and calorific value (Jeguirim

et al., 2010; Rabemanolontsoa & Saka, 2013) of giant reed. Studies have been carried out on the differences between the autumn and winter harvest periods (Nazli et al., 2018; Tansı et al., 2018). These features may differ depending on location.

Neto et al. (1997) reported the average basic chemical composition of giant reed as 57.7% holocellulose, 30.8% α-cellulose, 17.7% lignin, and 13.6% extractives (ethanol/toluene). In a separate study, Shatalov and Pereira (2013) reported lignin and extractives contents (based on dichloromethane, ethanol, and water extractions) as 21.85% and 12.22%, respectively.

Jeguirim and Trouvé (2009) studied the pyrolysis behaviour of giant reed using thermogravimetric analysis, identifying two main stages: the decomposition of hemicellulose and cellulose between 180 and 370 °C, accompanied by CO and CO_2 emissions, and the slower degradation of lignin between 370 and 750 °C, associated with the release of volatile organic compounds. Hemicellulose exhibited a relatively constant activation energy (~110 kJ/mol), whereas cellulose followed first-order kinetics, with its activation energy decreasing at higher heating rates. Lignin degraded more slowly, displaying kinetics close to zero order.

Fiore et al. (2014) investigated the FTIR spectrum of giant reed fibers and identified characteristic peaks corresponding to lignocellulosic components, such as O–H stretching (~3,400 cm^{-1}), C–H vibrations (2,923 and 2,854 cm^{-1}), and signals attributed to hemicellulose and lignin at 1,730 cm^{-1} and 1,506 cm^{-1}, respectively.

Jeguirim et al. (2010) and Rabemanolontsoa and Saka (2013) reported the calorific value and ash content of giant reed to be in the ranges 17,200–20,060 kJ/kg and 5–32 g/kg, respectively.

Nazli and Tansi (2019) observed that delaying the harvest of giant reed from autumn to winter led to significant reductions in its N, P, K, Ca, Mg, S, and Si contents, primarily due to leaf senescence, nutrient translocation to rhizomes, and leaching during rainfall. This reduction in mineral content resulted in improved combustion quality, as reflected by increased Si/K ratios. Additionally, the winter harvest produced a slightly increased cellulose content, while the lignin content remained relatively stable.

While several studies have examined the chemical characteristics, thermal properties, and calorific values of giant reed, a significant research gap remains regarding the investigation of these properties across three distinct harvest seasons: summer, autumn, and winter. The primary objective of this study is to identify variations in the chemical and thermal characteristics and calorific value of giant reed across different harvest periods (summer, autumn, and winter). Furthermore, the research aimed to provide information for determining the optimum harvest timing based on these properties.

Materials and methods

Plant material

The giant reeds were obtained from the same natural location (38°20'59.22"N, 26°47'15.47"E, Urla-İzmir, Türkiye). The aboveground samples were taken in August 2020, November 2020, and February 2021, representing three different harvest periods: the 6th, 9th, and 12th month of growth (Fig. 1). The cutting height during the harvesting of giant reed varies depending on the equipment and harvesting method used. Curt et al. (2013) reported that the residual stem height after harvesting ranged from 17 to 28 cm. In our study, the cutting height was set at 20 cm. The cutting process was carried out manually using an axe. After separating the leaves from the aboveground samples, the remaining parts were cut into small pieces and prepared for drying before grinding. The giant reed samples were

Fig. 1. Study area

kept at room temperature for 15 days, and were then ground. The resulting samples were passed through a 0.5 mm sieve for use in nutrient element, FTIR, thermogravimetric, and colorimetric analyses.

Nutrient elements

The samples were ground after 24–42 h air-drying. In addition, moisture content was determined (TS ISO 11465, 2015) by keeping the ground plant samples at 105 °C for 24 h. The corrected results for weight at 105 °C were calculated using the moisture correction coefficients.

To determine the macro and micro nutrients, the dried samples were digested via the wet-burning method using a microwave combustion system (Multiwave 5000, Anton Paar GmbH, Graz, Austria). The K, Ca, Mg, Na, Fe, Zn, Cu, and Mn contents were measured using the ICP-OES system (Perkin Elmer Optima 2100 DV, PerkinElmer Inc., Waltham, MA, USA). The P content was measured using a spectrophotometer (Thermo Scientific-Evolution 300 UV-VIS, Thermo Fisher Scientific, Waltham, MA, USA) at 479 nm according to the Vanadomolybdo phosphoric acid colorimetric technique. Moreover, the C, S, and N contents were analyzed via the Dumas (dry burning) method.

Chemical components analysis

Naturally dried giant reeds were ground in a laboratory-type Wiley mill (Retsch SM 100, Retsch GmbH, Haan, Germany). The samples remaining on the 60-mesh (210-μ) sieve were collected and used for chemical analysis. The main chemical components were holocellulose (Wise & Carl, 1962), α-cellulose (TAPPI, 1975), and lignin (TAPPI, 1988). Solubility properties were then determined, including for alcohol-benzene (TAPPI, 1997), 1% NaOH (TAPPI, 1998), hot and cold water (TAPPI, 1993). The chemicals used for determining the main chemical components were as follows: ethyl alcohol (95% purity, Sigma-Aldrich), benzene (99% purity, Sigma-Aldrich), sodium chlorite (80% purity, Sigma-Aldrich), acetic acid (96% purity, Sigma-Aldrich), sulfuric acid (98% purity, Merck Millipore), and sodium hydroxide (97.0% purity, pellets, Merck Millipore).

Fourier-transform infrared (FTIR) analysis

The samples were kept in a vacuum oven at 30 °C overnight before analysis to remove moisture. The FTIR spectra of the giant reed samples were taken with a PerkinElmer Spectrum Two FT-IR spectrometer with an ATR attachment (PerkinElmer Inc., Llantrisant, UK). Spectra were acquired in a wavenumber range of 650 to 4000 cm^{-1}, using a scanning speed of 8 and a step size of 1 cm^{-1}.

Thermogravimetric (TG) analysis

Thermogravimetric (TG) analysis of the 10 mg samples was carried out using the Perkin Elmer STA 6000 TG/DTA (PerkinElmer Inc., Waltham, MA, USA) simultaneous thermal analyzer in the temperature range 30–700 °C at a rate of 20 °C/min under nitrogen and airflow (100 mL/min). Applying the original graphical software, thermograms were created from the findings.

Calorific value

The biomass samples were compressed into pellets of approximately 1 g and dried in a vacuum oven at 30 °C overnight to eliminate residual moisture. The higher heating values (HHVs) were experimentally determined using the IKA-C 400 adiabatic calorimeter (IKA Werke GmbH & Co. KG, Staufen, Germany), operating under 30 bar of oxygen pressure. The instrument complies with DIN 51900 Part 3 and ASTM standards and provides high measurement accuracy (< 0.1%). The bomb has a volume of 300 mL and is designed for adiabatic conditions to ensure precise thermal isolation. Temperature measurements were performed using a Beckmann mercury thermometer, providing a measurement precision of 0.01 K. The calorimetric constant of the system was determined using benzoic acid as a reference substance, based on its known heat of combustion (6318 cal/g). Additionally, the calorimeter was calibrated prior to analysis using certified benzoic acid (NBS Standard Reference Material 39i, National Bureau of Standards, Washington, DC, USA), in accordance with the manufacturer's instructions.

Results and discussion

Nutrient elements

Table 1 shows the levels of macro and micro nutrients, moisture, and ash for the various harvesting seasons. The amount of ash is one of the significant parameters for fuel. This was measured as 5.7%, 4.6%, and 4.5%, respectively, for the 6th, 9th, and 12th month samples in our study. The amount of moisture was found as 7.2%, 6.5%, and 6.8%. Although the ash content of giant reed has been reported as 5% (Jeguirim et al., 2010), it has also been put as low as 1.9% (Fiore et al., 2014) and as high as 7.27% (Riggi et al., 2019). When examining combustion gases, the nitrogen and sulfur content of the fuel should be considered in terms of biomass, as they create greenhouse gas emissions. Licursi et al. (2015) determined the nitrogen content of giant reed as an energy crop to be around 0.3%, whereas Jegurim et al. (2010) measured the sulfur content as 0.2%. The nitrogen values obtained in this study were 0.95% in

the summer (6th month) harvest, and lower values of 0.15% and 0.16% in the 9th and 12th month harvests. The average amount of sulfur (0.09%) was lower than found in other studies, and no change could be detected according to the harvest time. The macronutrients most commonly found in biomass, i.e., sodium and potassium, can cause corrosion and high slag formation during the combustion process. Dahl & Obernberger (2004) found the sodium and potassium contents in giant reed to be 331 and 6497 mg/kg, respectively, and Krička et al. (2017) reported 113 and 1055 mg/kg. For bioenergy crops, sodium content should be kept below 100–150 mg/kg to reduce corrosion risk, while potassium content is ideally maintained below 5,000 mg/kg to minimize slag formation and high ash content during combustion. In general, high concentrations of such elements can increase operational challenges and maintenance costs; therefore, their levels and the heating value should be optimized accordingly. Since potassium and sodium tend to accumulate in the metabolically active tissues of young plants, pre-treatment or selective harvesting strategies may be necessary to mitigate their adverse effects (Dahl & Obernberger, 2004; Vassilev et al., 2017). This variability may have been due to the soil characteristics where the plants grew as well as to the time of harvest. In our study, these values were measured as 51, 38, and 43 mg/kg for sodium, and 15,278, 9,133, and 9,076 mg/kg for potassium in samples representing the 6th, 9th, and 12th month harvests. Marschner (1995) reported that, except for Ca, macronutrients (i.e., N, P, K, Na, and Mg) are highly mobile and easily transported up and down in the phloem. The micronutrients Fe, Zn, Cu, and Mo are less mobile, whereas Mn and Ca are known to be immobile in many plants. In their work, Nassi o Di Nasso et al. (2013) evaluated the seasonal dynamics (accumulation and mobility) of the elements, especially nitrogen, phosphorus and potassium, in the aboveground and belowground biomass of the giant reed over a three-year period. They determined that the nutrient elements reached the highest concentration in the aboveground stem during the summer, and then in the autumn the nutrients sharply decreased. They explained that this mobility towards the belowground part (the rhizome) reduces the need for fertilization, supplying the plant with nutrients that will contribute to its growth during the next vegetation.

Chemical components

The chemical composition of the giant reed at different harvest times is given in Table 2. For the different harvest periods, the holocellulose content (88.6%, 92%, 86.5%) and alcohol-cyclohexane solubility (4.51%, 10%, 7.26%) of giant reed first tended to increase and then decreased, whereas the α-cellulose content (72.4%, 60.2%, 69.8%) first tended to decrease and then increased. The lignin content

Table 1. Nutrient elements of giant reed harvested at different periods

	Nutrient elements	6th month	9th month	12th month
Macro nutrients	N (%)	0.95	0.15	0.16
	C (%)	46.11	46.23	46.00
	S (%)	0.09	0.08	0.09
	P (mg/kg)	988	342	199
	K (mg/kg)	15 278	9 133	9 076
	Ca (mg/kg)	387	435	704
	Mg (mg/kg)	484	481	788
	Na (mg/kg)	51	38	43
Micro nutrients	Fe (mg/kg)	782	216	170
	Zn (mg/kg)	14.79	6.06	1.81
	Cu (mg/kg)	4.94	1.67	6.45
	Mn (mg/kg)	8.50	4.72	5.14
Moisture (%)		7.18	6.53	6.77
Ash (%)		5.72	4.59	4.48

Table 2. Chemical composition of giant reed harvested at different periods

Chemical properties	6th month	9th month	12th month
Holocellulose (%)	88.6	92	86.5
α-Cellulose (%)	72.4	60.2	69.8
Lignin (%)	19.7	19.4	24
Alcohol-cyclohexane solubility (%)	4.51	10	7.26
Cold water solubility (%)	9.74	11.4	14.8
Hot water solubility (%)	10.8	13.1	15.8
1% NaOH solubility (%)	30	34.3	37.3

(19.7%, 19.4%, 24%) of giant reed remained constant at first and then increased. Other solubility values increased.

The holocellulose and α-cellulose contents of giant reed determined in this study were higher than those found by Shatalov & Pereira (2002). This difference may have been due to different habitat characteristics. The lignin content of giant reed has been reported in the literature as between 12.21% and 24% (Shatalov & Pereira, 2013; Nazli & Tansi, 2019). The lignin content obtained in this study was consistent with the literature. Giant reed has been found to exhibit a lignin content comparable to that of energy crops such as switchgrass (5–23%) and miscanthus (8–22%) as reported in the literature, but higher than that of other energy crops like reed canarygrass (4–14%) and corn cob (6–17%) (Tanger et al., 2013). While the chemical composition of wood may vary with tree species, environmental conditions, etc., it typically consists of 40–50% cellulose, 20–35% lignin, and 1–5% extractives (Fengel & Wegener, 1984; Sjostrom, 1993). In comparison, giant reed exhibits lower lignin content and higher levels of cellulose and extractives. When compared with hardwoods and softwoods, giant reed harvested at different periods has substantially higher water, alkali and alcohol-benzene solubility (Eroglu, 1998). Although the lignin content of giant reed harvested at different periods is close to that of other non-wood fiber resources, giant reed harvested at different periods exhibits high holocellulose and α-cellulose content (Akgul & Tozluoglu, 2009).

FTIR spectroscopy analysis

The FTIR spectra of the giant reed harvested at different times (6th, 9th, and 12th month) can be seen in Fig. 2. When the spectra are compared, it is seen that the same peaks were obtained, indicating that there had been no significant change in the structure of the giant reed over this six-month period. The broad band observed at 3,300 cm^{-1} corresponds to –OH stretching vibrations of the hydroxyl groups in the structure. The peaks at 2,918 and 2,850 cm^{-1} correspond to C–H stretching vibrations of the –CH and $–CH_2$ groups in cellulose and hemicellulose (Fiore et al., 2014; De Rosa et al., 2010). The peak at 1,730 cm^{-1} was attributed to the C=O stretching of the acetyl group in hemicellulose. The peak seen at 1,510 cm^{-1} corresponds to the C=C stretching of the benzene ring of lignin (Liu et al., 2004). The peak

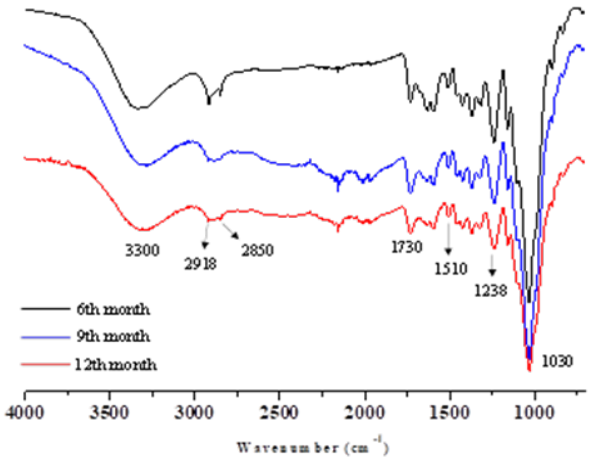

Fig. 2. ATR-FTIR spectra of giant reed harvested at different growth periods (6th, 9th, and 12th months)

at 1,238 cm^{-1} was associated with the C–O stretching of he acetyl group of lignin. The strong absorption peak at 1,030 cm^{-1} was ascribed to the hydroxyl and ether groups in cellulose (Liu et al., 2009).

Thermal characterization

The thermal characteristics of natural fibers are important for determining their potential applications in various areas. Therefore, the thermal character of giant reed was investigated by thermogravimetric analysis both in air and under an inert (nitrogen, N_2) atmosphere. Fig. 3 shows the TG and differential thermogravimetric (DTG) curves of giant reed in air at a heating rate of 20 °C min^{-1}. The thermogram obtained in air shows that the biomass decomposed in three main steps. The first step (30–30 °C) is related to the removal of water from the structure; here the weight loss was ~8%. The second degradation step (180–380°C) is associated with degradation of both hemicellulose and cellulose, and resulted in a weight loss of ~60% (Yang et al., 2007). The final step takes place in two stages at 390–560°C and may be associated with the oxidative degradation of the charred residue (Fiore et al., 2014). The remaining mass at the end of the analysis consisted of the ash formed as a result of combustion. On the other hand, from room temperature to 700 °C, the lignin in the biomass structure decomposed with a low weight loss.

Harvest time did not alter the degradation stages, although there were minor shifts in the maximum degradation temperatures. Differences in the chemical composition of the biomass depending on the harvest time may have caused shifts in the thermal degradation steps. In addition, some differences were obtained in the amount of residual ash: it was determined that the remaining amount of ash of the giant reed harvested at the 6th month was slightly higher (5.6% residual mass) than for the other harvest periods. This was also consistent with the results of the ash analysis (5.7%). This situation can be attributed to the high amount of inorganic elements and smaller amount of lignin in the giant reed harvested in the early time period. The pyrolysis process was carried out for giant reed harvested at different times, and the TG and DTG curves are given in Fig. 4. Although the pyrolysis steps and decomposition temperatures of giant reed harvested in the 9th and 12th months were almost the same, some differences were determined for the 6th month harvest. This shows that, as the harvest time increased, changes occurred in the amounts of components in the structure of the biomass. Generally, the pyrolysis of giant reed consists of two main degradation steps. The initial mass loss between 25 °C and 150 °C is associated with the loss of moisture and volatile components in the structure. The second step, which takes place between 180°C and ~370°C and produces the highest mass loss, corresponds to the degradation of hemicellulose and cellulose (Jeguirim et al., 2009; Licursi et al., 2018). The very slow decrease in mass after 400 °C is due to the slow degradation of lignin over a wide temperature range (100–800 °C) (De Rosa et al., 2010).

Yang et al. (2007) showed that hemicellulose pyrolysis begins in the range 220–315 °C, whereas for cellulose the process starts at a higher temperature (315–400°C). When the DTG curve of the biomass harvested in the 9th and 12th months is examined in detail, it is noted that there is a successive degradation step (seen as a shoulder) at ~210°C and ~290°C. These mass losses may be attributed to the separation of the side chains of the hemicellulose (Yeo et al., 2019) and the progressive degradation of the hemicellulose. This result shows us that there was an increase in hemicellulose content of giant reed at the late harvest time. In addition, the thermogram shows that the remaining mass from of the biomass harvested in the 6th month (~27 %) was slightly higher, and that the lignin content of the biomass was lower at the early harvest time than at the other times.

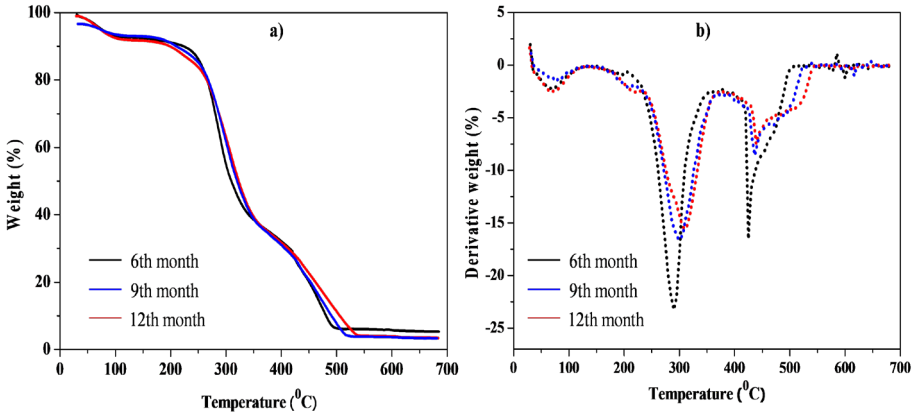

Fig. 3. a) TG and b) DTG thermograms in air atmosphere at 20 °C/min for giant reed harvested at different times (6th, 9th, and 12th months)

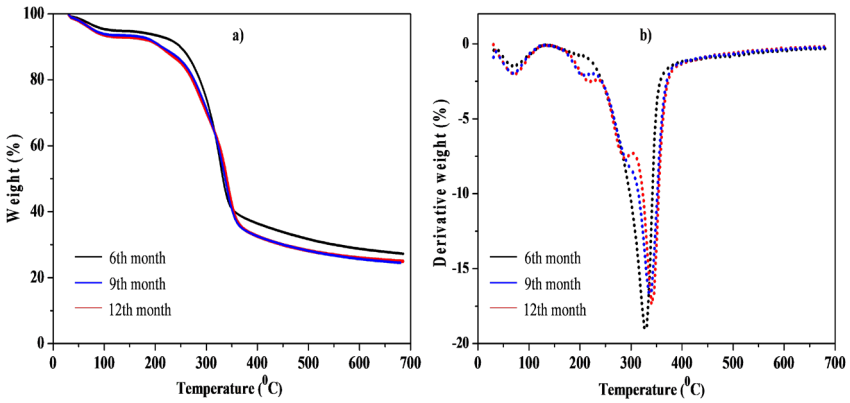

Fig. 4. (a) TG and (b) DTG thermograms in inert atmosphere (N2) at 20 °C/min for giant reed harvested at different times (6th, 9th and 12th months)

Calorific value

The calorific values of giant reed harvested at different times were found experimentally, and are given in Table 3 for comparative purposes (17,583 kJ/kg, 18,822 kJ/kg, 18,523 kJ/kg, respectively). Although there was no significant change in the calorific value of giant reed across the harvest periods, the lowest calorific value obtained was in the 6th month. This finding is related to the fact that the moisture (7.18%) and ash contents (5.72%) of the biomass harvested in the 6th month were higher than ni the others. The fact that the calorific value of the giant reed harvested in the 9th and 12th months was very similar and did not increase is very important for determining the best harvest time. In the literature, the lowest reported calorific value of the giant reed is 16,540 kJ/kg (Giudice et al., 2017), and the highest is 20,060 kJ/kg (Rabemanolontsoa and Saka, 2013). The calorific value of giant reed planted in Adana was determined as 17,230 kJ/kg (Tansı et al., 2018). Tansı et al. (2018) showed that the calorific value of giant reed planted in Adana and Çankırı increased in the first harvest year during the transition from autumn to winter. In addition, Nazli et al. (2018) reported that the calorific value of giant reed at harvest time increased during the transition from autumn to winter. In our study, on the other hand, there was a very small decrease in the calorific value of the giant reed during the transition from autumn to winter. It has been reported that the amount of biomass (dry matter) of giant reed decreases as the harvest period passes from autumn to winter (Tansı et al., 2018). In this study, the calorific values of giant reed harvested at different periods were similar to the calorific values of plants such as switchgrass (Dahl & Obernberger, 2004; Hu et al., 2010), miscanthus (Michel et al., 2006; Melligan et al., 2011), and trees such as pine (Baker et al., 2010) and poplar (Kieseler et al., 2013).

The calorific value plays a significant role in evaluating biomass for energy production, but it alone does not provide a comprehensive assessment. Other significant indicators of energy efficiency include biomass yield,

Table 3. Calorific values of giant reed harvested at different times, and different biomass sources

Entry	Raw material	Month	Calorific value (kJ/kg)	Source
1	Giant reed	6th	17,583	This study
2	Giant reed	9th	18,822	This study
3	Giant reed	12th	18,523	This study
4	Giant reed	-	16,540	Giudice et al., 2017
5	Giant reed	-	20,060	Rabemanolontsoa & Saka, 2013
6	Switchgrass	-	18,800	Hu et al., 2010
7	Miscanthus	-	17,800	Jeguirim et al., 2009
8	Broadleaf Wood	-	18,900	EN ISO 17225-1, 2014
9	Coniferous Wood	-	19,100	EN ISO 17225-1, 2014

feedstock availability, ash content, and the proportions of lignin and cellulose (Tanger et al., 2013; Corno et al., 2014). The calorific value of giant reed is comparable to that of wood (Cichy et al., 2017) and aligns with values reported for other common energy crops (Corno et al., 2014). In addition to its energy content, giant reed offers advantages such as wide geographical adaptability and high biomass productivity (Lewandowski et al., 2003; Arslan et al., 2021). Although its ash content is higher than that of wood, it remains within the typical range for herbaceous energy crops (Monti et al., 2008; Tanger et al., 2013). Moreover, the ash content of giant reed can be effectively reduced through the application of appropriate pre-treatment methods (Zouari et al., 2024). Finally, the lignin and cellulose composition of giant reed is comparable to that of other lignocellulosic energy sources, supporting its suitability for both thermochemical and biochemical conversion processes (Tanger et al., 2013).

Conclusions

In recent years, giant reed has attracted attention for its potential in bioenergy production because of its ability to grow in different ecological conditions, its biomass, and its high calorific value. According to the results of this study, the calorific value of giant reed was found to be similar to that of wood and other energy crops, supporting its suitability for bioenergy applications. There was no significant difference between giant reed harvested in autumn and winter in terms of thermal characteristics and calorific values. However, late summer harvesting is not recommended for bioenergy production from giant reed. Ash and mineral contents decreased as the harvest period progressed. In addition, chemical properties differed according to the harvest season. Consequently, since this study reveals that harvesting giant reed in autumn or winter does not affect its quality, if the giant reed is used as a raw material in bioenergy production facilities, variation in harvest time can provide flexibility in the context of production planning. Giant reed, a valuable source of lignocellulosic biomass, is comparable to other energy crops in terms of bioenergy production. Owing to its performance characteristics, which are similar to those of wood, it has the potential to alleviate the demand for wood-based raw materials. Future studies may explore the performance of giant reed harvested at different times in various biofuel applications such as bioethanol and biogas production, beyond direct combustion. Additionally, the impact of harvest timing on the carbon footprint of giant reed in bioenergy production may be investigated. Furthermore, studies investigating the potential of giant reed, harvested at various times, as a raw material for wood composite and paper pulp industries could offer valuable insight.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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