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ORIGINAL ARTICLE

Possibility of using three invasive non-forest tree species as an alternative source for energy production

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Abstract Non-woody biomass species have high-energy potentials, which could be used for bioenergy production. Invasive species are species spreading into areas, where they are not native, consequently causing environmental and economic problems. Therefore, the present study evaluated the proximate, ultimate, chemical, and fuel characteristics of wood and charcoal of three invasive non-forest tree species in Saudi Arabia: *Calotropis procera*, *Rhazya stricta*, and *Phragmites australis*, which were compared with the wood of *Acacia tortilis*, a preferable local fuelwood. All these data were discussed to investigate the possibility of using the invasive plants for energy production. The thermal behavior of wood was analyzed using thermo-gravimetric and derivative thermo-gravimetric methods. Overall, compared with the wood of *A. tortilis*, the woods of *R. stricta* and *P. australis* are suitable for energy production. The charcoal produced from *P. australis* emitted less nitrogen (N) oxide than that of *R. stricta.*

Keywords Invasive species · Charcoal · Fuelwood · Energy production

Introduction

Invasive species are "species spreading into areas, where they are not native" [1], and consequently cause environmental and economic problems [2]. The most important characteristics for invasive plants to dominate new habitats are efficient germination, high fecundity, early flowering, self-compatibility, production of large numbers of seeds, highly competitive, efficient carbon assimilation, rapid growth rates, effective dispersal, acclimation capacity, and vegetative reproduction [3].

Distributions of invasive plants vary globally, where large continents have a wide range of habitat—both dry and wet-that enhance the ability of the species to invade. For example, *Calotropis procera* is invasive in Caatinga and Restinga, Brazil [4], and Australia [5]; in wet habitats in the eastern, midwestern, and Mississippi River Delta regions of the United States, *Phragmites australis* has been very invasive [6]; and in extremely dry desert habitats in Saudi Arabia, *Rhazya stricta* is invasive [7].

The management of invasive species includes various measures. Some invasive plants may be grown in demarcated areas, provided a permit has been issued and steps are taken to prevent their spread. Many governments support the effort to add value to the clearing process instead [8]. Controlling invasive species, including mechanical, chemical, and biological methods, are expensive, and some have irreversible impacts on ecosystems when they are burnt on site, which causes a negative impact on the environment [8]. Controlling the spread of invasive plants through their reduction rather than eradication could provide a sustainable income source and job opportunities for local communities [9].

Wood harvested from natural forests has been the first and most important source of fuel used by humans for

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thousands of years. Increasing concern for the environment and climate change has resulted in significant reductions in wood harvest from national forests [10]; therefore, with increasing wood demand, there is a national and global shortage of fuelwood.

Research has focused on alternative fuel sources to overcome the fuel-wood shortage and avoid the dependence on crude oil, as well as to reduce CO_2 emissions [11]. A wide variety of biomasses have been investigated for energy production, i.e., tobacco stems [12], rice waste [13], switch grass, coffee weed [14], vine pruning [15], date palm seeds [16], and date palm midribs [17].

Among some non-woody materials that have not yet been assessed as alternative raw materials for fuel-wood production, is the wood from invasive plants distributed throughout the kingdom. Using these plants, especially in arid and semi-arid areas, for energy production is a very attractive and a potentially viable economic and ecological alternative. However, there has been limited research on the use of invasive plants for fuel production.

C. procera (Ait) is a spreading, evergreen, perennial shrub, or small tree growing to 4 m, and has few branches and leaves. Its native range includes southwest Asia and Africa in arid and semi-arid regions [18]. *C. procera* has been used as a source of many products, including fiber, rubber, and pulp, and paper [19, 20]. *C. procera* is widely distributed throughout Saudi Arabia, growing in open, dry habitats with little competition. Nasser et al. [20] predicted that the branch yield of the plant (oven-dry basis) is about 5.41 t ha^{-1}.

R. stricta Decne, locally known as Harmal, is an evergreen, perennial shrub. It is a small, glabrous, erect shrub and branched from the base to a height of approximately 115 cm, and then approximately to about 235 cm with a smooth central stem and dense semi-erect branches [21]. It is widely distributed in the sandy plains of Saudi Arabia and throughout western Asia from the Arabian Peninsula and Yemen to the North West Province of India, and is abundant in various regions of Pakistan [22]. *R. stricta*, characterizes the habitat of Saudi Arabia, is considered one of the most important medicinal plants that grow in most desert areas in the Arabian Peninsula [23]. However, *R. stricta* is unpalatable to animals, and has been invaded large areas of overgrazed rangelands in Saudi Arabia [24].

The common reed (*P. australis*) is a large perennial grass producing tall and hollow stems. It is one of the most widely distributed vascular plants globally [25]. *P. australis* grows up to 6 m high in dense stands with long, flat leaves spread out widely from the stem. It is found in wetlands throughout temperate and tropical regions of the world, which grows efficiently on the shores of streams, lakes, and ponds, as well as in shallow water, ditches, and aquatic wastelands [25]. In all regions of Saudi Arabia, *P. australis* is widely distributed in aquatic habitats [26]. In aquatic habitats in the eastern Atlantic, Midwest, and Mississippi River Delta regions of the United States, as well as parts of the Pacific Northwest, *P. australis* has been very invasive [6, 27, 28]. The aboveground biomass yield of *P. australis* varies between 4 and 12.6 t ha^{-1} with an average of 7.4 t h^{-1} $year^{-1}$.

Accordingly, using invasive plants for energy will help to clear the existing stock of plants, which present a serious problem on farmland and rangeland [7]. In Saudi Arabia, the abundance and range of *C. procera*, *P. australis*, and *R. stricta* have increased, necessitating effective management to avoid a negative impact on the ecosystem and environment. In these invasive species with rapid growth rates and vegetative reproduction, they are potentially useful as energy crops. The use of these species as energy crops would be an innovative way to manage the wastes of invasive plants as an alternative raw material for energy production. Therefore, the aim of the present study was to evaluate the potential of *C. procera*, *P. australis*, and *R. stricta* as energy crops to control their invasion into other habitats.

Materials and methods

Invasive species and sample preparation

Woody samples were collected from three invasive species grown in the Agricultural Experimental Station (24°6′N, 46°5′E), 60 km south of Riyadh, Saudi Arabia during December 2014. The invasive plants sampled were *C. procera*, *R. stricta*, and *P. australis*. The environmental factors of the study site included a temperature range of 10 °C in winter to 41 °C in summer, 50 mm annual rainfall, and calcareous soil. *A. tortilis* wood collected from natural indigenous forest in the El-Baha region, Saudi Arabia, was used as the control for comparison. For preparing wood particles, samples were debarked (to avoid the desirable effect of bark during determination), air-dried, cut, ground, and screened. Particles that passed through a 20 mesh sieve and were retained on a 40 mesh were used to determine the fuel characteristics of wood. However, particles that passed through a 40 mm mesh and retained on a 60 mm mesh were used for the chemical, ultimate, and proximate analyses of wood.

Chemical analysis of wood

Based on the oven-dried weight, the percentage of the total and benzene-alcohol extracts of the wood samples (−40/+60 mm mesh) were determined using the methods outlined in the ASTM standard. Using the free-extractives meal, the contents of cellulose, hemicelluloses, and lignin were determined according to the ASTM D-1037 standard [29]. For ash content determination, approximately 2 g of oven-dried wood particles (−40/+60 mm mesh) were burned in a muffle furnace at 575 ± 25 °C for 6 h. Ash content was calculated as a percentage based on the oven-dry weight of the sample [29].

Thermal behavior

The thermal behavior of wood was investigated by thermo-gravimetric analysis using a thermo-gravimetric analyzer (TGA). Wood samples were heated in nitrogen at a rate of 10 °C min^{-1} up to 900 °C to assess the devolatilization of organic matter. Both curves of the percentage of weight loss versus temperature (TGA) and the derivative weight loss versus temperature (DTG) were determined and analyzed.

Pyrolysis process

The woody parts of the four species were chopped into small pieces and oven-dried at 103 ± 5 °C for 24 h in a cylindrical stainless steel reactor (3.8 cm ID × 13 cm long), inside a muffle furnace. In the current study, slow pyrolysis using a temperature of 500 °C was selected as an indicative temperature for comparison of the charcoal properties of the invasive plants according to Lee et al. [30].

The reactor was sealed at one end, and the other end had a removable cover with 2 mm hole at the center to allow pyrolysis gases to escape [31]. The reactor was heated to a final temperature (500 °C) under oxygen-limited conditions at the rate of 10 °C min^{-1} for 4.5 h measured from the time that the furnace reached the final temperature [32]. After the pyrolysis process, the specimens (reactor and charcoal) were allowed to cool to 100 °C, and then cooled in a desiccator at room temperature of 25 ± 3 °C prior to measurements. The charcoal yield was calculated as a percentage of the oven-dried weight of the samples before pyrolysis, and the charcoal samples were ground for further analysis. The fixed charcoal yield (FCY) was calculated using the following equation [33]:

$$\text{FCY, \%} = \frac{\text{Charcoal yield} \times (100 - \text{\% volatile matter} - \text{\% char ash})}{100 - \text{\% wood ash}}.$$

Ultimate and proximate analysis

Elemental contents as percentages of carbon (C), hydrogen (H), and nitrogen (N) for wood and charcoal were determined using a CHN analyzer (Perkin Elmer model 2400). The oxygen (O) content was calculated using the following equation: O (%) = 100 − (C + H + N + ash). The proximate analysis, including moisture, ash, and volatile matter (VM) contents in both wood and charcoal, were determined according to ASTM D1762 [34]. Fixed C content was calculated by subtracting the contents of moisture, ash, and VM from 100.

Heating value

On a dry weight basis and according to ASTM D 2015-85 [35], heating values (HV) of the wood and charcoal were determined for the three invasive plants and control. Approximately 1 g of oven-dried ground sample (−20/+40 mm mesh) was pressed into pellets using a hydraulic pellet press and loaded into an oxygen bomb calorimeter (Parr model 6300). No correction was included in the HV calculations. Nine samples per species were combusted to estimate the HV. The fuel value index (FVI) was calculated using a modified method of Bhatt and Todaria [36]. The higher heating value (HHV) refers to the heating value determined by the calorimeter based on the oven-dry weight. The lower heating value (LHV or HV) as received (ar) and dry ash-free fuel (daf) was calculated [15].

Ranking of invasive plants

Separately and overall, the wood and charcoal of the three invasive plants and control were rated based on the positive and/or negative impacts on the energy content and environmental impact [8]. The property was assigned a value between 1 and 4, with 1 being the best and 4 being the worst. The rating was calculated as the sum of all values divided by the number of measured properties ($\Sigma/13$ for wood, $\Sigma/10$ for charcoal, and $\Sigma/23$ for both). If the difference between any two plants was not significant, we assigned them the same value.

Statistical analysis

Data were analyzed using a complete randomized design (CRD) to detect the statistical differences among the species. An analysis of variance (ANOVA) was used to detect the differences between them in all the measured properties. To test these differences, least significant differences at a 0.05 level of probability ($\text{LSD}_{0.05}$) were used. A correlation analysis was used to determine the relationship between the HV and each of the chemical constituents, and the ultimate and proximate analyses.

Results and discussions

Chemical composition of wood

The chemical composition of wood and/or lignocellulosic materials accurately determines their suitability for energy production. However, to understand the behavior of the biomass and its expected effects on the energy products from the pyrolysis process, the biomass should be characterized [37]. The statistical analysis showed that the chemical constituents between the four different wood samples were significantly different ($P < 0.01$). The average values of the chemical composition are shown in Table 1.

The content of total extractives (TEC) for the three invasive plants ranged from 15.8% (*C. procera*) to 19.6% (*P. australis*), which was much higher than that of *A. tortilis* (13.3%), softwood, and hardwood species. The higher TEC may be attributed to their open anatomical structure [17] and/or the environmental conditions, where the plants were growing [38]. The highest cellulose content was observed in wood samples of *P. australis* (52.8%), which is higher than that of *A. tortilis* (46.7%). However, the cellulose content of *R. stricta* was lower than *A. tortilis,* the softwoods, and hardwoods. The hemicellulose content fell in the range of that of either softwood or hardwood species, at 26.3 and 35.5% for *C. procera* and *R. stricta*, respectively, which was higher than that of *A. tortilis* (21.2%). The lignin contents were in the range of commercial wood (softwood and hardwood) and ranged from 19.3% (*P. australis*) to 28.3% (*C. procera*), which was lower than that of *A. tortilis* (32.0%).

The invasive plants used in the present study are characterized by higher total extractive and lower lignin contents. However, we expected that higher extractives of these plants will not increase the energy output, because there are no significant differences between them in the benzene-alcohol extractive (ranged from 5.2 to 7.1%, Table 1), indicating that most of the total extractives are soluble in water, which have little effect on the energy output [15]. Nasser et al. [15] reported that the correlation between total extractives and heating values was not significant, while the correlation between heating values and benzene-alcohol extractives was significant. The little effect of extractives soluble in water on the energy output is due to its chemical compositions, i.e., sugars, which have lower heating values.

These results agreed with the chemical composition reported by Nasser et al. [20] for *C. procera*, and partially agreed with Jiménez et al. [39] for *P. australis*. The chemical composition of the three invasive plants used was similar to that of commercial wood species, i.e., softwood and hardwood [40], as well as other non-woody plants [41]. Accordingly, based on their chemical composition, they could be suitable for energy production.

Ultimate and proximate analyses of wood

As shown in Table 2, C content of wood ranged between 46 (*C. procera*) and 50% (*R. stricta*), whereas H content ranged from 5.9 to 6.1% for *P. australis* and *R. stricta*, respectively. The highest content of N (0.75%) was recorded in *R. stricta* and the lowest in *P. australis* (0.14%). Combustion of wood mainly emitted water, CO_2, and nitrogen oxides (NO_x) to the atmosphere. The higher the N content, the higher the emission of NO_x gases, which has a negative impact on human health and the environment [8]. Although, N contents in all samples were low (0.14–0.75%), especially compared with coal, 1.4% [42], the N content of *R. stricta* should be taken into consideration if used for energy production. It is expected that during the burning of these invasive plants, NO_x release will be low. Accordingly, using these plants for energy production could have a relatively low impact on the environment due to their low N content [37, 43]. The

Table 1 Wood chemical composition (db, %) of the invasive plants compared with that of the indigenous wood species

Species	Total extractives[a]	BAE[b]	Cellulose[c]	Hemicelluloses[c]	Lignin[c]
Calotropis procera	$17.36^{B} \pm 1.2$	$6.85^{A} \pm 0.7$	$45.50^{B} \pm 1.4$	$26.25^{C} \pm 0.3$	$28.25^{B} \pm 1.6$
Phragmites australis	$19.56^{A} \pm 1.0$	$5.23^{B} \pm 0.7$	$52.76^{A} \pm 1.1$	$27.97^{B} \pm 1.3$	$19.27^{C} \pm 0.2$
Rhazya stricta	$15.80^{C} \pm 0.3$	$6.07^{AB} \pm 0.5$	$38.54^{C} \pm 1.8$	$35.46^{A} \pm 0.3$	$26.00^{B} \pm 2.1$
Acacia tortilis	$13.32^{D} \pm 0.2$	$7.12^{A} \pm 0.6$	$46.74^{B} \pm 0.7$	$21.24^{D} \pm 1.1$	$32.02^{A} \pm 1.4$
Hardwood	2–6	–	45–50	15–35	18–25
Softwood	2–8	–	45–50	20–32	25–35
Lopez et al. [40]	2.4–6.8	–	34–52	15–26	28–31

Means with the same capital letters in columns are not significantly different according to least significant differences (LSD) test

[a] As a percentage of oven-dry weight

[b] BAE: benzene-alcohol was done using a mixture of them 2:1 v/v, respectively, for 4 h

[c] As a percentage of free-extractive oven-dry weight

Table 2 Ultimate and proximate analyses and fuel properties of the invasive species compared with that of *Acacia tortilis*

Property	Species			
	C. procera	*P. australis*	*R. stricta*	*A. tortilis*
Ultimate analysis				
Carbon (C)	$45.81^{C} \pm 0.3$	$45.69^{C} \pm 0.1$	$49.91^{A} \pm 0.1$	$46.64^{B} \pm 0.2$
Hydrogen (H)	$6.03^{A} \pm 0.2$	$5.92^{A} \pm 0.1$	$6.13^{A} \pm 0.1$	$6.08^{A} \pm 0.04$
Nitrogen (N)	$0.31^{B} \pm 0.1$	$0.14^{C} \pm 0.1$	$0.75^{A} \pm 0.1$	$0.38^{B} \pm 0.1$
Oxygen (O)	$44.59^{B} \pm 0.3$	$46.06^{A} \pm 0.2$	$41.68^{C} \pm 0.2$	$44.95^{B} \pm 0.2$
Proximate analysis				
Moisture	3.49 ± 0.1	2.92 ± 0.1	3.06 ± 0.02	3.54 ± 0.1
Ash	$3.26^{A} \pm 0.03$	$2.19^{B} \pm 0.2$	$2.03^{C} \pm 0.3$	$1.95^{C} \pm 0.01$
Volatile matter	$83.86^{A} \pm 0.6$	$77.10^{C} \pm 0.3$	$80.63^{B} \pm 0.5$	$80.37^{B} \pm 0.3$
Fixed carbon	$9.39^{C} \pm 0.7$	$17.79^{A} \pm 0.3$	$14.28^{B} \pm 0.7$	$14.14^{B} \pm 0.3$
Fuel properties				
HHV (db, MJ/kg)	$18.77^{C} \pm 0.3$	$18.52^{C} \pm 0.2$	$19.79^{A} \pm 0.3$	$19.29^{B} \pm 0.3$
HHV (daf, MJ/kg)	$19.38^{B} \pm 0.2$	$18.93^{C} \pm 0.1$	$20.09^{A} \pm 0.2$	$19.67^{B} \pm 0.2$
FVI	554	825	1210	1521

Mean values of nine samples

Means with the same letters in rows are not significantly different according to least significant differences (LSD) test

O (%) = 100 − (C + H + N + ash) according to Pereira et al. [47]

HHV Higher heating value, *db* dry weight basis, *daf* dry weight ash-free, *FVI* Fuel value index

oxygen content ranged from 42% (*R. stricta*) to 46% (*P. australis*). *R. stricta* wood had the highest contents of C, H, and N, which were higher than those of *A. tortilis*. Furthermore, the elemental composition of the invasive plants fell in the range of woody biomasses [37, 40, 44], but was considerably lower than that of bituminous coal, 73.1% [42].

Increased C and H contents of biomass are preferable for energy production, whereas increased N content has a negative effect on the environment [8]. Therefore, it is expected that the energy output of *R. stricta* will be high compared with other invasive plants used in this study, but their negative impact on the environment will also be high.

From the proximate analysis, the volatile matter content (VMC) of the invasive plants ranged from 77.1% (*P. australis*) to 83.9% (*C. procera*). These values fell in the range reported by Yang et al. [43] for common biomass (65–85%) and by Telmo et al. [45] for woody biomass (75–87%). However, they were much higher than that of coal, 35% [42]. Therefore, the invasive plants studied were easy to ignite at a wide range of temperatures, including low temperatures [37]. The lowest ash content was observed in wood of *R. stricta* (1.5%), whereas the highest ash content was observed in wood of *C. procera* (3.3%). Ash content of wood is generally less than 1%, but may reach up to 20% in some wood species. Although the ash content of the invasive plants fell in the range of the biomass reported by several authors [37, 44, 45], these contents may be make them less desirable as an alternative biomass fuel [15]. The fixed carbon content (FCC) ranged from 9.4 to 18% for *C. procera* and *P. australis*, respectively. These values are in agreement with the values of common biomass published by several authors worldwide, which ranged from 7 to 20% [37, 44, 45].

Fuel properties of wood

Table 2 shows that there were significant differences among the studied invasive plants compared to *A. tortilis* concerning measured fuel properties of wood. With the exception of *R. stricta*, the other two invasive plants had HV based on dry basis and dry ash basis lower than *A. tortilis*. The HVs (db) ranged from 18.5 (*P. australis*) to 19.8 MJ/kg (*R. stricta*). The highest values of HV_{db} and HV_{daf} were obtained in *R. stricta*; however, the lowest values were obtained in *P. australis*. The HV of the invasive plants fell in the range of typical wood biomass fuels published in the literature, i.e., 18–21 MJ/kg for four species in the Mediterranean area [37], 18–19 MJ/kg for seven vine varieties in Saudi Arabia [15], 18–20 MJ/kg for four species of waste wood in Spain [40], 18–21 MJ/kg for 17 wood species in Portugal [44], 18.7–19.1 MJ/kg for five species of African fuelwood [8], and 18.6–19.7 MJ/kg for seven *Acacia* species in Riyadh [46]. However, the HVs of the invasive plants were greater than that of some biomass fuels published in the literature, which were 13–17 MJ/kg for six biomass residues in Indonesia [47], and 17–18 MJ/kg for five date palm cultivars in Saudi Arabia [17]. Consequently, the wood of the invasive plants was considered a promising energy source.

The FVI of the invasive plants ranged from 554 (*C. procera*) to 1210 (*R. stricta*) and were lower than that of *A. tortilis* (1521). The lower values of FVI may be attributed to increased ash content, the most important variable adversely affecting the FVI. Nasser et al. [15] found low FVI values for vine stalks ranged from 225 to 508, whereas Kataki and Konwer [48] reported a wide range of FVI from 369 (*Litsea polyantha*) to 2089 (*A. nilotica*).

Thermal properties

TGA and DTG are the best tools to determine the thermal behavior of biomass samples, and they are important factor for the reactor design during the pyrolysis process [49]. TGA provides the weight loss of the sample versus temperature, whereas DTG provides the rate of weight loss. The TGA curves (Fig. 1) show that the thermal decomposition of the wood of the invasive plants occurred below 500 °C. The DTG curves showed a single peak for *C. procera* and three peaks for *A. tortilis*, *R. stricta*, and *P. australis*. This indicated that *C. procera* is thermally simpler than the other species.

The main chemical constituents of the woody biomass are cellulose, hemicellulose, and lignin. The conspicuous two peaks in Fig. 1 may possibly be assigned as hemicellulose and cellulose. In some literatures, the assignment is avoided, because thermal decomposition generally includes multiple reactions, being interactive each other. However, Manasray and Ghaly [50] and El May et al. [51] dared to assign a peak with a shoulder as overlap of hemicellulose and cellulose. Following their assignment, here, we assume that the three main fractions at 150-350 °C, 275–350 °C, and 250–500 °C correspond to hemicellulose, cellulose, and lignin, respectively. On the basis of this assumption, we try to discuss the thermal properties of the species relating to their components. As shown in Table 3 and Fig. 1, three distinct peaks of weight loss were obtained during pyrolysis. The first peak was located at temperatures ranging from 72 (*C. procera*) to 86 °C (*A. tortilis*) corresponding to moisture evaporation from wood samples, which confirms that the moisture content of the samples was approximately 3–4% (Table 3). The second peak corresponded to the thermal decomposition of hemicellulose, and ranged from 320 (*P. australis*) to 345 °C (*R. stricta*). For *C. procera*, the overlapping of the decomposition temperatures of hemicellulose and cellulose was occurred and this observation was reported previously [50, 51]. The third peak occurred at temperatures ranging from 372 (*P. australis*) to 400 °C (*R. stricta*) and corresponded to the decomposition of cellulose. These results are consistent with the data on different types of biomasses [43, 47, 49, 52, 53]. For lignin decomposition, there was no peak for any of the species studied, which may be because of its wide range of decomposition temperatures from 150 to 900 °C without a sharp weight-loss peak [52–54].

Table 3 shows the devolatilization data of the wood of the invasive plants and *A. tortilis*, which were extracted from the curves of TGA and DTG according to Salaheldeen et al. [49] and Chen and Kuo [52]. Although the wood of the three invasive plants used in the present study has thermal behavior similar to those of the *A. tortilis* wood for bioenergy production (Table 3), there were some

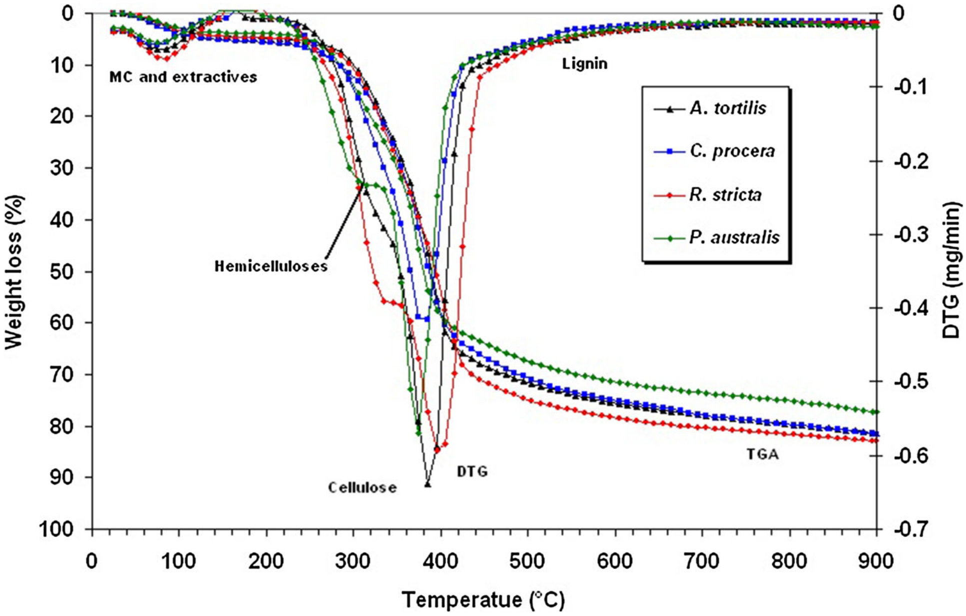

Fig. 1 Thermo-gravimetric analysis (TGA) and derivative thermo-gravimetric (DTG) *curves* of the three invasive plants and *Acacia tortilis* at a heating rate of 10 °C min^{-1} in nitrogen

Table 3 Devolatilization of the invasive plants and *Acacia tortilis*

Species	T_i (°C)	Peak temperature (°C)			Temperature of APZ (°C)	T_{50} (°C)	R_{50} (wt% min^{-1})	Residue (%)
		P_{MC}	P_{HEM}	P_{CEL}				
C. procera	221	72	–	382	235–405	384	7.23	18.4
P. australis	198	76	320	372	240–390	379	7.40	22.7
R. stricta	240	82	345	400	238–410	393	6.32	17.0
A. tortilis	**255**	**86**	**330**	**388**	**280–410**	**389**	**6.93**	**18.6**

These data were extracted from the thermo-gravimetric analysis (TGA) curve with a heating rate 10 °C min^{-1} in nitrogen

Bold values of *A. tortilis* for comparison

T_i is ignition temperature, WL is weight loss, T_{50} is the temperature at the level of 50% weight loss, and R_{50} is the rate of weight loss at T_{50}, P_{MC}, P_{HEM}, and P_{CEL} that are peak temperatures of moisture, hemicellulose, and cellulose, respectively

T_{50} and R_{50} according to Chen and Kuo [52]

Residue at 900 °C (ash and fixed carbon content)

APZ active pyrolysis zone

differences. The percentage of residue (ash and charcoal) ranged from 17 (*R. stricta*) to 23% (*P. australis*). These differences may be attributed to the differences in the chemical composition of wood, especially ash and lignin contents or due to the combination of higher hemicellulose and lignin contents [55]. The initial ignition temperatures (T_i) of the invasive plants were lower than those of *A. tortilis*. The lowest T_i was recorded for *P. australis* (198 °C), whereas the highest one was obtained for *A. tortilis* (255 °C), indicating that the wood of the invasive plants was more reactive than that of *A. tortilis*. These differences may result from differences in the ultimate analysis and chemical constituents of the species studied [49, 56, 57].

At the end of active pyrolysis zone, the temperature differed between species and ranged from 390 (*P. australis*) to 410 °C (*R. stricta*). As shown in Table 3, two indices, T_{50} and R_{50}, were used to compare the weight loss among the invasive plants and *A. tortilis* according to Chen and Kuo [52]. The former is the temperature at 50% weight loss, while the latter is the rate of weight loss at T_{50}. The T_{50} values ranges from 379 °C (*P. australis*) to 393 °C (*R. stricta*). This indicates that the heated wood of these invasive plants up to 400 °C resulted in >50% weight loss. The value of R_{50} ranged between 6.3 (*R. stricta*) and 7.4 wt% min^{-1} (*P. australis*). The R_{50} value was relatively high for the three invasive species, implying that the intensity of weight loss of wood is relatively dramatic near T_{50} [52]. Increasing R_{50} for material indicates that the material is relatively active. This confirms the fact that the thermal decomposition of wood is characterized by a rapid loss in the second region [53]. As shown in Table 3, the values of T_{max}, *C. procera,* and *P. australis* lost most of their volatile matter at lower temperatures than *A. tortilis* and *R. stricta* [37]. Accordingly, these results suggesting that the wood of *C. procera* and *P. australis* was more reactive than that of *R. stricta* and *A. tortilis*, because they had a maximum degradation rate and lower T_{max} of weight loss [49].

Charcoal properties

Three technologies in thermo-chemical conversion processes use biomass as a biorenewable source for bioenergy production, i.e., pyrolysis, gasification, and combustion [58]. The most efficient process is pyrolysis, which produces gases, bio-oil, and bio-char [49, 59].

Table 4 shows the charcoal characteristics produced from the three invasive plants compared with that of *A. tortilis*. The gravimetric charcoal yields ranged from 29 (*R. stricta*) to 31.7% (*P. australis*), which were lower than the value of *A. tortilis* (35%). In addition, the same trend was observed with the amounts of FCY, which ranged from 21 to 26%. These values fell in the range of charcoal produced from typical biomass and were close to the charcoal yields reported by Lee et al. [30] for six biomass residues at 500 °C (25% for bagasse to 41% for paddy straw), and El-Juhany and Aref [46] for seven acacia species at 450 °C (29% for *A. amplecips* to 34% for *A. asak*).

Regarding the ultimate analysis, the C content of the charcoal ranged from 65 (*C. procera*) to 79% (*R. stricta*). However, there was no significant difference between the C content in charcoal of *R. stricta* and *A. tortilis*. However, these values were lower than those reported by Lee et al. [30] for six biomass residues (84–89%). The highest H content was measured in *P. australis* (3.1%), but was lower than the value of 3.2% in *A. tortilis*. The N content ranged from 0.42 (*P. australis*) to 1.0% (*R. stricta*). Only the N content of *R. stricta* was lower than the value measured in *A. tortilis* (0.54%). The O content of the charcoal of the invasive plants ranged between 16.7 (*P. australis*) and 27% (*C. procera*), whereas that of *A. tortilis* was 16.5%. All the O values in the three invasive plants were higher than that of *A. tortilis*.

Table 4 Charcoal[a] properties of the invasive plants compared with the char of *Acacia tortilis*

Property	*Calotropis procera*	*Phragmites australis*	*Rhazya stricta*	*Acacia tortilis*
Yield				
Gravimetric	$30.28^{BC} \pm 0.6$	$31.69^{B} \pm 0.6$	$28.98^{C} \pm 1.3$	$34.66^{A} \pm 1.4$
FCY	$21.37^{BC} \pm 0.5$	$22.58^{B} \pm 0.4$	$20.84^{C} \pm 0.7$	$26.14^{A} \pm 1.2$
Ultimate analysis				
Carbon (C)	$65.33^{C} \pm 1.2$	$75.34^{B} \pm 0.5$	$78.90^{A} \pm 0.7$	$77.73^{A} \pm 0.5$
Hydrogen (H)	$2.86^{C} \pm 0.1$	$3.05^{B} \pm 0.1$	$2.99^{B} \pm 0.02$	$3.22^{A} \pm 0.03$
Nitrogen (N)	$0.63^{B} \pm 0.1$	$0.42^{C} \pm 0.1$	$1.00^{A} \pm 0.02$	$0.54^{B} \pm 0.03$
Oxygen (O)	$26.98^{A} \pm 1.1$	$16.56^{C} \pm 0.4$	$17.38^{B} \pm 0.7$	$16.52^{C} \pm 0.6$
Proximate analysis				
Moisture	$1.29^{B} \pm 0.3$	$1.58^{B} \pm 0.1$	$0.92^{C} \pm 0.1$	$1.95^{A} \pm 0.2$
Ash	$4.20^{B} \pm 0.2$	$4.63^{A} \pm 0.2$	$3.73^{C} \pm 0.2$	$1.99^{D} \pm 0.04$
Volatile matter	$27.68^{A} \pm 0.7$	$25.70^{B} \pm 0.2$	$25.47^{B} \pm 0.7$	$24.24^{C} \pm 0.4$
Fixed carbon	$66.93^{D} \pm 1.0$	$68.09^{C} \pm 0.1$	$69.88^{B} \pm 0.7$	$71.82^{A} \pm 0.6$
Fuel characteristics				
HHV (db, MJ/kg)	$25.68^{D} \pm 0.5$	$27.73^{C} \pm 0.6$	$28.93^{B} \pm 0.2$	$30.13^{A} \pm 0.7$

Means with the same superscript letters in rows are not significantly different according to least significant differences (LSD) test

O (%) = 100 − (C + H + N + ash) according to Pereira et al. [47]

FCY fixed carbon yield, *HHV* higher heating value, *db* dry weight basis

[a] Produced at 400 °C for 4 h

The lowest charcoal ash content of the invasive plants was found in wood samples of *R. stricta* (3.7%), whereas the highest value was obtained in *P. australis* (4.6%), which was higher than that of *A. tortilis* (2.0%). These values were lower than those reported by El-Juhany and Aref [46] for seven acacia species (4.5–7.0%). Increased ash content from the biomass reduces its value as a fuel source [8].

Regarding the proximate analysis of the charcoal, the results in Table 4 showed the VMC on the charcoal produced by the invasive plants ranged from 25.5% (*R. stricta*) to 27.7% (*C. procera*), which were higher than the VMC of *A. tortilis* charcoal (24.2%). The VMC values of the charcoal fell in the range of typical biomass (21–32% [60]; 27–32% [46]; and 24–26% [61]. The VMC in charcoal can vary from <5 to 40% [62]. High volatile charcoal is easy to ignite but may burn with a smoke flame, whereas low volatile charcoal is difficult to light and burns clearly. A good quality charcoal has a net VMC of about 30% [32]; however, Santos [63] reported that charcoal should have a VMC of 20–25% to be suitable for the steel industry. As a result, the VMC from the charcoal produced from the invasive plants indicated it is of high quality and is suitable for the steel industry.

The FCC of the charcoal ranged from 67 (*C. procera*) to 70% (*R. stricta*), which were lower than those obtained from charcoal of *A. tortilis* (72%). The FCC values were similar to those from other wood species (68–75%) [60] and 67–77% [62] and 68–75% [60]). However, they were slightly higher than values reported by El-Juhany and Aref [46] on seven acacia species (57–63%), and slightly lower than those reported by Lopez et al. [40] (79–89%).

According to the HV of the charcoal, the charcoal made from *R. stricta* (29 db, MJ/kg) was the highest among the three invasive plants, but was lower than that of *A. tortilis* (30 db, MJ/kg). Despite having higher ash contents, the charcoal from the invasive plant species exhibited higher calorific values, similar to that of *A. tortilis* charcoal. HVs of the invasive plant charcoal were similar to or greater than those produced from woody biomass reported in the literature (26.9–31.1 MJ/kg) [60], 27.6–29.4 MJ/kg) [46], but lower than the values of 30–35 MJ/kg reported by Lopez et al. [40].

Ranking of invasive plants

Overall, compared with the wood of *A.* tortilis, the results shown in Table 5 indicated that the wood of *R. stricta* and *P. australis* is suitable for energy production. Concerning the problems with the expected N oxide emissions, the charcoal from *P. australis* has a lower nitrogen content (0.42%) than that of *R. stricta* (1.0%).

Conclusions

The results showed that the content of total extractives for the three invasive plants were higher than that of *A. tortilis*, softwood and hardwood species. The highest cellulose

Table 5 Rating[a] of the three invasive plants regarding all determined properties

Property	Invasive species			
	C. procera	*P. australis*	*R. stricta*	*A. tortilis*
Lignin content	2	3	2	1
Ash content	3	2	1	1
Volatile matter	1	3	2	2
Fixed carbon content	3	1	2	2
Carbon content	3	3	1	2
Nitrogen content	2	1	3	2
Oxygen content	2	3	1	2
Heating value	3	3	1	2
Fuel value index	4	3	2	1
Rating value (wood)	**3**	**2**	**1**	**1**
Charcoal				
Heating value	4	3	2	1
Char yield	2	2	3	1
Carbon content	3	2	1	1
Hydrogen content	3	2	2	1
Nitrogen content	3	1	4	2
Oxygen content	3	1	2	1
Moisture content	2	2	1	3
Volatile matter	3	2	2	1
Fixed carbon content	4	3	2	1
Ash content	2	4	3	1
Rating value	**3**	**2**	**2**	**1**
Overall rating value	**4**	**3**	**2**	**1**

Bold values are the rating values of wood, charcoal and overall, respectively

[a] Based on Munalula and Meincken [8]

content was observed in wood samples of *P. australis*, which was higher than the value of *A. tortilis*. Hemicelluloses and lignin contents were between that of softwood and hardwood species. The invasive plants used in the present study were characterized by higher total extractive and lower lignin contents. With the exception of *R. stricta*, the other two invasive plants had HVs lower than that of *A. tortilis*.

The highest and lowest values of HV_{db} and HV_{daf} were obtained in *R. stricta* and *P. australis*, respectively. The HV of the invasive plants falls in the range of typical wood biomass fuels published in the literature. The highest and lowest N contents was recorded in *R. stricta* and *P. australis*, respectively, indicating a negative effect on the environment. Therefore, it is expected that the energy output of *R. stricta* will be high compared with other invasive plants used in this study, but their negative impact on the environment will be also high. The gravimetric charcoal and amounts of fixed C yields were higher in *P. australis*, but lower in *A. tortilis*. The fixed C content of the charcoal was higher in *R. stricta*, which was lower than those obtained from *A. tortilis*. VMC from the charcoal made from invasive plants was higher in *C. procera*, which was higher than that of *A. tortilis*.

The utilization of invasive plants as alternative sources for energy production could be an innovative management technique for the control of these species. The wood of the invasive plants could be fundamental in meeting the shortage in wood supply. Thus, it may be concluded that these invasive plants could be used to effectively produce industrial grade charcoal.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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