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Studies on Characteristics of Some Shrubaceous Non-woody Biomass Species and Their Electricity Generation Potentials

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Abstract *This article presents the results of chemical compositions, ash fusion temperatures, and energy values of various components of four different types of surplus non-woody biomass species (viz. Eupatorium, Anisomales, Sida, and Xanphium) and their impact on decentralized power generation structure. Among these biomass species, the components of Sida were found to have the highest carbon and hydrogen contents and energy values. In general, the results indicated lowest ash contents and highest energy values for their stumps, followed by branch, leaf, and bark, respectively. The fusion temperature results have been reported to be relatively higher (1,250–1,500°C) for Anisomales and Sida biomass ashes, indicating safe boiler operation up to about 1,100–1,200°C with these biomass materials. The calculation results have shown the requirements of approximately 67, 15, 39, and 64 hectares of land for energy plantations with Eupatorium, Anisomales, Sida, and Xanphium biomass species in order to ensure a perpetual supply of electricity for a group of 10–15 villages. Altogether, the authors recommend the exploitation of Anisomales and Sida biomass species for energy plantations in wastelands and their subsequent utilization in power generation, either individually or in co-firing with locally available high ash coals.*

Keywords analysis, ash fusion temperatures, electricity generation, energy value, non-woody biomass

Introduction

In view of increased electricity demand (@ 7% annually in India) and the grim situation in its generation and supply through a centralized grid system, depleting fossil fuel resources and their growing concern over the environmental degradation, power generation on a decentralized basis from biomass and its residues has become of greater significance throughout the world. India occupies the 4th position in generating power through biomass and is poised to become a world leader in this regard (CII, 2005). The details of the estimated renewable energy potential and cumulative power generation in the country have been outlined in Table 1 (PIB, 2007), indicating that the available biomass has a potential to generate around 17,000 MW of electricity. The world-wide biomass energy

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Table 1
Power generation potentials of renewable energy sources in India

Sources/Systems	Estimated potential, MW	Cumulative achievements as on Sept. 30, 2007, MW
Biomass energy	16,881	705.83
Wind energy	45,195	7,660.20
Small hydro power (up to 25 MW)	15,000	2,014.66
Bagasse	5,000	692.33
Waste-to-energy (urban and industrial)	2,700	75.96
Solar energy	20 MW/km^2	—

potential has been discussed in our previous article (Kumar and Patel, 2008b), indicating the share of non-woody biomass to be about 60% (62 EJ/a approx.). Hence, there is a world-wide growing interest in using non-woody biomass as renewable and non-polluting fuels for generating electricity. Policies to promote renewables have mushroomed over the past few years and at least 48 countries have fixed up a target to produce 5–30% of their electricity requirements from renewable energy sources by 2012 (International News, 2005). Many scenarios, developed to explore the future role of renewable energy, have been presented in Table 2 (Johansson et al., 2004). The results of all these scenarios are more optimistic and indicate a significant increase in the use of renewables by 2050 to meet the higher energy needs.

In order to fully understand the biomass energy potential benefits in future electricity needs, it is essential to gain a basic knowledge of its various properties, such as chemical composition, energy value, combustibility, ash fusion temperatures, bulk density, etc. In the present investigation, the findings of studies on proximate and ultimate analyses, energy values and ash fusion temperatures of different components of Eupatorium (local name: Putush), Anisomales (local name: Kuru), Sida (local name: Sonaka), and Xanphium (local name: Jhagra), biomass species (non-woody and non-fodder) and their impact on

Table 2
Global energy scenarios exploring contributions of renewable energy by 2050

Scenario	Total energy demand, EJ	Renewable energy share, EJ		
		Bioenergy	Others	Total
Renewable energy use, 2000	425	47 (11%)	9 (2%)	56 (13%)
RIGES	512	169 (33%)	67 (13%)	236 (46%)
IPCC	642–1,611	—	—	73–444 (9–35%)
IIASA & WEC	479–1,040	—	—	96–308 (22–40%)
Dynamics as usual	852	—	—	282 (33%)
Spirit of coming age	1,217	—	—	336 (28%)

RIGES—Renewables Intensive Global Energy Scenario; IPCC—Intergovernmental Panel on Climate Change Scenario; IIASA—International Institute for Applied Systems Analysis; WEC—World Energy Council.

power generation have been described. The aim was to examine their comparative power generation potentials and judge their suitability for growing in a commercial short rotation energy plantation scheme. As seen in the fields, these biomass species have sufficient vigor to regrow even after several harvests and reach maturity in less than six months. They appear to be the most productive species through planned and systematic energy plantations, and will reduce the expensive replanting operation and, thus, the overall biomass production costs.

Advantages of Decentralized Biomass Power Generation Systems

The biomass-based decentralized power generation systems are expected to provide the following multiple social, economic, and environmental benefits to the village people:

1. Electricity for lighting and development of small-scale industries, thus making the villagers/small industries self dependent
2. Establishment of labor-intensive energy forests leading to employment and income generation in rural areas
3. Fossil fuel conservation and mitigation in the emissions of suspended particulate matters and greenhouse gases
4. Reliable and safe water supply most of the days
5. Development and reclamation of degraded or waste lands
6. Reduction in peaking loads and maintenance cost of power distribution networks
7. Drastic decrease in power transmission losses
8. Feasibility of operation for different periods and thus no requirement of electricity storage facility
9. Feasibility of installation of biomass gasifiers in any location or village
10. Easy availability of technology and backup systems
11. Support for the domestic and industrial waste management projects
12. Despite the above advantages, the rate of spread of biomass-based power generation systems is low due to a number of policy and financial barriers.

Experimental

Materials Selection

In the present investigation, four types of shrubaceous biomass species were procured from the local area, and the components of these non-woody plants were removed separately and dried under sunlight for about a month. The air-dried biomass samples were then processed for the determination of their chemical properties and ash fusion temperatures.

Evaluation of Chemical Properties

The biomass samples were analyzed for their moisture, volatile matter, ash, and fixed carbon contents by standard methods (IS: 1350, 1969), and the calorific values were measured by using a oxygen bomb calorimeter (Agrawal and Jain, 1980). The total carbon and hydrogen contents in some of these biomass samples were determined by an instrumental technique (CHN analyzer) at Punjab University (SAIF), Chandigarh, India.

Determination of Ash Fusion Temperatures

The four characteristic fusion temperatures (IDT, ST, HT, and FT) of biomass ashes were determined as per the German standard test method (DIN: 51730, 1984). The details of the procedure have been illustrated in our previous article (Kumar and Patel, 2008a).

Results and Discussion

Chemical Properties of Studied Plant Components

The results obtained for the chemical compositions (proximate and ultimate analyses) and calorific values of different components of Eupatorium, Anisomales, Sida, and Xanphium plant species have been summarized in Table 3. It is evident from this table that Eupatorium and Anisomales plant species have approximately the same chemical compositions (C and H contents) and calorific values for their components, while the components of Xanphium possessed the lowest values for these properties. It is worthy to note that the energy values and carbon and hydrogen contents of stump, branch, and leaf of Sida are considerably higher than those of the same components of other studied

Table 3
Chemical compositions and calorific values of different components of Eupatorium, Anisomales, Sida, and Xanphium shrub plants

	Proximate analysis, wt% (dry basis)			Ultimate analysis, wt% (dry basis)		
Component	Volatile matter	Ash	Fixed carbon	Total carbon	Hydrogen	Calorific value, kcal/kg (dry basis)
			Eupatorium			
Stump	74.44	5.55	20.01	48.14	7.16	4,742
Branch	72.06	7.73	20.21	47.45	7.06	4,640
Leaf	70.00	14.60	15.40	45.56	6.67	4,546
Bark	70.45	12.50	17.05	44.75	6.79	4,327
			Anisomales			
Stump	78.31	2.19	19.50	49.81	7.17	4,611
Branch	78.22	3.88	17.90	47.51	6.87	4,567
Leaf	68.23	10.58	21.19	46.96	6.94	4,416
Bark	74.44	5.55	20.01	46.20	7.14	4,653
			Sida			
Stump	76.26	4.43	19.31	57.22	7.17	7,695
Branch	74.40	5.67	19.93	57.18	8.18	7,810
Leaf	73.03	12.92	14.05	47.07	7.39	4,718
Bark	75.55	9.44	15.01	43.54	6.78	3,465
			Xanphium			
Stump	72.22	8.88	18.90	47.18	6.95	4,653
Branch	68.82	9.06	22.12	—	—	4,444
Leaf	71.11	11.89	17.00	44.54	6.78	4,371
Bark	68.96	9.94	21.10	44.82	6.85	4,423

plant species. In all of the plant species, the stump, in general, exhibited the highest energy value, followed by branch, leaf, and bark, respectively. The results (Table 3) also indicate that the leaves and barks of all the plant species have higher ash contents than other components.

The major chemical constituents affecting the energy values of carbonaceous materials are carbon and hydrogen. The above variation in energy values of plant components is undoubtedly related to the combined effects of their C and H contents.

Assessment of Ash Fusion Temperatures

Ash fusion temperatures (AFTs) are widely used as a measure of ash fusibility and its slagging behavior, and give prior information to the designers and operators about the likely clinker formation in the boilers. During boiler operation, the ash having low AFT fuses, partially adheres to the char surface reducing its combustibility, forms agglomerated mass with the interruption in air supply, and finally stops combustion. In order to ensure no agglomeration and ample availability of oxygen inside the boiler/gasifier, the softening temperature of ash should be at least 130–150°C more than the operating temperature of the reactor.

From the ash fusion data of studied biomass species (Table 4), it can be seen that the measured values of ST (softening temperature), HT (hemispherical temperature), and FT (fluid temperature) fall in two groups of data range: (i) 1,100–1,240°C for Eupatorium and Xanphium ashes, and (ii) 1,250–1,500°C for Anisomales and Sida ashes. This variation in AFTs of these biomass ashes is believed to be associated with the difference in contents of their mineral constituents. On the basis of available literature (Kumar and Gupta, 1992; Paulrud et al., 2001) on related works, the biomass ashes are expected to consist of the minerals of K, Si, Ca, Mg, Fe, Na, etc. However, the dominant contributors to the biomass AFTs are believed to be the oxides of Si, K, and Ca (major ash forming constituents). As a rule, the contents of Al_2O_3, SiO_2 and TiO_2 increase, while the quantities of Fe_2O_3, CaO, MgO, and Na_2O normally decrease the ash fusion temperatures (Vassilev et al., 1995). The relative influence of these oxides in increasing AFT is normally $TiO_2 > Al_2O_3 > SiO_2$ and for decreasing AFT is $CaO > MgO > Fe_2O_3 > Na_2O$. K_2O shows an intermediate behavior. Anisomales and Sida biomass ashes with relatively higher AFT values (Table 4) are expected to have increased contents of K_2O and SiO_2, and decreased concentrations

Table 4
Ash fusion temperatures of Eupatorium, Anisomales, Sida, and Xanphium biomass materials

	Ash fusion temperatures, °C			
Biomass	IDT	ST	HT	FT
Eupatorium	670	1,109	1,233	1,242
Anisomales	740	1,250	1,412	1,441
Sida	760	1,360	1,460	1,490
Xanphium	670	1,105	1,191	1,207

IDT—Initial deformation temperature; ST—Softening temperature; HT—Hemispherical temperature; FT—Flow temperature.

of fluxing minerals (CaO, MgO, Fe_2O_3, etc.), while lower AFTs of Eupatorium and Xanphium ashes appear to be due to a reverse trend in the contents of these phases. Data listed in Table 4 showed a very close association of FT with HT, and the temperature intervals (spreads) between them increased with increasing HT. As is evident from this table, all the studied biomass ash samples indicated HT–FT fusion intervals in the range 9–30°C. In contrast to the Anisomales and Sida biomass ashes (HT–FT intervals: 29 and 30°C), Eupatorium and Xanphium biomass exhibited lower HT–FT intervals (9 and 16°C) for their ashes and this is most probably because of higher contents of fluxing minerals (CaO, MgO, Fe_2O_3, etc.) in them.

Decentralized Power Generation and Energy Plantation Structures

For the estimation of power generation to meet the electricity requirements in rural areas, a group of 10–15 villages consisting of 3,000 families may be considered, for which one power station could be planned. As outlined in our previous article (Kumar and Patel, 2008b), the power requirement for domestic work, irrigation, and small-scale industries in these villages may be around 20,000 kWh/day (73×10^5 kWh/year). Therefore, a power plant, capable of generating 20,000 kWh/day of electricity, needs to be constructed for the above group of villages.

Table 5 presents the design of energy plantations of Eupatorium, Anisomales, Sida, and Xanphium biomass species for a power plant of above capacity. As evident from this table, about 67/15/39/64 hectares of land, covered with Eupatorium/Anisomales/Sida/Xanphium biomass species, should always be ready for harvesting to meet the annual electricity requirement of 73×10^5 kWh. In order to maintain continuity in power generation, the entire energy plantation area may be divided into two blocks, each comprising an area of about 34/8/20/32 hectares for Eupatorium/Anisomales/Sida/Xanphium biomass species. In the first six months, the first block should be planted followed by a second block in the successive six months. When plants are starting in the second block, the first block plants will be six months old (fully matured) and ready for harvesting. In addition to the above, approximately 50 hectares of land may be required for making roads, residential quarters, and power plants. Thus, the net requirement of land is likely to reach up to the level of 118/66/90/114 hectares for Eupatorium/Anisomales/Sida/Xanphium biomass species. The requirement of higher land areas in case of use of Eupatorium and Xanphium is due to their relatively lower biomass yields and calorific values.

Prospects of the Studied Biomass Species in Power Generation

In planning the electricity generation from biomass on decentralized basis, the main points to be taken into consideration are (i) quality, yield, sustainability, and cost of biomass to be used; (ii) methods of biomass drying and electricity generation and their economic viability; and (iii) costs and qualities of locally available fossil fuels.

Data listed in Tables 3 and 4, and the available literature (Kumar and Gupta, 1994) reveal that some of the properties (e.g., combustibility, energy value, sulphur and ash contents, ash fusion temperatures, etc.) of biomass materials are very much favorable for their use in boilers, while high volatile matter contents in them may pose some operational problems during their combustion. The ST results (Table 4) suggest that the boiler could be safely operated (without agglomeration problems) up to about 950°C with Eupatorium and Xanphium, 1,100°C with Anisomales and 1,200°C with Sida biomass

Table 5
Total energy contents and power generation structures from six months old (approx.) for Eupatorium, Anisomales, Sida, and Xanphium shrub plants

Component	Calorific value, kcal/t (dry basis)	Biomass production, t/ha (dry basis)[a]	Energy value, kcal/ha
Eupatorium			
Stump	$4,742 \times 10^3$	39.60	$18,778.32 \times 10^4$
Branch	$4,640 \times 10^3$	13.50	$6,264.00 \times 10^4$
Leaf	$4,546 \times 10^3$	14.10	$6,409.86 \times 10^4$
Bark	$4,327 \times 10^3$	12.90	$5,581.83 \times 10^4$
Total energy from one hectare of land = $(18,778.32 + 6,264.00 + 6,409.86 + 5,581.83) \times 10^4 = 37,034.01 \times 10^4$ kcal			
Anisomales			
Stump	$4,611 \times 10^3$	45.00	$20,749.50 \times 10^4$
Branch	$4,567 \times 10^3$	163.40	$74,624.78 \times 10^4$
Leaf	$4,416 \times 10^3$	92.60	$40,892.16 \times 10^4$
Bark	$4,653 \times 10^3$	71.80	$33,408.54 \times 10^4$
Total energy from one hectare of land = $(20,749.50 + 74,624.78 + 40,892.16 + 33,408.54) \times 10^4 = 169,674.98 \times 10^4$ kcal			
Sida			
Stump	$7,695 \times 10^3$	47.30	$36,397.35 \times 10^4$
Branch	$7,810 \times 10^3$	18.00	$14,058.00 \times 10^4$
Leaf	$4,718 \times 10^3$	4.80	$2,264.64 \times 10^4$
Bark	$3,465 \times 10^3$	29.70	$10,291.05 \times 10^4$
Total energy from one hectare of land = $(36,397.35 + 14,058.00 + 2,264.64 + 10,291.05) \times 10^4 = 63,011.04 \times 10^4$ kcal			
Xanphium			
Stump	$4,653 \times 10^3$	43.40	$20,194.02 \times 10^4$
Branch	$4,444 \times 10^3$	11.20	$4,977.28 \times 10^4$
Leaf	$4,371 \times 10^3$	22.00	$9,616.20 \times 10^4$
Bark	$4,423 \times 10^3$	9.00	$3,980.70 \times 10^4$
Total energy from one hectare of land = $(20,194.02 + 4,977.28 + 9,616.20 + 3,980.70) \times 10^4 = 38,768.20 \times 10^4$ kcal			

[a]Data from field studies.

Assumptions used in the calculations for this study are as follows:

Conversion efficiency of biomass fueled thermal power plants = 30%

Overall efficiency of power plants = 85%

Total energy from 1 hectare of land at 30% efficiency of power plant:

For Eupatorium biomass = $37,034.01 \times 10^4 \times 0.30$ kcal = $11,110.20 \times 10^4$ kcal = 12.92×10^4 kWh

For Anisomales biomass = $16,9674.98 \times 10^4 \times 0.30$ kcal = $50,902.50 \times 10^4$ kcal = 59.19×10^4 kWh

For Sida biomass = $63,011.04 \times 10^4 \times 0.30$ kcal = $18,903.31 \times 10^4$ kcal = 21.98×10^4 kWh

For Xanphium biomass = $38,768.20 \times 10^4 \times 0.30$ kcal = $11,630.46 \times 10^4$ kcal = 13.52×10^4 kWh

Power generation at 85% overall efficiency:

From Eupatorium = $12.92 \times 10^4 \times 0.85 = 10.98 \times 10^4$ kWh/ha

From Anisomales = $59.19 \times 10^4 \times 0.85 = 50.31 \times 10^4$ kWh/ha

From Sida = $21.98 \times 10^4 \times 0.85 = 18.68 \times 10^4$ kWh/ha

From Xanphium = $13.52 \times 10^4 \times 0.85 = 11.49 \times 10^4$ kWh/ha

Land required to supply electricity for the whole year:

For Eupatorium = $\frac{73\times10^5}{10.98\times10^4} = 66.50 \approx 67$ ha

For Anisomales = $\frac{73\times10^5}{50.31\times10^4} = 14.50 \approx 15$ ha

For Sida = $\frac{73\times10^5}{18.68\times10^4} = 39.10 \approx 39$ ha

For Xanphium = $\frac{73\times10^5}{11.49\times10^4} = 63.50 \approx 64$ ha species. As outlined in our previous articles (Kumar and Patel, 2008a, 2008b), the locally available coals are of much higher ash content and lower energy value and, thus, they are not cost effective and environment friendly. It may be preferred to mix these high ash coals with the presently studied biomass materials in order to maintain moderate ash and volatile matter contents in the blend. Relatively higher energy values and much lower ash contents (Table 4) in the studied biomass species also indicate that any contribution from them, either individually or in combination with coals, will be a positive step in increasing power generation and minimizing the accretion, clinker, and pollutant emission problems. In addition, much higher combustion reactivities in non-woody biomass chars are quite evident and this characteristic could be exploited to reduce the boiler operation temperature and time, and thus the energy consumption. Experimental results (Tables 3 and 4) and calculations carried out in Table 5 clearly indicate that it would be more beneficial to do energy plantations in the wastelands with Anisomales and Sida biomass species. The authors think that by developing and utilizing the available wasteland and cultivation pattern, one can generate sufficient biomass to meet the power demand of more villages/cities.

Suggestions in the Development of Power Generation Structure

In planning the biomass-based decentralized power generation structure to meet the rural energy needs in a sustainable way, the following suggestions may be taken into account:

1. Several social, economical, environmental and reliability criteria need to be considered by multimedia approach while selecting a proper alternative for medium/long-term power generation system. There is a need to develop calculation models for assessment of these criteria of each individual biomass species.
2. The indigenous biomass resource energy potential and its likely contribution in power generation needs to be addressed for the full realization of this energy source. A biomass atlas to accurately assess the state-wise energy potentials of different categories of biomass must be prepared.
3. Wastelands are spread in different regions with diversified climatic conditions and rain fall patterns. Research is required to recognize varieties of high biomass yielding plant species suited for these wastelands.
4. Coppicing power, biomass yielding capacity, properties, and power generation potential of each individual biomass species need to be examined in order to develop a sustainable energy plantation system for the considered power plant. Sustainability in the supply of biomass must be ensured.
5. There is a need for the construction of a set of reasonable biomass species for the considered electric system development.
6. Biomass is a poorly documented energy source and lack of data appears to be the hurdle in sound decisionmaking when the question comes for its utilization. Intensive research work is required in this area by various disciplines of science and engineering, and the expertise and experience of scientists and engineers should be made available to the users (farmers and entrepreneurs) through human and computer assisted interface.
7. The majority of the current energy plantations are following traditional agricultural and forestry practices. This needs to be changed.
8. Use of forest lands to supply biomass or conversion of natural forests to energy plantations should be discouraged.

9. Appropriate guidelines to discourage monoculture plantations should be provided to the farmers.
10. There is a need of support from governments, laboratories, institutes, etc. for large-scale spread of biomass power generation systems.
11. A number of research and development centers for characterization of biomass properties (chemical composition, energy value, density, combustion reactivity, etc.) and development of its gasification technology must be established.
12. Methods of biomass drying and electricity generation and their economic viability must be assessed.
13. Development of several designs of gasifier/combustion systems on the basis of different biomass fuels and assessment of their economic viability are of prime importance.
14. Arrangements must be made for proper planning, implementation, and monitoring of biomass-based electrification systems.

Conclusions

The main findings derived from the present investigation can be summarized as follows:

1. In general, all the studied plant species showed highest energy values for their stumps, followed by branch, leaf, and bark, respectively.
2. Among all of the studied biomass species, Sida exhibited the highest energy values, and C and H contents for its components, Xanphium being at the lowest values.
3. In comparison to other components, somewhat higher ash contents were observed in leaves and barks of all the presently studied plant species.
4. Anisomales and Sida biomass ashes exhibited higher fusion temperatures (1,250–1,500°C) and ensured for safe boiler operation up to about 1,100–1,200°C.
5. The fusion temperature results of Eupatorium and Xanphium biomass ashes have been reported to be lower (1,100–1,240°C), indicating the safe boiler operation with these biomass materials up to about 950°C.
6. Comparison of the present experimental results with those of the locally available coals indicates higher power generation potential in biomass than coal.
7. In order to maintain a continuous supply of electricity for a group of 10–15 villages, the calculation results have suggested that the net requirements of about 67, 15, 39, and 64 hectares of land for energy plantations with Eupatorium, Anisomales, Sida, and Xanphium biomass species, respectively.
8. Altogether, it appears that Anisomales and Sida biomass species are more suitable for energy plantations in wastelands and their exploitation in power generation either individually or after blending with high ash coals.
9. The present study may be useful in the exploitation of non-woody biomass species for power generation and such approach needs to be extended to the state level to select more suitable plant species and their optimal cultivation pattern.

References

Agrawal, B. C., and Jain, S. P. 1980. *A Text-Book of Metallurgical Analysis, 3rd ed.* New Delhi: Khanna Publishers.

Confederation of Indian Industry. 2005. Biomass energy—Potential and prospects. Godrej GBC Publication. Available at http://greenbusinesscentre.com/Documents/biomass.pdf (accessed on June 1, 2005).
DIN: 51730 (German Standard). 1984. *Testing of Solid Fuels—Determination of Fusibility of Fuel Ash*. Berlin, Germany: Germany Institute for Standardization.
International News. 2005. Renewable energy investment at record high. *Akshay Urja* 1:14.
IS: 1350 (Indian Standard). 1969. *Part I—Methods of Tests for Coal and Coke*. New Delhi: Bureau of Indian Standards, p. 3.
Johansson, T. B., McCormick, K., Neij, L., and Turkenburg, W. 2004. The potentials of renewable energy. *International Conference for Renewable Energies*, Bonn, Germany, June 1–4, pp. 1–40.
Kumar, M., and Gupta, R. C. 1992. Properties of Acacia and Eucalyptus woods. *J. Mater. Sci. Lett.* 11:1439–1440.
Kumar, M., and Gupta, R. C. 1994. Influence of carbonization conditions and wood species on carbon dioxide reactivity of resultant wood char powder. *Fuel Proc. Technol.* 38:223–233.
Kumar, M., and Patel, S. K. 2008a. Characteristics of Indian non-coking coals and iron ore reduction by their chars for directly reduced iron production. *Miner. Proc. & Extrac. Metal. Rev.* 29:258–273.
Kumar, M., and Patel, S. K. 2008b. Energy values and estimation of power generation potentials of some non-woody biomass species. *Energy Sources* 30:765–773.
Paulrud, S., Nilsson, C., and Ohman, M. 2001. Reed canary-grass ash composition and its melting behaviour during combustion. *Fuel* 80:1391–1398.
Press Information Bureau, Government of India (PIB). 2007. Development of Renewable Energy Resources. Available at: http://www.pib.nic.in.
Vassilev, S. V., Kitano, K., Takeda, S., and Tsurue, T. 1995. Influence of mineral and chemical composition of coal ashes on their fusibility. *Fuel Proc. Technol.* 45:27–51.