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EVALUATION OF MULBERRY SPECIES (*MORUS* SPP.) AS A POTENTIAL SOURCE OF BIOENERGY THROUGH THERMOCHEMICAL CHARACTERIZATION AND GASIFICATION

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ABSTRACT

This study investigated the thermochemical properties and gasification potential of three mulberry species (*Morus laevigata*, *Morus nigra* and *Morus australis*) as potential sources of renewable energy. The analysis revealed that all three species possessed favourable characteristics for fuelwood, including low moisture content (8.43% - 8.65%), moderate ash content (1.26% - 2.00%) and high volatile matter content (81.67% - 82.10%). The calorific value and higher heating value ranged from 18.04 MJ Kg^{-1} to 19.87 MJ Kg^{-1} and 18.73 MJ Kg^{-1} to 20.64 MJ Kg^{-1}, respectively, indicating their suitability for energy generation. Gasification analysis showed that the syn-gas composition primarily consisted of CO (24.3% - 27.9%), H_2 (12.0% - 12.7%), CH_4 (2.1% - 2.3%), CO_2 (10.2% - 10.9%), and N_2 (47.2% - 50.7%). The syn-gas calorific value ranged from 5.51 MJ m^{-3} to 5.97 MJ m^{-3}, and the thermal conversion efficiency varied between 59.18% and 62.18%. These findings suggest that mulberry species hold promise as a sustainable and efficient source of bioenergy.

Key words : Mulberry, Thermochemical properties, Gasification, Syn-gas, Bioenergy.

Introduction

The need for energy resources to meet the growing human energy use is on the rise. However, the energy sources we currently rely on, such as petroleum, coal, and natural gas, are finite. Consequently, there's a growing focus on creating systems for producing renewable fuels. Among all renewable energy options, biomass stands out as a highly promising alternative energy carrier that can replace traditional resources. Unique among renewable energy sources, biomass can directly replace fossil fuels due to its wide availability and its ability to ensure consistent power generation and the production of various products such as chemicals and transportation fuels (Safarian *et al.*, 2021).

It is estimated that around 2.5 billion individuals depend on biomass fuels for their cooking, heating, and lighting purposes (Desta and Ambaye, 2020). Direct combustion of biomass for purposes such as cooking or heating can lead to pollution. This pollution is a result of incomplete burning process and release of carbon monoxide, carbon dioxide, organic particulate matter and other gases. Moreover, nitrogen oxides are produced at high combustion temperatures, which have harmful health effects (Demirbas, 2001). To extract energy from biomass, three primary technologies are used: thermochemical, biochemical, and mechanical extractions (Kumar *et al.*, 2015). Among these, thermochemical conversion, which includes drying, pyrolysis, combustion, and reduction (gasification), has been gaining interest due to its higher efficiency and lower emissions compared to direct combustion (Kumar *et al.*, 2009). The combustible gas resulting from gasification, known as producer gas, is a blend of carbon dioxide, carbon monoxide, methane and hydrogen. This gas is more versatile than the original biomass and can be used for heating as well as a supplementary or standalone fuel in various engines and other engineering applications (Goswami and Das, 2020). Additionally, producer gas can replace furnace oil as a fuel in industrial boilers. Biomass gasifiers are classified into three types based on the airflow direction relative to the biomass: updraft gasifiers, downdraft gasifiers, and cross-draft gasifiers. Of these, the downdraft gasifier is particularly noteworthy for research due to its lower tar production (Sutar *et al*., 2017).

In recent decades, extensive studies have been conducted to grow tree species rapidly for the purpose of creating energy from woody biomass. Mulberry trees have emerged as a potential choice due to their fast growth, easy propagation and adaptability to various agroclimatic conditions, and ability to withstand intensive coppicing. In addition to providing high-quality fuelwood, these trees also offer a range of other economic and social benefits (Guha and Reddy, 2012). The present work is an attempt to determine the thermochemical properties, elemental composition (ultimate analysis) and syngas propertiesof mulberry wood using a small downdraft biomass gasifier.

Materials and Methods

Sample preparation

Lignocellulosic woody materials of *Morus laevigata* (MI-0252), *Morus nigra* (ME-0008) and *Morus australis* (ME-0001) were obtained from Forest College and Research Institute in Mettupalayam, Tamil Nadu India located at a latitude between 11°19′37′′N and 11°19′39′′N and a longitude of 76°56′09′′E, at an altitude of 338m above sea level. For each species, a single five-year-old tree, exhibiting a clean trunk and no damage, was chosen at random. These trees were cut down at the base, and were then chipped, air-dried, ground into powder and subsequently used for various tests and analyses.

Thermochemical properties

Determination of moisture content (%)

The moisture content of the samples was determined in accordance to ASTM D3173 standard method. Empty crucibles were subjected for drying in oven, with a temperature of 105°C for 1 hour. Subsequently, the crucibles were taken out from the oven, cooled in a desiccant for 30 minutes and empty weight of crucibles was recorded. One gram of sample was weighed and placed in the crucibles, followed by drying them in oven at 105°C for 24 hours. Followed by, the crucibles were cooled in desiccators until they reached room temperature and their weight was measured again. The loss in weight and the moisture content of the samples were calculated using the following formula.

$$\text{Moisture content (\%)} = \frac{w_2 - w_3}{w_2 - w_1} \times 100$$

Where,

w_1 = weight of empty crucible, (in grams)

w_2 = weight of empty crucible + sample, (in grams)

w_3 = weight of empty crucible + sample after heated, (in grams).

Determination of ash content (%)

The ash content percentage of the samples was calculated following the ASTM D3174 standard method. A gram of each sample was placed in crucibles. These crucibles, along with the samples, were subjected to heat in a muffle furnace for an hour. The temperature was progressively increased from 450°C to 600°C during this heating phase. Afterwards, the temperature was further elevated to 750°C and sustained for two hours. The crucibles were also left inside the furnace for an additional hour. The ash content percentage was then computed using a specific formula:

$$\text{Ash content (\%)} = \frac{w_3 - w_1}{w_2 - w_1} \times 100$$

Where,

w_1 = weight of the empty crucible (in grams)

w_2 = weight of the empty crucible plus the original sample (in grams)

w_3 = weight of the empty crucible plus the ash (in grams)

Determination of volatile matter (%)

The volatile matter percentage of the biomass materials was calculated following the ASTM D3175 standard. Two grams of each sample were placed in crucibles and then heated in a furnace at a temperature of 550°C for duration of 10 minutes. The crucibles were then cooled to room temperature in desiccators and weighed again. The volatile matter of the samples was determined by comparing the mass of the volatiles before and after the weight analysis. The volatile matter percentage was then computed using a specific formula:

$$\text{Volatile matter (\%)} = \frac{w_i - w_f}{w_i - w_c} \times 100$$

Where,

w_c = weight of the crucible and cover (in grams)

w_i = initial weight (in grams)

w_f = final weight (in grams)

Determination of fixed carbon (%)

The fixed carbon percentage of the samples was calculated following the ASTM D3172 standard. This calculation involves determining the fixed carbon content by subtracting the percentages of moisture content, volatile matter and ash content from the original mass of the sample. Fixed carbon refers to the remaining solid residue after the volatile components have been removed through combustion. The fixed carbon percentage was then computed using a specific formula:

Fixed carbon (%) = 100(%) - MC (%) - VM (%) - AC (%)

Where,

MC = moisture content (%),

VM = volatile matter (%), and

AC = ash content (%).

Determination of calorific value

The calorific value of the samples was measuredfollowing the ASTM D5865 standard. This analysis was performed using a device known as a bomb calorimeter. Each sample, which weighed around 1 gram, was incinerated in the bomb calorimeter until it was completely combusted. The temperature difference between the highest and lowest recorded temperatures was then utilized to calculate the gross calorific values of the biomass materials. This calculation was performed based on the specific formula:

$$Q = \frac{(\theta_3 - \theta_1)\gamma}{Z}$$

Where,

Q = calorific value (kcal/g)

θ_1 = Galvanometer deflection without sample

θ_3 = Galvanometer deflection with sample

Z = mass of sample (g)

γ = calibration constant

Determination of fuel value index

The fuelwood value index was determined using the method given by Deka *et al.* (2007). This method considers calorific value and density as positive attributes while treating moisture content as a negative attribute. The calculation was performed based on the specific formula.

$$FVI = \frac{\text{Calorific value (KJ g}^{-1}\text{)} \times \text{Density (gcc}^{-1}\text{)}}{\text{Ash content (g/g)}}$$

Determination of higher heating value

The higher heating value of biomass was calculated using an empirical correlation based on proximate analysis (Yin, 2011). This correlation was established through the application of the linear regression method.

HHV = 0.1905VM + 0.2521FC

Where,

VM = Volatile matter (%) and

FC = Fixed carbon (%).

Determination of elemental composition through ultimate analysis

Mulberry wood powder was subjected to an ultimate analysis using a carbon, hydrogen, nitrogen, and sulphur CHNS/O Analyzer (2400 Series II – PerkinElmer). Oxygen was calculated by subtracting the sum of CHN and ash percentage from 100% (Goswami and Das, 2020).

Gasification

Gasification is a promising method to unlock the substantial thermochemical energy potential of wood.

Gasification of mulberry wood chips

Mulberry wood chips of three genetic resources were gasified in a laboratory scale 1kg downdraft gasification system. Once the hopper is filled with biomass fuel, the lid on top is closed to seal the whole system. The biomass in the reactor, after being ignited, goes through drying, pyrolysis, combustion, and reduction processes. A blower fan powered by a motor is attached to the air inlet to allow air to enter the combustion zone. Syn-gas is produced after the four processes and comes out from the reduction zone at the bottom of the reactor. A gradually bending stainless steel gas outlet pipe was connected to the reduction zone. The outlet pipe was further connected to a simple burner. An incision was made in the outlet pipe to collect the syn-gas. The syn-gas was collected with the help of bladder.

Determining syn-gas composition

A gas monitoring system was used to measure the percentage composition of the generator gas. Using the system, the concentrations of CO, CO_2, CH_4, H_2 and N_2 within the synthesis gas were monitored and recorded.

Determining the calorific value of syn-gas

Calorific value of syn-gas was calculated in accordance to a specific formula (Wang, 2013). Since only H_2, CO and CH_4 are combustible, the higher heating values of these gases gives the calorific value of the syn-gas.

ΔH = (12.76 MJ m^{-3} × H_2%) + (12.63 MJ m^{-3} × CO%) + (39.76 MJ m^{-3} × CH_4%)

Where,

Standard HHV for H_2 = 12.76 MJ m^{-3}, CO = 12.63 MJ m^{-3}, CH_4 = 39.76 MJ m^{-3} (Waldheim and Nilsson, 2001)

Determining the thermal conversion efficiency of syn-gas

The thermal conversion efficiency of gasification can be calculated by the equation developed by Rajvanshi (1986). Thermal conversion efficiency of gasification could be calculated based on the factors of gas calorific value ($\Delta Hgas$), biomass calorific value (ΔH *biomass*) and Volume of syn-gas from 1kg biomass (V). The volume produced from 1kg biomass is fixed at 2m^3 (Wang, 2013).

$$\eta = \frac{\Delta H\ gas\left(kJm^{-3}\right) \times V\left(m^{-3}\right)}{\Delta H\ biomass\left(kJg^{-1}\right) \times 1\left(kg\right)} \times 100$$

Results and Discussion

Thermochemical properties

Moisture content

According to Akowuah *et al*. (2012) the moisture content in biomass significantly influences its combustion properties.In general, wood types with more moisture tend to have a lower heat value. On the other hand, denser wood species with less moisture are favoured as firewood. This is because they have higher energy content per unit volume and burn at a slower rate (Kataki and Konwer, 2002). In the present study, the moisture content of the wood varied between 8.43% (*M. nigra*) to 8.65% (Table 1). Similar results were reported by Goswami and Das (2019), where the moisture content of red mulberry was found to be 7.13%. Desta and Ambaye (2020) recorded similar trend for moisture content in five selected plant species which ranged from 5.9 to 9.9% which confirms the current findings.

Ash content

Increased ash content in fuel wood has adverse effects on the combustion process. This parameter plays a crucial role in assessing both fuel wood quality and environmental impact. In our study, ash content exhibited variation across the three species, as summarized in Table 1. *M. laevigata* demonstrated the highest ash content (2.00%), while *M. nigra* had the lowest (1.26%). The presence of higher ash content renders fuel less desirable, as it limits energy conversion due to the non-combustible nature of ash residues (Kumar *et al*., 2011). Goswami and Das (2019) found ash content of mulberry to be 2.21% which align with the current study.Similarly, in the study by Baqir *et al*. (2019), the ash content of 12 wood species ranged from 0.82% to 2.81%. Additionally, Dai *et al*. (2015) emphasized that woody biomass fuel should ideally have an ash content percentage lower than 2.5%, which supports the present investigation

Table 1 : Thermochemical and ultimate analysis of mulberry genetic resource.

Properties	*M. laevigata*	*M. nigra*	*M. australis*
Moisture content (%)	8.65	8.43	8.46
Ash content (%)	2.00	1.23	1.26
Volatile matter (%)	81.67	81.71	82.10
Fixed carbon (%)	16.55	17.06	16.64
Calorific value (MJ Kg^{-1})	19.23	19.19	18.04
HHV (MJ Kg^{-1})	19.73	19.87	19.83
FVI	692.66	1080.64	906.93
Carbon (%)	49.32	49.94	49.69
Hydrogen (%)	6.20	6.14	6.16
Nitrogen (%)	0.45	1.68	0.02
Oxygen (%)	44.03	42.24	44.03

Volatile matter

Volatile matter is the portion of biomass that converts into gas when heated between 400°C and 500°C. It consists of carbon, hydrogen, and oxygen present in the biomass, which vaporizes into a combination of short and long-chain hydrocarbons (Koppejan and Loo, 2012). An increase in volatile matter leads to a decrease in the percentage of fixed carbon and *vice versa* (Table 2). A higher volatile content reduces the ignition temperature of the biomass and enhances its combustion reactivity (Marques *et al*., 2020). The volatile matter ranged from 81.67% (*Morus laevigata*) to 82.10% (*M. australis*) among all the three samples studied (Table 1). An earlier research on red mulberry (*Morus rubra*) yielded similar findings, where the volatile matter constituted 85.13% of the total (Goswami and Das, 2019). The current study also aligns with the findings of Baqir *et al*. (2019), wherein the volatile matter varied from 2 76.89% (*Eucalyptus* spp.) to 85.64% (*P. dulce*) for 12 wood species.

Fixed carbon

Fixed carbon of fuel refers to the proportion of carbon that is available for combustion into char. It is not equal to the total amount of carbon in the fuel since a significant amount is released as hydrocarbons in the volatile. Fixed carbon plays a crucial role in gasification as it is the main contributor to the production of synthesis gas or syn-gas. In the absence of fixed carbon, there would be no solid source of carbon to generate carbon-intensive gases such as carbon monoxide (Assima *et al.*, 2018). The percentage of fixed carbon in Table 1 ranged from 16.55% (*M. laevigata*) to 17.06% (*M. nigra*) in the firewood samples. However, these findings are lower compared to the research by Mithilashri (2022), who reported that the fixed carbon percentage of mulberry clones ranged from 18.47% (MI-0017) to 30.11% (MI-0718). According to Baqir *et al.* (2019), *P. Juliflora* had the highest fixed carbon content at 22.04%, while *P. dulice* had the lowest at 12.19%. Additionally, Goswami and Das (2020) reported that the red mulberry (*M. rubra*) contained a fixed carbon content of 12.65%, which is lower when compared to current study.

Calorific value

The calorific value of wood greatly affects its energy content, making it an essential aspect when comparing various fuels. The best way to understand the characteristics of fuelwood is by evaluating its calorific value, which is determined by the chemical composition of different tree species (Sofer and Zaborsky, 1981). The earlier studies on mulberry branches indicated the calorific value was17.053 MJ Kg^{-1} (Lu *et al.*, 2009). However, in the present study highest level of calorific value was recorded at 19.23 MJ Kg^{-1} (*M. laevigata*) and lowest value at 18.04 MJ Kg^{-1} (*M. australis*) (Table 1), which extended a greater scope of utilization of mulberry wood as a raw material for energy generation. Baqir *et al.* (2019) also obtained comparable results of different wood species which ranged from 17.32 MJ Kg^{-1} to 22.56 MJ Kg^{-1}.

Table 2 : Syn-gas composition of selected mulberry genetic resources.

Species	CO (%)	CO_2 (%)	CH_4 (%)	H_2 (%)	N_2 (%)
M. australis	24.3±0.12^c	10.7±0.16^a	2.3±0.03^a	12.0±0.06^b	50.7±0.12^a
M. nigra	27.9±0.12^a	10.2±0.16^b	2.1±0.00^b	12.2±0.06^b	47.2±0.06^c
M. laevigata	25.8±0.06^b	10.9±0.06^a	2.2±0.07^b	12.7±0.12^a	48.9±0.11^b
Mean	26.0	10.6	2.2	12.3	48.9
P value	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001

Data expressed as Mean ± SE. Values within the same column with different superscript are significant.

Table 3 : Syn-gas properties of selected mulberry genetic resources.

Species	Syn-gas calorific value (MJ m^3)	Thermal conversion efficiency, η (%)
M. australis	5.51±0.02^c	61.14 ±0.01^b
M. nigra	5.97±0.02^a	62.18 ±0.02^a
M. laevigata	5.69±0.03^b	59.18 ±0.01^c
Mean	5.72	60.83
P value	P<0.001	P<0.001

Data expressed as Mean ± SE. Values within the same column with different superscript are significant.

Higher heating value (HHV)

The term higher heating value refers to all the heat produced when fuel burns, considering both the water already in the fuel and the water vapour that forms during burning. This helps us understand how much energy a fuel can provide, when it's burned completely. Taking into account the energy from the water vapour makes HHV a complete measure of a fuel's energy potential (Acar *et al.*, 2016). The higher heating value of the current study ranged from 19.73 MJ Kg^{-1} (*M. laevigata*) to 19.87 MJ Kg^{-1} (*M. nigra*) (Table 1). Similar findings were recorded by Goswami and Das (2020) in *Morus rubra* where the HHV was recorded as 18.36 MJ Kg^{-1}. Mithilashri (2022) investigated the HHV of 21 mulberry clones which ranged from 17.74 MJ Kg^{-1} (MI-0017) to 20.02 MJ Kg^{-1} (MI-0718) which support the outcomes of the present study. The higher heating values of five energy species reported by Marques *et al.* (2020) are also in agreement of the HHV of the current investigation.

Fuel value index (FVI)

The fuel value index depends on calorific value, bulk density, and ash content of fuel wood. Combining three factors - calorific value and bulk density as positive traits, and ash content as a negative trait - provides an effective way to determine the quality of wood as a fuel source (Saravanan *et al.*, 2013). When ash content is high, it leads to a lower fuel value index (FVI), which in turn reduces the energy potential of the wood (Ramos *et al.*, 2008). Consequently, wood species with higher FVI values are considered more desirable for use as fuel. The fuel value index (FVI) estimates species combustibility and the ability to produce hot flame and is the quality criterion most frequently used in ranking the preferred fuel wood species (Deka *et al.*, 2007; Cardoso *et al.*, 2015). In the current study, fuel value index ranged from 692.66 (*M. laevigata*) to 1080.64 (*M. nigra*) (Table 1). Bhatt *et al.* (2010) reported similar trend for FVI in some fire wood trees and it ranged from 306.9 to 1178.6 and Nabi *et al.*

(2017) when evaluating FVI of species, the highest FVI observed in *Prunus dulcis* (1067.42). Comparable results of FVI were also obtained by Nabi *et al*. (2017) for five important wood species from the Kashmir valley.

Ultimate analysis

The ultimate analysis plays a crucial role in determining the theoretical air-fuel ratio in thermochemical conversion processes. Carbon, hydrogen, and lignin are the key elements that contribute to heat production. They significantly influence the heating potential of fuelwood types that contain low levels of nitrogen, sulphur, and extractive substances (Dadile *et al*., 2020). The energy derived from carbon-hydrogen and carbon-oxygen bonds in any fuel is inferior to that from carbon-carbon bonds. Furthermore, an increase in hydrogen and oxygen content in biomass reduces the energy value of the fuel (Nordin, 1994; Kumar *et al*., 2010). The carbon contents of the mulberry species varied from 49.32% to 49.94%; Hydrogen between 6.14% and 6.20%; Nitrogen varied between 0.02% and 1.68% and oxygen varied between 42.24% and 44.03% (Table 1). Similar findings were recorded by Goswami and Das (2020) in red mulberry where the compositions of C, H, N, S, and O are found as 45.03%, 6.16%, 0.27%, 0.02% and 40.75%, respectively.

Gasification

Syn-gas composition

Fixed carbon plays a vital role in the gasification reactions, such as Boudouard reaction, water gas reaction and hydrogasification reaction. These reactions help to generate product gas mainly comprising of CO, H_2 and CH_4 which are responsible for the enhancement of the HHV of the product gas (Chavan *et al*., 2012). Syn-gas plays a pivotal role as one of the principal outputs derived from the biomass gasification process. This amalgamation of gases holds substantial importance as it serves as a valuable source for the production of eco-friendly fuels and chemicals. Beyond its chemical significance, syn-gas emerges as a highly suitable fuel choice, offering a versatile option for generating electricity as part of the energy landscape (Sikarwar *et al*., 2016). The current study's analysis of syn-gas composition revealed carbon monoxide (CO) from 24.3% to 27.9%, carbon dioxide (CO_2) from 10.2% to 10.9%, methane (CH_4) from 2.1% to 2.3%, hydrogen (H_2) from 12.0% to 12.7%, and nitrogen (N_2) from 47.2% to 50.7% (Table 2). Similarly, Nwokolo *et al*. (2020) reported a comparable pattern for Eucalyptus wood chips, with syn-gas composition ranging from 22.3% to 22.5% for hydrogen, 22.3% to 24.3% for carbon monoxide, 1.9% to 2.1% for methane, 9.8% to 10.7% for carbon dioxide and 41.5% to 42.9% for nitrogen. The present results align with the findings of Rajvanshi (2015), who observed that syn-gas produce from wood chips in downdraft gasifier contain 17%-22% CO, 16%-20% H_2, 2%-3% CH_4, 10%-15% CO_2 and 50%-55 % N_2. Sharma *et al*. (2020) also reported that syn-gas from *lantana camara* was composed of about 20% to 22% carbon monoxide (CO), 18% to 20% hydrogen (H_2), 3% to 5% carbon dioxide (CO_2), 1% to 4% methane (CH_4) and rest nitrogen (N_2).

Syn-gas s calorific value

The calorific value of syn-gas derived from wood typically falls within the range of 5-5.86 MJ m^{-3} (Rajvanshi, 1986). This energy content can vary based on factors such as the moisture content of the wood chips, the gasification process employed, and the efficiency of gas cleaning and conditioning steps. While wood chips syn-gas may have a lower calorific value compared to some other fuels, it still holds significance as a renewable energy source for applications such as heat production, power generation, and industrial processes.In the current study, syn-gas composition of ranged from 5.51 MJ m^{-3} (*M. australis*) to 5.97 MJ m^{-3} (*M. nigra*) (Table 3). At optimum operating condition, the maximum calorific value of red mulberry (*M. rubra*) was obtained as 5.846 MJm^{-3} (Goswami and Das, 2019). Wang (2013) also found comparable outcomes, wherein the mean calorific content of synthetic gas was measured at 5.8 MJ m^{-3} for woodchips, 5.5 MJ m^{-3} for a 50/50 mixture, and 4.9 MJ m^{-3} for pure *Arundo donax*. Sharma *et al*. (2020) also investigated the calorific value of syn-gas produced from *lantana camara*. The results they obtained showed a variability in the range of 5.47 MJ m^{-3} to 6.42 MJ m^{-3}, which depended on different equivalent ratios.

Thermal conversion efficiency

Biomass gasification functions as a thermal conversion mechanism. In this process, the calorific value of biomass fuel fed into the process is considered as energy input while the calorific value of syn-gas produced by gasification is the energy output. The assessment of thermal conversion efficiency in biomass gasification is possible through the comparison of energy output to energy input. Thermal conversion efficiency is a very critical indication for the energy value of biomass fuel as well as an important factor for identifying cost effective alternative biomass source for gasification (Wang, 2013). In the present study, the highest thermal conversion efficiency was observed in *M. nigra* (62.18%) followed by *M. australis* (61.14%), while the lowest thermal conversion efficiency was recorded in *M. laevigata*

(59.18%) (Table 3). These results match with the findings of Goswami and Das (2019), who also reported a thermal conversion efficiency of 68.45% for Red mulberry (*M. rubra*). Wang (2013) obtained comparable findings regarding the thermal conversion efficiency of various fuel compositions. They observed that the thermal conversion efficiency for woodchips was approximately 80%, while the 50/50 mix exhibited a range of 67-69%. Conversely, the thermal conversion efficiency for 100% *Arundo donax* was notably lower, falling within the range of 42-48%. Sharma *et al*. (2020) also reported that the thermal efficiency of *Lanatana camara* was around 60% aligning with the findings of the current research.

Conclusion

The study explored the potential of three mulberry species (*M. nigra*, *M. laevigata* and *M. australis*) as a source of bioenergy through gasification. All three species showed promise with good calorific value, higher heating value, and fuel value index. The gas produced from them had a similar composition to other wood-based gasification and offered comparable calorific value and thermal conversion efficiency. While all three species are viable options, *M. nigra* might be slightly preferable due to its lower ash content. Further research is needed to optimize the process and assess its economic feasibility for large-scale production.

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