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Characteristics of selected non-woody invasive alien plants in South Africa and an evaluation of their potential for electricity generation

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Abstract

Alien invasive plants (AIPs) pose a threat to the existence of plant and animal biodiversity in the ecosystems they invade. They need to be cleared, monitored and eventually eradicated from the landscape. The potential and the economic viability to supply non-woody AIP biomass for electricity generation were assessed in this study, which was conducted on samples from 13 common non-woody AIPs in South Africa, namely: Arundo donax (giant reed), Lantana camara (lantana), Pontederia cordata (pickerel weed), Ricinus communis (castor-oil plant), Opuntia ficus-indica (sweet prickly pear), Solanum mauritianum (bugweed), Atriplex nummularia (saltbush), Cestrum laevigatum (inkberry), Senna didymobotrya (peanut butter cassia), Chromoleana odorata (chromoleana), Eichhornia crassipes (water hyacinth), Cerus jamacaru (queen of the night) and Agave sisilana (sisal plant). Proximate and ultimate analysis was made in order to assess the suitability of the biomass for different thermo-chemical conversion techniques for electricity generation. A financial evaluation of the costs to supply biomass to the plant gate was performed by combining the harvesting, chipping and transport costs. The results showed that the biomass of giant reed, lantana, bugweed, saltbush, inkberry, cassia and Chromoleana may be used to generate electricity through combustion, although the total average cost was approximately 50% higher than that of woody biomass feedstock, requiring a 'fuel cost subsidy' to justify their utilisation for energy production.

Keywords: *invasive plants, biomass, bioenergy, energy potential*

Highlights

- *Physical and chemical properties make some non-woody alien invasive plants suitable for electricity generation.*
- *Economic analysis showed that, without subsidy, some non-woody alien invasive plants are not suitable as feedstock.*

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1. Introduction

Alien invasive plants (AIPs) have significant negative effects on the environment in South Africa, because they invade natural ecosystems and degrade the biodiversity in these systems (Le Maitre et al., 2011). In South Africa, the current legislative and policy framework governing the management of invasive species is the National Environmental Management: Biodiversity Act No. 10 of 2004. Under this legislation, the Department of Environmental Affair's Natural Resource Management Programme is responsible for clearing and monitoring invasive plants. The use of AIPs from clearing operations as bioenergy feedstock is promising as it facilitates the creation of value-added industries and potentially reduces the net cost of the clearing operation by creating revenue streams through the sale of value-added products, in this case energy. Clearing has the added advantage of minimising potential negative environmental impacts, such as decreasing the fire hazard and creating rural employment through harvesting and processing (Working for Water, 2014).

To date, various researchers have studied the potential use of both woody and non-woody invasive plants as feedstock for bioenergy (Young et al., 2011, Liao et al., 2013, Amaducci & Perego, 2015). In South Africa the potential use of woody AIPs for energy purposes has been well documented (Munalula & Meincken, 2009, Smit, 2010, Mugido et al., 2014), but there is limited knowledge on the feasibility of non-woody AIPs for bioenergy.

Converting biomass to energy requires understanding the physical and chemical properties that influence energy conversion (Meincken 2011). The properties of interest when choosing biomass sources are moisture content (MC), heating value (HV), ash content (AC), alkali metal content, and the proportion of fixed carbon and volatiles (McKendry, 2002). These parameters determine whether the biomass feedstock is suited to a particular conversion process. The HV of the feedstock determines the maximum possible energy output, while chemical elements such as silicon (Si), sulphur (S) and chlorine (Cl) have potentially a negative effect on the conversion reactors. The environmental effect in terms of emissions (for example NO_x, SO_x and CO_x) can be estimated from the elemental composition of biomass (Munalula & Meincken, 2009).

There are several conversion routes that can be used to convert biomass to energy, which can be grouped into thermochemical (combustion, gasification, and pyrolysis) and biochemical (anaerobic digestion, microbial fermentation) technologies (McKendry, 2002; Gorgens et al., 2014). The type of biomass feedstock influences the choice of conversion technique and equipment. For thermochemical conversion processes, such as combustion, pyrolysis or gasification, biomass with low ash, moisture, and volatile content is preferred, whereas anaerobic digestion can handle high moisture content biomass and the ash and volatile content are less important (McKendry, 2002). Thermochemical conversion processes have specific requirements for the feedstock properties (von Doderer, 2012). The biomass needs to be reduced and homogenised in size through comminution, as it typically comes in different sizes and shapes; the MC and AC should not be too high; and if sophisticated reactor designs were used Si, S and Cl should not exceed a specified amount, as they either corrode the reactor or form slag (Skrifvars et al., 2004).

Biomass properties, suitable conversion techniques, and the environmental effects of the chosen biomass feedstock, requires understanding in order for the conversion of biomass to energy to be economically feasible.

The objectives of this study were to (i) assess the potential for electricity generation of selected non-woody IAPs in South Africa, based on their physical and chemical properties; (ii) determine the most suitable thermochemical conversion technology options for the different species; and (iii) determine whether the biomass supply costs for these non-woody invasive species were economically feasible.

2. Materials and methods

2.1 Biomass collection and preparation

Biomass samples were obtained from the following common non-woody invasive species: sisal (*Agave sisilana*), giant reed (*Arundo donax*), saltbush (*Atriplex nummularia*), castor-oil plant (*Ricinus communis*), queen of the night (*Ceres jamacaru*), inkberry (*Cestrum laevigatum*), chromoleana (*Chromoleana odorata*), water hyacinth (*Einchornia crassipes*), lantana (*Lantana camara*), sweet prickly pear (*Opuntia ficus-indica*), pickerel weed (*Pontederia cordata*), cassia (*Senna didymobotrya*), and bugweed (*Solanum mauritianum*). The biomass was collected from the Western Cape, KwaZulu-Natal and Mpumalanga provinces of South Africa. Plant material of between 0.5-1 kg was collected in sealed plastic bags to prevent loss of moisture. The samples consisted of the whole plant as it was extracted, where possible, i.e. the leaves (dead or living), flowers and stem, to ensure a representative sample collection. The samples were ground wet in an attrition mill to reduce particle size to a more homogenous size and mixed well to ensure good representation of all plant parts. Samples were received from Working for Water (WfW) as clearing operations proceeded according to their schedule, so no particular harvesting season was chosen. This would be the realistic scenario, should biomass from WfW clearing operations be utilised for further processing.

2.2 Determination of loose bulk density

The loose bulk density of the wet and dry biomass was determined according to standard BS EN ISO 17828:2015 by filling a vessel with known volume and weighing it.

2.3 Determination of moisture, ash, volatile and energy content

The MC, AC, VC and higher heating value (HHV) were determined in triplicates according to BS EN ISO 18134-2:2015 (MC), BS EN 14775:2009 (AC) and BS EN 15148:2009 (VC) and reported as weight %. The MC was reported on wet basis. The HHV was determined according to ISO 1928 in an EcoCal2K bomb calorimeter.

2.4 Determination of chemical composition

Prior to chemical characterisation the dry samples were further reduced to a size of 180 μm with a Retsch rotor mill and screened with a vibratory sieve to obtain a uniform particle size. The C, N, S, Si and Cl content were determined in an accredited external analytical laboratory (Bemlab, Somerset West, South Africa). The entire sample preparation process is illustrated in Figure 1.

2.5 Feedstock requirements

The amount of biomass required to supply 1 MJ/s to an energy plant was calculated for all samples. One MJ was used as a base unit to allow easy comparison. Since biomass feedstock is typically not dry when it is fed into the reactor, the LHV at 30% MC (which is acceptable for most conversion reactors) was calculated for all biomass from the HHV value, according to Equation 1 (Sokhansanj, 2011).

$$LHV_{30}[\frac{MJ}{kg}] = HHV \times (1 - MC_{30}) - 2.443 \times MC_{30} \tag{1}$$

where MC is the moisture content at 30% on wet basis as mass fraction.

The feedstock requirements for 1 MJ per hour, per day and per number of working days (365 days) were then calculated, respectively. Equation 2 shows the calculation procedure with inkberry used as an example.

$$\left\{\begin{array}{c} \text{1kg of inkberry contains} \pm 12.75\ \text{MJ/kg} \\ \text{at 30\% MC} \\ 1/12.75 = 0.08\ \text{kg/s needed} \\ (\text{x } 3600) => 282.42\ \text{kg/hr} \\ (\text{x } 24) => 6.78\text{t/day} \\ (\text{x } 365) => 2474.04\ \text{t/year} \end{array}\right\} \tag{2}$$

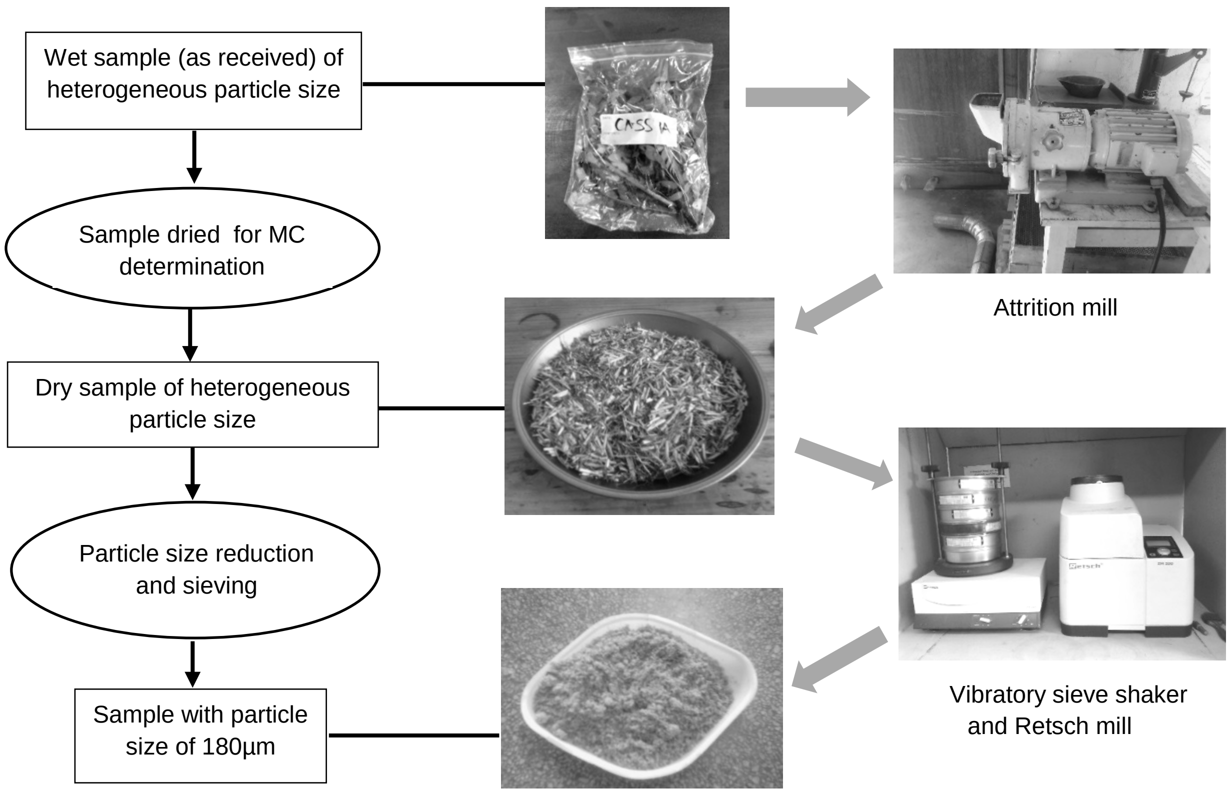

Figure 1: Preparation steps for all biomass samples.

2.6 Costs of biomass feedstock

The input data in the financial viability analysis included the clearing, chipping and transport costs of delivering the chipped biomass to a conversion plant gate. Costs were calculated in South African rand (ZAR). Harvesting (ZAR 176/wet ton) and chipping costs (ZAR 149/wet ton) were obtained from a study by Mugido *et al*. (2014). These costs were then inflated with producer price index values in 2016 to ZAR 208/wet ton and ZAR 176/wet ton for harvesting and chipping respectively. Equation 3 was used to calculate the average cost of clearing per gigajoule (GJ).

$$\frac{ZAR}{GJ} = \frac{Clearing\ costs\ \left(\frac{ZAR}{t}\right)}{energy\ content\ \left(\frac{MJ}{kg}\right)} \tag{3}$$

Chipping costs were calculated according to Equation 4:

$$\frac{ZAR}{GJ} = \frac{Chipping\ costs\ \left(\frac{ZAR}{t}\right)}{energy\ content\ \left(\frac{MJ}{kg}\right)} \tag{4}$$

Transport costs per GJ were calculated according to Equation 5, assuming an average transport distance of 25 km from the source to the conversion plant:

$$\frac{ZAR}{GJ} = \frac{Feedstockfor\frac{1MJ}{s}(t)}{Av.transport\ costs\ \left(\frac{R}{t*km}\right)\times 25} \tag{5}$$

A ZAR/ GJ cost was calculated by adding the costs obtained from Equations 3, 4 and 5 to obtain the supply chain cost for each species and to allow comparison of the different AIPs with each other and also with other biomass types, such as woody AIPs and plantation residue, and furthermore to determine whether the supply costs make non-woody invasive plants a viable option for electricity generation.

3. Results and discussion

3.1 Biomass characteristics

3.1.1 Loose bulk density and processability

The wet and dry bulk densities for the evaluated AIPs ranged from 82.04 to 915.35 kg/m^3 and 28.56 to 216.46 kg/m^3, respectively (Table 1). The density of sweet prickly pear, queen of the night, castor-oil plant, pickerel weed and sisal plant as received were very high because of their high MC, which translated into high transport costs. The dry bulk densities were generally low, but compared well with non-woody biomass feedstock studied by Tanger *et al*. (2013). Bulk density not only impacts on the transport costs, it also has an effect on the processability (comminution) of the biomass (Tanger et al. 2013).

Processability was used as a first decision step to discard the species that were difficult to grind, as a resource for combustion. Sweet prickly pear, water hyacinth, queen of the night and sisal had soft plant parts that clogged the mill and made processing difficult. The long fibres of the queen of the night plant were also problematic during grinding. In addition, sweet prickly pear had thorns, which had to be removed before milling.

Table 1: Loose bulk density per species.

Species	*Wet density (kg/m^3)*	*Dry density (kg/m^3)*	*%MC*
Giant reed	86.67	60.48	49.2
Lantana	155.87	60.75	73.6
Pickerel weed	119.45	28.56	84.3
Castor-oil plant	253.12	63.75	84.3
Sweet prickly pear	915.35	216.46	92.4
Bugweed	163.70	42.11	65.7
Saltbush	82.04	167.25	54.9
Inkberry	298.89	138.67	70.9
Cassia	200.48	80.39	70.0
Chromoleana	196.03	108.05	61.6
Water hyacinth	160.61	44.21	94.7
Queen of the night	804.26	168.71	87.5
Sisal	642.22	110.01	83.3

3.1.2 Moisture content, carbon content and heating value

The results of the physical and chemical properties of the different biomass samples are listed in Table 2. The green MC for all analysed plants was very high. Biomass cannot be combusted when it is too wet, in which case it needs to be dried (Meincken, 2011; Ackerman et al., 2013). Fuel moisture is a limiting factor in biomass combustion because of its negative effect on the energy conversion efficiency. The MC varied between 49.2 and 94.7%, with giant reed (49.2%), saltbush (54.9%) and Chromoleana (61.6%) recording comparatively low MCs.

The HHV was measured on ovendry biomass, thus MC had no effect on it. For energy crops the heating value is viewed as the most important fuel characteristic as it indicates the potential energy output (Meincken, 2011; Kolodziej et al., 2015). As can be seen in Table 2, the HHV ranged between 13.3

to 19.3 MJ/kg, which is somewhat lower than the typical HV range of woody biomass in South Africa of about 19–20 MJ/kg (Meincken and Tyhoda, 2014). The HV is directly related to the carbon content, which contributes positively to the HV (Meincken and Tyhoda, 2014). Sisal (60.4%), chromoleana (58.6%), lantana (57.0%) and inkberry (56.6%) had C contents comparable with woody biomass and correspondingly high HVs. Sisal showed good potential as energy feedstock, with the highest C content and a relatively high HV, but high MC, AC, VC, as well as difficulty with comminution make it unsuitable for combustion.

3.1.3 Ash content, volatile matter and chemical composition

The AC ranged from 3.4 ± 0.6% to as high as 17.1 ± 1.2%, as shown in Table 2. Wood without bark usually contains < 1% ash [6], while faster-growing biomass, like straw and hay, contains 5–10% ash (Stahl et al. 2003). When biomass with a high AC is combusted, a smaller amount of its mass is converted into energy, as only the organic parts contribute to the energy output. Furthermore, a high AC can contribute to processing problems, due to clogging and slagging.

The VC of biomass is typically 60–90% (Ackerman et al., 2013). All analysed species were highly volatile, with values above 80%, as shown in Table 2, and can therefore not be considered for char production, where a low VC and correspondingly high fixed carbon content are desirable. The VC of lantana, saltbush, water hyacinth and queen of the night are comparable to that of woody biomass.

A big concern with utilising AIPs for bioenergy is the high levels of nitrogen, which are undesirable when released into the environment in the form of NO_x emissions and nitric acid, which are toxic and harmful to the environment (Smit 2010). The content of elements such as Si, Cl and S should be as low as possible, as they cause chemical reactions that might damage the conversion reactor linings, such as slagging and corrosion in the reactor (Meincken and Tyhoda, 2014). The Cl, N, S and ash content of all species exceeded the allowed limit for biomass pellets in compliance with EN14961-2 within the class ENplus-A1. Castor-oil plant (5.8 %), water hyacinth (3.2 %) and bugweed (3.0%) had the highest N content, while sisal, queen of the night and giant reed presented the best alternative. The sisal plant had reasonably low N, S, and Cl contents, but was difficult to comminute because its characteristic long fibres clogged the mill.

3.2 Recommended conversion pathways for non-woody IAPs

The biomass conversion options potentially suitable for the conversion of non-woody IAPs are combustion, gasification and anaerobic digestion. Pyrolysis was not seen as a suitable conversion pathway, as the volatile content of all samples was rather high, which leads to a low fixed carbon content and makes them unsuitable for char production. Compared to conventional combustion, gasification is more sophisticated and more sensitive to fuel properties and requires uniform size and low MC, S, Si and Cl content (Pierce, 2015). The non-woody IAPs analysed in this study had higher MC, AC, VC, N,

Table 2: Proximate and ultimate analysis on dry basis (db) of the different biomass samples.

Species	*Proximate analysis (%)*			*Elemental analysis*					*Green density*	*HHV*
	MC	*Ash*	*VC*	*C (%)*	*N (%)*	*S (ppm)*	*Si (ppm)*	*Cl (ppm)*	*(kg/m^3)*	*(MJ/kg)*
Giant reed	49.2±1.2	3.4±0.6	97.0±0.7	51.9	0.9	1566.6	91.8	2308.8	86.7	17.1±0.2
Lantana	73.6±2.2	5.8±0.2	83.4±7.1	57.0	2.6	2138.0	270.7	3108.0	155.9	16.9±0.3
Pickerel weed	84.3±0.1	6.9±0.3	91.2±0.6	46.2	2.2	1127.3	199.3	16747.6	119.5	15.9±0.3
Castor-oil plant	84.3±1.5	5.6±0.9	96.8±1.1	56.3	5.8	3609.2	53.5	6322.6	253.1	16.4±0.5
Sweet prickly pear	92.4±0.1	8.3±0.8	90.7±0.2	50.7	0.9	935.7	64.5	15682.1	915.4	16.0±0.4
Bugweed	65.7±3.3	4.1±1.0	95.8±0.7	43.3	3.0	1528.9	31.6	7690.1	163.7	16.9±0.2
Saltbush	54.9±1.9	14.2±0.3	86.2±0.2	44.3	1.5	1900.7	43.7	1642.8	82.0	16.1±0.4
Inkberry	70.9±0.6	6.3±0.3	93.4±0.9	56.6	2.0	2314.7	284.9	4031.5	298.9	19.3±0.9
Cassia	70.0±0.2	6.2±0	94.1±0.5	54.6	2.3	1693.8	221.9	4422.2	200.5	16.9±0.1
Chromoleana	61.6±2.0	4.7±0.5	94.4±1.1	58.6	1.4	1579.9	24.0	9004.3	196.0	17.2±0.1
Water hyacinth	94.7±0.1	17.1±1.2	85.5±0.8	36.7	3.2	2262.1	41.7	16925.3	160.6	13.9±0.1
Queen of the night	87.5±0.2	16.6±0.4	84.6±0.4	43.1	0.6	1990.7	117.9	603.8	804.3	13.3±0.1
Sisal	83.3±0.3	9.2±0.2	91.3±0.6	60.4	0.8	557.4	108.2	692.6	642.2	17.4±0

Table 3: Harvesting, chipping and transport costs (R/GJ) of non-woody AIP biomass.

Species	*Harvesting cost (ZAR/GJ)*	*Chipping costs (ZAR/GJ)*	*Transport costs (ZAR/GJ)*	*Total supply chain costs (ZAR/GJ)*
Giant reed	12.15	10.29	5.69	28.13
Lantana	12.30	10.42	10.24	32.96
Bugweed	12.31	10.42	10.25	32.98
Saltbush	12.95	10.97	5.41	29.33
Inkberry	10.81	9.15	15.63	35.59
Cassia	12.31	10.42	12.81	35.54
Chromoleana	12.10	10.25	12.59	34.93

Si, S, Cl, but lower density and HV, than woody IAPs found in South Africa (Munalula and Meincken, 2009; Smit, 2010). Thus, none of the species were considered suitable for gasification and many of them had too excessive MC to be considered for combustion in the absence of prior drying.

Sweet prickly pear, water hyacinth, queen of the night, sisal, pickerel weed and castor-oil plant were discarded as they had excessive MC and would require extremely long drying times ahead of further processed. These species could be recommended for energy conversion through biochemical conversion pathways, such as anaerobic digestion, which is suitable for feedstock with high MC. Considering physical and chemical properties of the analysed biomass, the preferred species for combustion were giant reed, saltbush, chromoleana, bugweed, inkberry, cassia, and lantana. These species were selected for economic evaluation.

3.2 Profitability of supplying non-woody IAPs for electricity production

Table 3 shows the total costs – consisting of chipping, harvesting and transport costs per GJ for each species. The total costs ranged from ZAR 28.13 to ZAR 35.59/GJ. The harvesting costs were the largest contributor to the total costs, followed by transport and chipping, as shown in Table 3. The most widely used harvesting methods by the Natural Resource Management Programme to clear AIPs are labour-intensive and often linked to low productivity rates, which increases harvesting costs (Kitenge, 2011). A more mechanised approach could reduce the costs of clearing, but this would result in fewer job opportunities (Pierce, 2015). The study assumed that chipping took place infield. Potentially, chipping at the power plant could reduce costs, as was found in the study by Ofoegbu (2010), but this would increase transport costs, as lower density fuel is transported.

Comparing the costs per GJ for harvesting, chipping and transporting non-woody AIPs with other types of feedstock such as pine forest residue (Ofoegbu, 2010) and woody invasive plants (Kitenge, 2011), energy from non-woody AIP biomass is more expensive. The harvesting costs of non-woody AIPs from this study (ZAR 10.81–12.95/GJ) were significantly higher than the harvesting costs reported by Kitenge (2011), which ranged from ZAR 0.0.92 to ZAR 2.31/GJ for woody AIPs. Ofoegbu (2010) estimated that the cost of chipping pine forest residue at a landing was approximately ZAR 3/GJ (with HV of 18.44 MJ/kg). The chipping costs for the non-woody AIPs analysed in this study, however, ranged from ZAR 9.15 to 10.97/GJ.

The total supply chain costs of woody AIPs, as reported by Kitenge (2011), which included manual harvesting, motor-manual harvesting, extraction, chipping and road transport, ranged from ZAR 16.56 to ZAR 35.39/GJ, with an average cost of ZAR 26/GJ. In comparison with this, the costs of supplying non-woody AIP biomass to an energy plant gate ranged from ZAR 28.13 to ZAR 35.59/GJ, with an average of ZAR 32.78/GJ. The higher costs were attributed to very low energy density of non-woody AIP biomass (Table 2), which increases the total cost to produce the same amount of energy.

4. Conclusions

The results of this study showed that non-woody invasive biomass has the potential to be used as feedstock for bioenergy production through combustion. Also evident from this study is that heat value was not the only determining factor when evaluating the suitability of biomass for bioenergy conversion. Other properties such as ash content, nitrogen, silicon, chlorides, density, moisture content and ease of processability were also important. Overall when taking physical, chemical and financial aspects into consideration, giant reed, saltbush and chromoleana were the best suitable species to be utilised as feedstock for combustion. However, the feasibility study showed that using non-woody alien invasive plants (AIPs as feedstock for bioenergy production did not compare favourably with other biomass feedstock such as forest residue and woody AIPs. The economic analysis showed that the cost per GJ for harvesting, chipping and transporting non-woody AIP biomass was approximately 50% more than for the woody AIPs. Thus, despite the job creation opportunities offered by natural resource management programme in this sector, non-woody AIP biomass currently does not offer a cost-effective way of producing electricity through thermo-chemical conversion processes.

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