

Thermal processing technologies for biomass conversion to energy

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Abstract

Bio-energy is now accepted as having the potential to provide a major part of the projected renewable energy provisions of the future. There are three main routes to providing these bio-fuels, such as biological conversion, physical conversion, and thermal conversion. A number of primary and secondary products can be derived as gas, liquid and solid fuels, and electricity as well as a considerable number of chemicals. In this paper, we will be discussing existing techniques and recent progress in combustion, pyrolysis and gasification techniques for the conversion of bioenergy into a viable source of energy, fuel and chemicals. Topics of discussion will include biomass combustion for heat, biomass gasification to produce syngas and process concerns, as well as various ways to address these issues, biomass pyrolysis for production of bio-oil and, co-firing of biomass and coal and the use of co-gasification and co-pyrolysis, the combination of pyrolysis and gasification to process pyrolysis products to syngas through gasification and liquefaction of syngas and its conversion to fuels.

Keywords : Bioenergy; combustion, pyrolysis, gasification; renewable energy, bio-oils

1. Introduction

Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable energy resources available. These can provide the only source of renewable liquid, gaseous, and solid fuels. Biomass is considered the renewable energy source with the

highest potential to contribute to the energy needs of modern society for both the developed and developing economies worldwide (Table 1). Energy from biomass based on short-rotation forestry and other energy crops can contribute significantly towards the objectives of the Kyoto Agreement in reducing the greenhouse gases emissions and to the problems related to climate change [1-3].

Table 1. Role of biomass energy by major region in 2000 (EJ/year)

Region	World	OECD	Non-OECD	Africa	Latin	
					America	Asia
Primary energy	423.3	222.6	200.7	20.7	18.7	93.7
of which biomass (%)	10.8	3.4	19.1	49.5	17.6	25.1
Final energy	289.1	151.2	137.9	15.4	14.6	66.7
of which biomass (%)	13.8	2.5	26.3	59.6	20.3	34.6
Estimated modern bioenergy	9.8	5.2	4.6	1.0	1.9	1.5
as percent of primary energy (%)	2.3	2.3	2.3	4.7	10.0	1.6
Electricity, CHP & heat plant	4.12	3.72	0.39	0.0	0.14	0.07
as percent total sector inputs (%)	2.7	4.1	0.6	0.0	3.4	0.2
Industry (approximately)	5.31	1.34	3.97	0.98	1.45	1.44
as percent total sector inputs (%)	5.8	3.0	8.6	30.3	26.0	6.3
Transport	0.35	0.10	0.26	0.0	0.29	0.03
as percent total sector inputs (%)	0.5	0.2	1.1	0.0	6.3	0.4

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Biomass fuels and residues can be converted to energy via thermal, biological, and physical processes (Table 2 and 3). Each process area is described with the greatest emphasis on the technologies that are attracting the most attention in the research, demonstration, and commercial arenas. In the

thermochemical conversion technologies, biomass gasification has attracted the highest interest as it offers higher efficiencies compared to combustion, and fast pyrolysis is still at a relatively early stage of development [4-20].

Table 2. Types and examples of biomass fuel

Residues	Examples
<u>Primary residues</u>	
Residues produced in the field or forest from biomass production and harvesting	
(a) dispersed residues: substantial labor or other costs to collect for on site energy production or onward transportation to energy facility	-biomass collected from natural resources: for example fallen tree branches, woody weeds and shrubs, grasses, swamp and water plants. -forestry thinnings, logging wastes and bark. -crop residues normally left or burned in the field: for example cereal straw; cotton, tobacco and maize stems; sugarcane tops and leaves. -dung from grazing cattle.
(b) concentrated residues: few costs to collect for site energy production or onward transportation to energy facility.	-harvested cereal straws, crop stalks -dung from stalled cattle, caged poultry.
<u>Secondary residues</u>	
Residues arising from the processing of wood, food and other organic materials, at or close to the energy production site.	-sawmill bark, chips, sawdust; black liquor from pulp mills; slaughterhouse wastes. -sugarcane bagasse, sugarcane tops and leaves, oil pressing pulp, nut shells and husks.
<u>Tertiary residues</u>	
Wastes arising after the consumption of biomass (and other organic materials)	-municipal solid organic wastes (incineration for energy production or gas from landfills); sewage gas. -wood recovered from demolition of buildings, wooden containers.
Energy crops	
<u>Dedicated energy crops</u>	
Agricultural or forestry crops with biomass fuels as the sole or principal product	-trees, bamboo, palms, grasses including sugarcane, cereals such as maize, starchy roots, oilseed crops.
(a) crops do not displace other crops	-energy crops grown on presently unused land, field boundaries
(b) crops do displace other crops	-energy crops replace agricultural or forestry crops.
<u>Biofuel co-production</u>	
Agricultural or forestry activities designed to provide several products including biomass fuel.	-integrated sugarcane production providing a mix of sugar, alcohol, molasses and use of bagasse to generate electricity. -timber or fruit, nut and other trees grown principally for nonenergy purposes but designed to deliver thinnings, prunings or harvest wastes as biomass fuel.
Harvesting natural resources	
Cutting live trees, shrubs, grasses, water plants, growing naturally: harvesting may be at sustainable or unsustainable rates	

As the crude oil supply has become unstable, biomass has been gaining great attention as a means to valuable alternative energy. Biomass surpasses many other renewable energy sources, because of its abundance [11], high energy values [12], and versatility [13]. Many methods have been suggested for converting biomass into various energy forms.

These methods include, but are not limited to, combustion, fermentation, anaerobic digestion, gasification, and pyrolysis. Depending on the type of biomass and conversion technology, different energy forms are possible such as direct thermal energy, liquid biofuels, and gaseous hydrogen [21-37].

Table 3. Some biomass energy conversion technology pathways

Electricity	
All systems include biomass feedstock plus Generator set; some may provide low to medium temperature heat (cogeneration)	-combustion boiler + steam turbine -thermal gasification: gasifier + gas turbine or gas engine -external combustion engine + generator -anaerobic fermentation: biogas digester – gas engine
Transport fuels	
Sugar and starch crops (sugarcane)	-fermentation + distillation – ethanol
Lignocellulosic biomass	-hydrolysis + fermentation – ethanol -gasification + gas processing – methanol, hydrogen -gasification + Fischer-Tropsch synthesis – synthetic gasoline
Oil seed crops	-esterification-biodiesel
Cooking energy	
Wood, woody residues	-charcoal
Wood wastes, residues	-briquettes, pellets
Sugar and starch crops	-ethanol (+ gel)
Prepared biomass	-gasifier-producer gas (+ methanol)
Biomass & animal wastes	-biogas digester - biogas
Process heat	
Any biomass	-direct combustion
Prepared biomass	-gasifier-producer gas
Pyrolysis oils	-substitute for fuel oil

In an effort to convert biomass to usable energy more effectively, with less pollution and at least as economical as today's practices, many new technologies are being developed. A great number of research articles on biomass energy are published everyday and it's becoming hard to keep up with new findings and technologies. Sometimes it's even confusing and frustrating to comprehend the details and validity of the techniques and to make a decision on a method to use for a certain type of biomass [6-8].

In this paper, it will focus on the past and current progresses in gasification and pyrolysis technologies for conversion of biomass to energy. Because of the large range of biomass types, we are focusing only on cellulosic biomass such as rice husk, corn stalk, switch grass, plants, plant-derived materials, and sludge. As a result, biodiesel which is produced by either photosynthesis of algae or from waste oil is not included in this review although these days it is gaining great interest as a valuable alternative energy.

2. Thermal Processing of Biomass

2.1. Combustion

Biomass or bioenergy can be directly burned to provide thermal energy for heating and cooking purposes [8]. Direct combustion of wood, for example, has been the predominant energy source for a long time and is still being used in many developing countries [14, 15]. Combustion of biomass and related materials is widely practiced commercially to provide

heat and power. The technology is commercially available and presents minimum risk to investors. The product is heat, which must be used immediately for heat and/or power generation as storage is not a viable option. Overall efficiencies to power tend to be rather low at typically 20% for small plants and up to 30% for larger and newer plants. Costs are only currently competitive when wastes are used as feed material such as from pulp and paper and agriculture. Emissions and ash handling remain technical problems [8-15].

Gasification of biomass has been investigated for no more than 30 yr although gasification of coal is not a new technology [13, 18]. Gasification run on a wider variety of input materials can be used to produce a wider variety of output fuels, and is an extremely efficient method of extracting energy from biomass. Therefore, biomass gasification is one of the most technically and economically convincing energy possibilities for a carbon neutral economy [19, 20]. Syngas (H_2 and CO) or hydrogen can be produced by catalytic (<900 °C) or non-catalytic (<1300 °C) gasification [21, 22]. Fluidized-bed type gasifiers with a catalytic reformer are becoming common and have been operated for biomass mostly in EU countries [23-27].

2.2. Gasification

Fuel gas can be produced from biomass and related materials by either partial oxidation to give a mixture of CO , CO_2 , H_2 , and CH_4 or by steam or pyrolytic

gasification as shown in Table 4. Gasification occurs in a number of sequential steps [26-29]:

- Drying to evaporate moisture

- Pyrolysis to give gas, vaporized tars, or oils and a solid char residue
- Gasification or partial oxidation of the solid char, pyrolysis tars, and gases

Table 4. Modes of thermal gasification

Partial oxidation with air	Main products are CO, CO ₂ , H ₂ , CH ₄ , N ₂ , and tar. This gives a low heating value gas of 5 MJ/m ³ . Utilization problems can arise in combustion, particularly in gas turbines.
Partial oxidation with oxygen	The main products are CO, CO ₂ , H ₂ , CH ₄ , and tar. This gives a medium heating value gas of 10-12 MJ/m ³ . The cost of providing and using oxygen is compensated by a better quality fuel gas.
Steam (pyrolytic) gasification	The main products are CO, CO ₂ , H ₂ , CH ₄ and tar. This gives a medium heating value gas of 15-20 MJ/m ³ . The process has two stages with a primary reactor producing gas and char, and a second reactor for char combustion to reheat sand, which is recirculated.

When a solid fuel such as biomass was heated to 300–500 °C in the absence of an oxidizing agent, pyrolysis to solid char, condensable hydrocarbons, and gases occurred. The relative yields of gas, liquid, and char depend mostly on the rate of heating and the final temperature. Generally in gasification, pyrolysis proceeds at a much quicker rate than gasification and the latter is thus the rate-controlling step. The gas, liquid, and solid products of pyrolysis then react with the air to give permanent gases of CO, CO₂, H₂, and lesser quantities of hydrocarbon gases. Char gasification is the interactive combination of several gas–solid and gas–gas reactions in which solid carbon is oxidized to carbon monoxide and carbon dioxide, and hydrogen is generated through the water gas shift reaction. The gas–solid reactions of char oxidation are the slowest and limit the overall rate of the gasification process. Many of the reactions are catalyzed by the alkali metals present in wood ash, but still do not reach equilibrium. The gas composition is influenced by many factors such as feed composition, water content, reaction temperature, and the extent of oxidation of the pyrolysis products [26-33].

Atmospheric fixed and circulating fluidized bed gasifiers (Figs. 1-2) have proven very reliable with a variety of feedstocks and are relative easy to scale up from a few MW_{th} up to 100 MW_{th}. Even for capacities above 100 MW_{th}, there is confidence that the industry would be able to provide reliable gasifiers. This appears to be the preferred system for large-scale applications and is used by most industrial companies; these systems, therefore, have high market attractiveness and are technically well proven [12, 29].

Atmospheric bubbling fluidized bed gasifiers have proven to be reliable with a variety of feedstocks at pilot scale and commercial applications in the small to medium scale up to about 25 MW_{th}. They are limited in their capacity size range as they have not been scaled up significantly and the gasifier diameter is significantly larger than that of circulating fluid beds for the same feedstock capacity. On the other hand, they are more economic for small to medium range capacities. Their market attractiveness is thus relatively high as well as their technology strength [26-31].

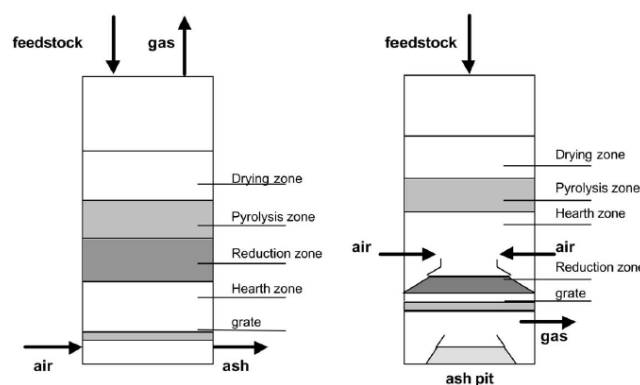


Figure 1. Updraft (left hand side) and downdraft (right hand side) fixed bed direct gasifiers.

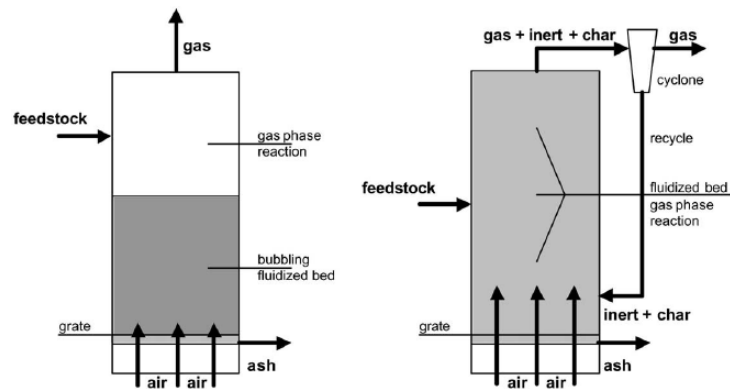


Figure 2. Bubbling (left hand side) and circulating (right hand side) fluidized bed direct gasifiers.

Atmospheric downdraft gasifiers are attractive for small-scale applications up to about 1.5 MW_{th} as there is a very big market in both developed and developing economies. However, the problem of efficient tar removal is still a major problem and a higher level of automation is needed especially for small-scale industrial applications. Nevertheless, recent progress in catalytic conversion of tar gives more credible options and these systems can therefore be considered to be average technical strength [14-29].

Atmospheric cyclonic gasifiers have only recently been tested for biomass feed stocks and although they have medium market attractiveness due to their simplicity, they are still unproven. Finally, atmospheric entrained-bed gasifiers are still at a very early stage of development and since they require feedstock of a very small particle size, their market attractiveness is very low. No company is known to be developing pressurized systems for downdraft,

updraft, cyclonic, or entrained bed gasifiers for biomass feedstocks and it is difficult to imagine that such a technology could ever be developed into a commercial product due to the inherent problems of scale, tar removal, and cost [12-29].

2.3. Pyrolysis

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products. Lower process temperature and longer vapor residence times favor the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapor residence time are optimum for producing liquids. Table 5 shows the product distribution obtained from different modes of pyrolysis process [29].

Table 5. Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood

Types of process	Temperature and time	Liquid, %	Char, %	Gas, %
Fast pyrolysis	Moderate temperature, short residence time	75	12	13
Carbonization	Low temperature, very long residence time	30	35	35
Gasification	High temperature, long residence time	5	10	85

Fast pyrolysis occurs in a time of a few seconds or less. Therefore, not only chemical reaction kinetics but also heat and mass transfer processes, as well as phase transition phenomena, play important roles. The critical issue is to bring the reacting biomass particle to the optimum process temperature and minimize its exposure to the lower temperatures that favor

formation of charcoal. One way this objective can be achieved is by using small particles, for example in the fluidized bed processes that are described later. Another possibility is to transfer heat very fast only to the particle surface that contacts the heat source. Figure 3 shows a schematic view for pyrolysis reactor with twin-screw conveyor [29].

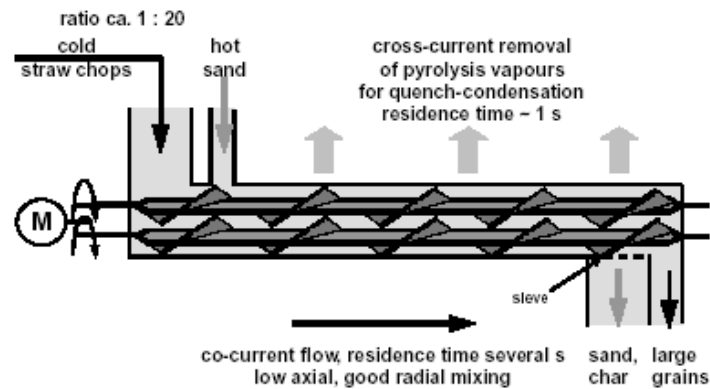


Figure 3. A schematic view of the pyrolysis reactor with twin-screw conveyor.

In fast pyrolysis, biomass decomposes to generate mostly vapors and aerosols and some charcoal. After cooling and condensation, a dark brown mobile liquid is formed which has a heating value about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process, with carefully controlled parameters to give high yields of liquid. The essential features of a fast pyrolysis process for producing liquids are [5, 29, 34]:

- Very high heating and heat transfer rates at the reaction interface, which usually requires a finely ground biomass feed,
- Carefully controlled pyrolysis reaction temperature of around 500°C and vapor phase temperature of 400–450 °C,
- Short vapor residence times of typically less than 2 s, and
- Rapid cooling of the pyrolysis vapors to give the bio-oil product.

A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimize the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, pyrolysis reaction, separation of solids (char), and collection of the liquid product (bio-oil). Any form of biomass can be considered for fast pyrolysis. While most work has been carried out on wood due to its consistency, and comparability between tests [36, 37], nearly 100 different biomass types have been tested by many laboratories ranging from agricultural wastes such as straw, olive pits, and nut shells to energy crops such as miscanthus and sorghum and solid wastes such as sewage sludge and leather wastes [14-29].

2.4. Co-Firing of Biomass

Increasing concerns about the environmental impacts of power generation from fossil fuels have prompted the development of more sustainable means of generating power. These have included increasing the fraction of renewable and sustainable energy in the national energy supply. Historically, renewable energy sources have struggled to compete with fossil energy, due to their relatively high costs, and high technical risk [13].

The co-firing of biomass with coal in conventional coal-fired boilers can provide a reasonably attractive option for the utilization of biomass for the generation of power, and in some cases heat. Co-firing makes use of the extensive infrastructure associated with the existing fossil fuel-based power systems, and requires only relatively modest additional capital investment. In most countries, the co-firing of biomass is one of the most economic technologies available for providing significant CO₂ reductions [13-15].

An inventory of the application of co-firing worldwide in 2009 indicated that more than 160 coal-fired power plants had experience with co-firing biomass or waste, at least on a trial basis [28]. The power plants involved are in the range 50–700 MW_e, although a number of very small plants have also been involved. The majority are pulverized coal boilers, including tangentially fired, and cyclone fired units. Bubbling and circulating fluidized bed boilers, and stoker boilers, have also been used. The co-firing activities have involved all of the commercially significant solid fossil fuels, including lignites, sub-bituminous coals, bituminous coals, anthracites, and petroleum coke. These fuels have been co-fired with a very wide range of biomass materials, including herbaceous and woody materials, wet and dry agricultural residues and energy crops [25].

The plant experience to date has indicated that successful biomass co-firing technologies have to be suitable for retrofit to existing coal-fired power plants or for new build plants, simple to operate and control, and involve minimum risk to the normal operation and performance, both technical and environmental, of the plant. The potential costs of significant interference with the coal plant operation are likely to be high compared to any additional revenues from co-firing. The key technical risk areas are [10-14];

- fuel preparation, processing and handling issues;
- combustion related issues affecting plant operation and control;
- ash related issues, and;
- emissions and other environmental impacts.

Likewise, co-pyrolysis has advantages over sole biomass or coal pyrolysis. Although pyrolysis of coal is a good method for producing liquid fuels, the yields of these products are limited because of the low hydrogen-to-carbon ratio in coal [4]. The high hydrogen-to-carbon ratio in biomass renders biomass to act as a hydrogen donor in co-pyrolysis of biomass/coal blends. Moreover, the high thermochemical reactivity and high content of volatiles of biomass facilitate the conversion and the upgrading of the fuel. Therefore, it's considered promising to co-fire the two fuels as a step towards valid, sustainable utilization of coal and biomass and to minimize the impact on the environment.

3. Conclusions

Traditional bioenergy in the form of fuel wood, charcoal, and residues has been with humanity since the discovery of fire, but only in the past 100 years or so has it reappeared in a more advanced and modern version. Biomass is a locally available energy source with the highest versatility among the renewable energies; that is to say, it can be made available in solid, liquid, or gaseous forms. As technology continues to advance, the potential of biomass as a viable energy source will increase. Recent advances in both pyrolysis and gasification techniques provide us with great insight into the future direction of research and industrial practices. This includes areas such as the gasification of biomass and coal together, which provides an environmentally friendly modification to standard coal combustion or the plasma technique which yields a high heating value gas whereas lowering the amount of contaminants formed as a result of the process. The use of nano-catalysts in thermochemical conversion is also a

promising area for more efficient clean energy production from biomass.

One of the issues in conversion of biomass to energy is an inconsistency of compositions and physical properties of different types of biomass. The better utilize biomass wastes, the gasification/pyrolysis systems should be able to handle the inconsistency of feedstocks to maintain the stable product yields and properties. High capital costs for building a gasification system is also a challenge to overcome. Small and medium size plasma gasification, for example, may be a reasonable direction to resolve these issues, because its performance is efficient compared with other thermochemical conversion technologies and is less picky on the types of biomass.

References

- [1] REN21, Renewable Energy Network. 2010. Renewables 2010 Global status report.
- [2] WEC, World Energy Council. 2010 Survey of Energy Resources, WEC, London, 2010.
- [3] IEA, International Energy Agency. World Energy Outlook 2009. Paris: IEA, 2009.
- [4] Bridgwater, T., and Manitas, K. 2004. The production of biofuels by the thermochemical processing of biomass. In: Molecular to Global Photosynthesis, Archer, M. D., and Barber, J. (Eds.).Oxford, UK: Imperial College, pp. 521–611.
- [5] Bridgwater, AV., Peacocke, GVC. Fast pyrolysis processes for biomass. Renewable and Sustainable Energy Reviews 1999; 4:1–73.
- [6] Kartha, S., Leach, G., and Rjan, S. C. Advancing bioenergy for sustainable development: guidelines for policymakers and investors. Energy Sector Management Assistance Program (ESMAP) Report No. 300/05. Washington, DC: The World Bank, 2005.
- [7] Kaygusuz, K., and Keles, S. Use of biomass as a traditional strategy to a sustainable and clean energy system. Energy Sources, Part A 2009; 31:86–97.
- [8] Klass, DL. Biomass for renewable energy, fuels and chemicals. San Diego, California: Academic Press/Elsevier, 1998.
- [9] Manitas, K. 2001. Progress in biomass gasification: An overview. In: Progress in thermo - chemical biomass conversion, Bridgwater, AV (Ed.). pp. 1-32, Oxford, UK: Blackwell.

- [10] Thornley, P., and Wright, E. 2005. Evaluation of bioenergy projects. In: *Fast Pyrolysis of Biomass: A Handbook*, vol. 2 (Ed. Bridgewater, A.V.) London, UK: CPL Press.
- [11] Friedrich, K., Hacker, V. The increased use of biomass as a transitional strategy to a sustainable energy system. 17th WEC Energy Congress, Houston, Texas, USA, September 13-18, 1998.
- [12] Belgiorno V., De Feo G., Della Roca C., Napoli R. Energy from gasification of solid wastes. *Waste Management*, 2003; 23: 1-15.
- [13] Digman, B., Joo, HS., Kim, DS. Recent progress in gasification technologies for biomass conversion to energy. *Environ Progress Sustain Energy*, 2009; 28: 47-51.
- [14] Van Loo, S., Koppejan, J (Eds.). *The handbook of biomass combustion and co-firing*, Earthscan, London, UK, 2007.
- [15] Rosillo-Calle, F., de Groot, P., Hemstock, SL., Woods, J (Eds.). *The biomass assessment handbook: bioenergy for a sustainable environment*, Earthscan, London, UK, 2007.
- [16] Liu, R., Yuan, H. Kinetics of low-temperature pyrolysis of walnut shell, *Int. J. of Global Energy Issues*, 2008; 29: 248-261.
- [17] Speight, J. *Synthetic fuels handbook*; McGraw-Hill, New York, NY, USA, 2008.
- [18] Basu, P. *Biomass gasification and pyrolysis: practical design and theory*, Academic Press/Elsevier, New York, 2010.
- [19] Wang, L., Weller, CL., Jones, DD., Hanna, M. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production, *Biomass and Bioenergy*, 2008; 32: 573-581.
- [20] Kaygusuz, K. Biomass as a renewable energy source for sustainable fuels. *Energy Sources, Part A* 2009; 31: 535-545.
- [21] Kaygusuz, K. Bioenergy as a clean and sustainable fuel. *Energy Sources, Part A* 2009; 31: 1069-1080.
- [22] Lee, S., Speight, JG., Loyalka, SK. *Handbook of alternative fuel technologies*, Boca Raton, FL: CRC Press, 2007.
- [23] Kayhainan, M., Tchobanoglous, G., Brown, RC. Biomass conversion process for energy recovery in "Handbook of Energy Efficiency and Renewable Energy" Eds., Kreith and Goswami, CRC Press, Boca Raton, Florida, 2007.
- [24] Hernandez, J. Parallel-current fluidized-bed biomass gasification plant. *Energia*, 2004; 179: 45-48.
- [25] Kirubakaran, V., Nalini, R., Sekar, T., Premalatha, M., Subramanian, P. A review on gasification of biomass. *Renew Sustain Energy Reviews* 2009; 13: 179-186.
- [26] Mohan, D., Pittman, CU., Steele, PH. 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy Fuels*, 20, 848-889.
- [27] Bridgewater, AV. *Biomass pyrolysis technologies, biomass for energy and industry*. Elsevier Applied Science, London, 1990
- [28] Baxter, L., Koppejan, J. Co-combustion of biomass and coal. *Heat Power* 2004; 4: 34-39.
- [29] Bridgewater, AV. *Renewable fuels and chemicals by thermal processing of biomass*. *Chemical Engineering Journal*, 2003; 91: 87-102.
- [30] Devi, L., Ptasinski, K.J., Janssen, FJG. A review of the primary measures for tar elimination in biomass gasification processes. *Biomass Bioenergy* 2003; 24: 125-140.
- [31] IEA, International Energy Agency. *Bioenergy: a sustainable and reliable energy source*. IEA, Paris, 2010.
- [32] Li, J., Xiao, B., Liang, DT., Du, L., Yan, R. Development of Nano-NiO/Al₂O₃ catalyst to be used for tar removal in biomass gasification. *Env Sci Tech* 2008; 42: 6224-29.
- [33] Tang, L., Huang, H. Biomass gasification using capacitively coupled RF plasma technology. *Fuel* 2005; 84: 2055-2063.
- [34] Puig-Arnavat, M., Bruno, JC., Coronas, A. Review and analysis of biomass gasification models. *Renew Sustain Energy reviews* 2010; 14: 2841-2851.
- [35] Zhang, L., Xu, S., Zhao, W., & Liu, S. Copyrolysis of biomass and coal in a free fall reactor, *Fuel*, 2007; 86: 353-359.
- [36] Bao, W., Cao, Q., Lv, Y., & Chang, L. Acetylene from the co-pyrolysis of biomass and waste tires or coal in the H₂/Ar plasma, *Energy Sources Part A* 2008; 30: 734-741.
- [37] Keleş, S., Kaygusuz, K., Akgün, M. Pyrolysis of woody biomass for sustainable bio-oil. *Energy Sources, Part A* 2010; 33: 879-889.