archives
of thermodynamics
Vol. **34**(2013), No. 3, 185–195
DOI: 10.2478/aoter-2013-0024

Carbonization of biomass – an efficient tool to decrease the emission of CO_2

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Abstract The paper presents the results and analysis of biomass processing in order to provide the conditions for the most profitable use of the biomass in modern and efficient power generation systems with particular attention put on the decrease of the emission of carbon dioxide (CO_2) and no need to develop carbon capture and storage plants. The promising concept of CO_2 storage via the production of biochar and the advantages of its application as a promising carbon sink is also presented and the results are supported by authors' own experimental data. The idea enables the production of electricity, as well as (optionally) heat and cold from the thermal treatment of biomass with simultaneous storage of the CO_2 in a stable and environmentally-friendly way. The key part of the process is run in a specially-designed reactor where the biomass is heated up in the absence of oxygen. The evolved volatile matter is used to produce heat/cold and electricity while the remaining solid product (almost completely dry residue) is sequestrated in soil. The results indicate that in order to reduce the emission of CO_2 the biomass should rather be 'cut and char' than just 'cut and burn', particularly that the charred biomass may also become a significant source of nutrients for the plants after sequestration in soil.

Keywords: Biochar; Biocoal; Biocarbon; Biomass; CCS; CO_2 removal

1 Introduction

Despite the fact that in numerous countries the majority of electricity is still produced from fossil resources the renewable fuels are becoming more

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and more popular among the power industry decision-makers. The main reasons are limited fossil fuel resources, as well as the strategies of 'sustainable development' and 'waste minimization' that are promoted throughout the world. Recently many papers have been published on those issues, either dealing with larger implementation of renewable fuels and biomass for power production [1–4,10–12,15–16] or focused on fuel processing and energy recovery [5–6,13–14,17]. However, since those fuels contain quite large amounts of moisture, they are characterized by relatively low energy density, low LHV (low heating value), and often contain significant amounts of pollutants like, e.g., chemically-treated energy crops. Accordingly, the combustion of such fuels often brings about several operational difficulties to the combustion facility (e.g., fouling, corrosion, emission problems, lower efficiency, etc.), and thus their direct application for efficient and clean production of power is quite difficult. The combustion of biomass is welcomed, however, from some other reasons associated with 'zero' emission of CO_2 and the policy of promotion and subsidies for the cogeneration, trigeneration, and – recently – polygeneration technologies, as well as the promotion of dispersed power production facilities where local fuel resources are used.

The biomass for those technologies is usually processed in order to get rid of moisture and increase the process efficiency, and so far, many fuel pretreatment technologies have been investigated, mostly based on gasification, pyrolysis, or hydrothermal treatment as discussed in [2–4,7,13–15,17,27–29] among others. Although well managed in lab scale, those processes are quite expensive and thus still not very much profitable in commercial operation [7]. Therefore, apart from fuel processing in order to produce gas or bio-oils, other researchers have focused their investigations on fuel processing, to obtain solid residue the called 'biochar' or 'biocarbon'. This approach seems to be a more interesting way for inexpensive and efficient production of power from renewable/alternative fuels since it is technically simpler, much cheaper, and can be easily adopted for power production [10–20]. Should it be possible to combine the processing of biomass and the production of power with simultaneous minimization of the emission of carbon dioxide to the atmosphere [20,21], additional significant environmental benefits might also be achieved. An interesting way to reach those goals is based on thermal treatment (thermolysis) of the biomass and the use of fuel volatiles for power production with simultaneous sequestration of the residual biochar in soil [16–17,20,21]. Compared with 'classical' combustion of biomass such approach brings about much more than just a 'zero CO_2

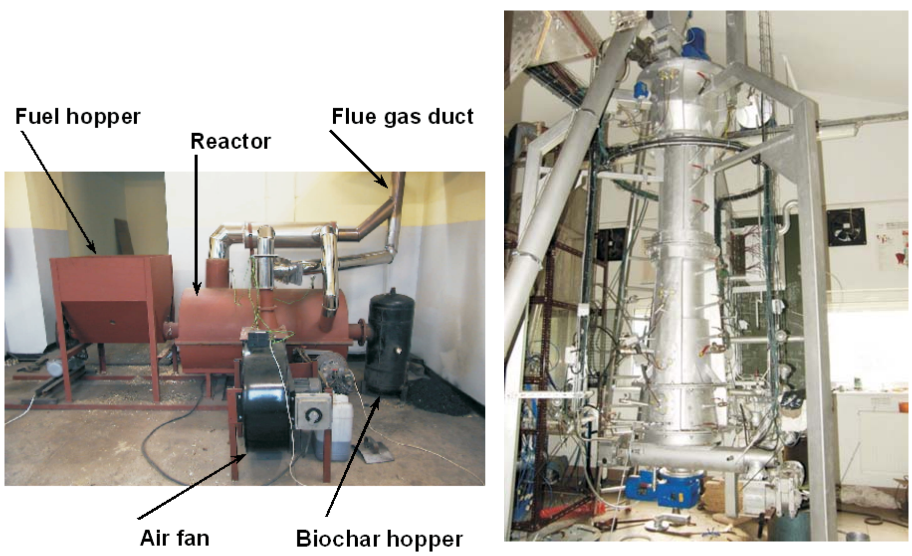
emission' since, in fact, significant decrease of the net emission of CO_2 and other greenhouse gases (like methane, formed during uncontrolled putrefaction and fermentation of waste biomass among others) may be achieved. The technology thus becomes an alternative option for classical CCS (carbon capture and storage) providing the possibility to minimize the concentration of CO_2 in the atmosphere without significant investment costs. An idea for such combination is discussed in the present paper based on some experimental works conducted by the authors. Some brief discussion of the literature data is also given.

2 Carbonization of the biomass

There are numerous technologies focused on efficient processing and carbonization of biomass, the most common ones are based either on gasification [4], or pyrolysis [30,31], or hydrothermal carbonization (HTC) treatment [27–29] and focus mainly on the maximizing of the yield of gas and bio-oils [2–4,8,9,26], or the 'destruction' of problematic biomass [27–29]. Although promising (like gasification and HTC processes), they are unfortunately endothermal and still face operational difficulties associated particularly with the formation of soot and tar in the piping system that bring about the blockage of the installation and the necessity of an emergency shutdown [4,26]. In this paper the carbonization process that can be operated in an autothermal mode is presented and shown as a possible way to minimize the tar and soot-related problems, and enable significant reduction of the atmospheric CO_2 emission. Instead of gas and bio-oils the process is focused on the production of a solid residue (biochar) and autothermal operation of the carbonization reactor can be maintained due to its specific construction design providing the possibility to immediately burn the pyrolytic gases evolved during thermal treatment of the fuel and thus to avoid the formation of any soot and tars, and the occurrence of endothermic reactions. Part of the heat evolved during the combustion of the gases is used to maintain the process, while the remaining enthalpy of the flue gases can be efficiently used in other processes (e.g., for the production of electricity, or heat and/or cold, or the sequestration in soil to avoid its oxidation and thus the associated emission of CO_2 [22].

The technology has been under development by the authors since 2003 and so far various horizontal- and vertical-type reactors have been constructed at the Czestochowa University of Technology. The device shown in Fig. 1a is a simple retort-type reactor allowing to achieve reliable and easy control of the fuel residence time and thus the product yield. The horizontal reactor is, however, characterized by quite low (<50%) degree of filling of the retort by the biomass, and larger reactor geometries are required to achieve higher outputs. In the cases where more compact reactors are required the above disadvantage can be eliminated by the use of the vertical reactor design where the whole retort volume was occupied by the biomass (Fig. 1b). More details of the carbonization technology are given elsewhere [23–25].

During the investigations and experiments conducted by the authors



a) b)

Figure 1. Examples of horizontal (a) and vertical (b) reactors for the thermal treatment of biomass fuels at the Czestochowa University of Technology.

so far, several fuel types have been tested and processed: various biomass types, straw, sewage sludge, municipal waste, agricultural residue, demolition wood, etc. Some examples of chosen parameters of original fuels and the corresponding biochars are shown in Tab. 1. The experiments were carried in the horizontal reactor. The temperature and the fuel residence time during experiments were adjusted to the fuel type and were maintained at roughly 700–900 °C, and 180–600 s, respectively. The yield of the biochar was usually between 20–60 wt% of the initial biomass mass.

Table 1. Some chosen parameters of the biomass and the produced biochars.

Parameter	Moisture [%]	Element C [%]	LHV [MJ/kg]
Biomass A (alder chips)	34.9	33.6	13.2
Biochar from alder chips	0.8	74	27.8
Biomass B (furniture waste)	11.9	34.5	16.4
Biochar from furniture waste	1.4	77	25.9
Biomass C (pine chips)	35	39	10.4
Biochar from pine chips	0.9	71	26.6
Biomass D (RDF&woodchips mixture)	9.2	51.5	18.1
Biochar from RDF&woodchips mixture	0.94	63.8	26.8

The results in Tab. 1 indicate that the biochar is almost completely dry, and its LHV is of similar value to good quality coal. Compared to the mass of the input biomass the mass yields of the biochar in Tab. 1 were 23% for alder chips, 38% for furniture waste, 25% for pine chips, and 26% for the mixture of refuse-derived fuel (RDF) and woodchips. The results are dependent on fuel type; however, they are in satisfactory agreement with the literature data [16,18,21] where the authors reported the biochar yield of roughly 15–60% and the carbon content in the biochar of roughly 20–87%.

Taking into consideration the properties and parameters of the produced biochar it seems that its production may become an interesting option for the sequestration of carbon dioxide. Combination of the biochar production via the technology presented above with simultaneous use of the enthalpy of the flue gases for, e.g., power generation and with the sequestration of the biochar in soil would become an interesting option and a cheap alternative for 'classical' and very expensive CCS technologies that are planned to be implemented soon to European power plants.

Apart from CO_2 removal the sequestration of organic carbon in soil increases also soil physical and chemical fertility, as well as plant productivity [32]. Furthermore, it decreases the emission of greenhouse gases from soil with simultaneous decrease of the carbon footprint of agricultural resources. The proposed approach is also much less harmful to the environment than 'classical' cofiring processes and enables to get rid of much more carbon dioxide per unit of the energy produced. The benefits of such approach are schematically explained in Fig. 2a–c.

The situation shown in Fig. 2a takes place naturally. The carbon is

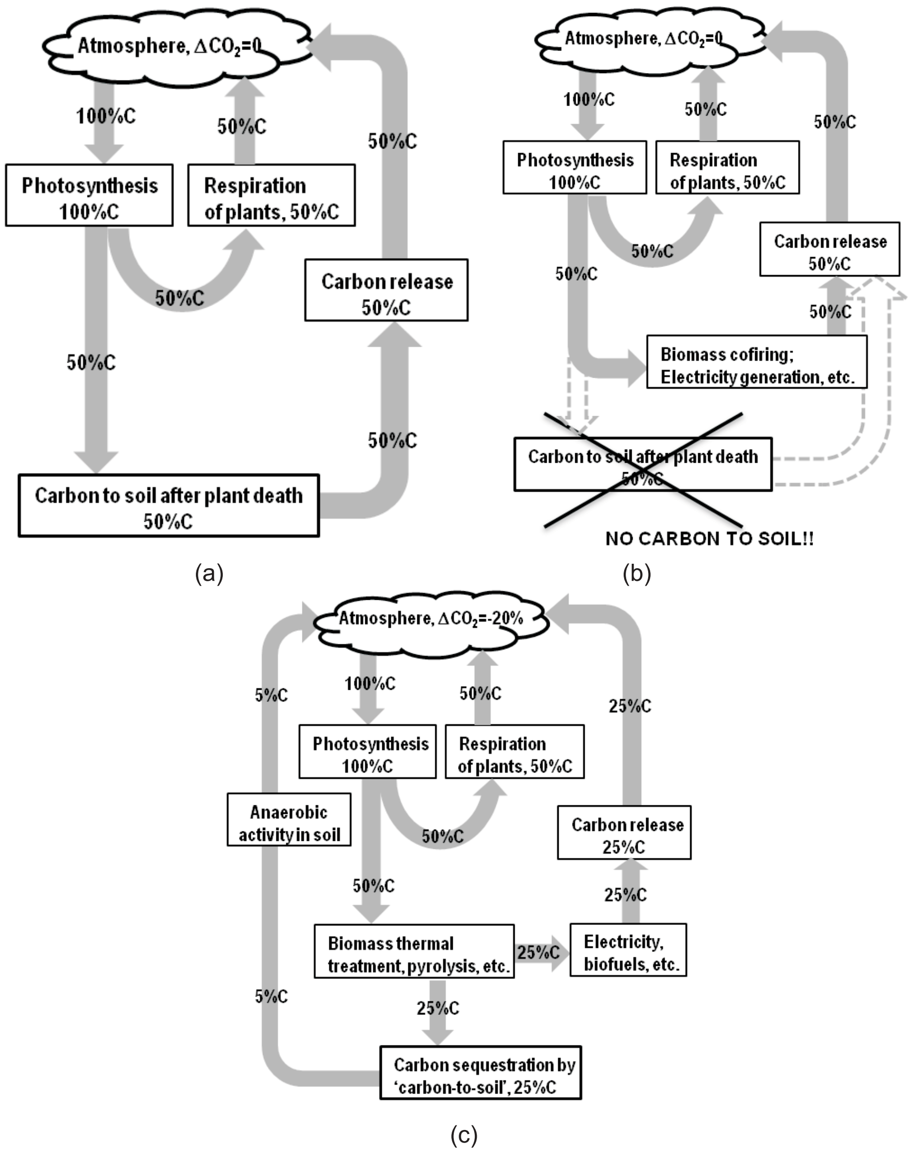


Figure 2. The comparison of carbon flows: natural cycle (a), biomass production and cofiring for power generation (b), biomass thermal treatment and power generation from the combustion of biomass volatiles + carbon (biochar) sequestration in soil (c).

gradually absorbed by the plant from the atmosphere in the form of CO_2. After the plant death the carbon in the plant body is transferred into soil and then slowly returned to the atmosphere, due to, e.g., fermentation processes. Implementation of the biomass combustion (Fig. 2b) looks similar to the case (a); the plant is grown up and then cut and burnt to produce electricity, and by doing this the whole cycle is 'balanced'. However, there is one significant difference between the case shown in Figs. 2a and 2b since the carbon bypasses the soil in the case (b). It is of tremendous importance and significantly affects the whole ecosystem. Numerous data indicate that, e.g., in Poland any soil requires recultivation if the amount of carbon in soil decrease below 26 kg/m2 (for the soil thickness of 0.25 m). Bearing this in mind, simple biomass cofiring cannot be accepted since it eliminates the supply of carbon to soil bringing about slow degradation of the soil.

The solution of the problem is shown in Fig. 2c where the biomass is thermally treated and the evolved volatiles are used to produce electricity while the solid residue (biochar) is fed to soil to maintain the required carbon concentration. By doing this the process becomes similar to the situation shown in Fig. 2a but becomes, in fact, a 'carbon negative' activity since it brings about the decrease of the overall concentration of atmospheric carbon dioxide (more CO_2 is absorbed by plants from the atmosphere during plant life than is returned during the combustion of the plant residue). Since the element C in the biochar is not combusted it is also not emitted to the atmosphere as CO_2. Instead, it is sequestered in a stable form in soil and the process meets the same criteria as 'classical' sequestration (CCS).

Some example calculation of the amount of CO_2 stored in soil in the form of the biochar is shown in Tab. 2. However, compared to 'classical' CCS technologies the process of biomass carbonization and the sequestration of CO_2 in the form of the biochar in soil is much cheaper and simpler and provides the conditions for stable storage of CO_2 without any danger of gas leakage. Furthermore, there occurs no uncontrolled emission of the greenhouse gases that are produced by anaerobic organisms in soil, and, furthermore, the permeability and physical properties of the soil are significantly improved. Some other advantages brought about by the use of the proposed complex biomass processing technology combined with biochar storage in soil are also associated with the increase of soil fertilization (due to the improvement of the potential of cationic exchange brought about by the introduction of the biochar) and thus the increase of nutrients uptake by the plants, as well as the suppression of fertilizer leaching that are generated, e.g., by rainfalls. The addition of porous biochar to soil brings also about an increase of the soil ability to immobilize nutrients at the zones close to plant roots thus reducing the leaching of nitrogen compounds to rivers and water reservoirs (the leaching of nitrogen is a serious problem of intensive cultivation and farming).

The idea proposed and described in the present paper provides excellent conditions for the combination of biomass production with electricity and (optionally) heat/cold generation, and simultaneous removal of CO_2 from the atmosphere. It thus combines the issues of energy conversion from renewable sources, climate change, and sustainable agriculture/farming. The schematic idea is shown in Fig. 3.

Table 2. Estimation of the amount of CO_2 stored in soil in the form of the biochar (calculation conducted from authors' laboratory data, dry).

Biochar type	C [kg/kg]	HHV [MJ/kg]	$CO_2^{avoided}$ [kg/GJ]
Biochar from Salix	0.82	28.0	106.9
Biochar from sawdust	0.89	25.9	125.3
Biochar from waste	0.62	17.5	129.9
Biochar from mixed fuel No.1	0.64	23.4	100.0
Biochar from mixed fuel No.2	0.44	13.8	115.6

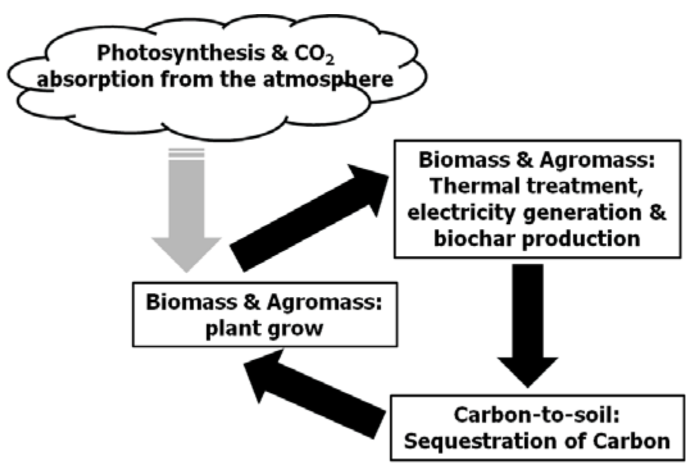


Figure 3. Enhanced biomass-to-energy cycle with biochar sequestration.

3 Summary

1. The proposed new concept of biomass thermal treatment provides interesting opportunity for the production of electricity, as well as heat and/or cold with simultaneous removal of the atmospheric CO_2 and storage of the carbon dioxide in soil in a stable and environmental-friendly way in the form of the biochar.

2. The presented idea seems to be a cheap, simple, and environmentally-friendly alternative for 'classical' CCS technologies, since it not only enables to reduce the emission of CO_2, but also to combine the issues of energy conversion from renewable sources, climate change, and sustainable agriculture (due to the increase of soil fertility brought about by the storage of the biochar in soil).

Received 8 July 2013

References

[1] Baxter L.: *Biomass-coal co-combustion: opportunity for affordable renewable energy.* Fuel **84**(2005), 1295–1302.

[2] McKendry P.: *Energy production from biomass (Part 1): Overview of biomass.* Bioresource Technol. **83**(2002), 37–46.

[3] McKendry P.: *Energy production from biomass (Part 2): Conversion technologies.* Bioresource Technol. **83**(2002), 47–54.

[4] McKendry P.: *Energy production from biomass (Part 3): Gasification technologies.* Bioresource Technol. **83**(2002), 55–63.

[5] Hilber Th., Martensen M., Maier J., Scheffknecht G.: *A method to characterise the volatile release of solid recovered fuels (SRF).* Fuel **86**(2007), 303–308.

[6] Zevenhoven R., Axelsen E.P., Hupa M.: *Pyrolysis of waste-derived fuel mixtures containing PVC.* Fuel **81**(2002), 507–510.

[7] Raveendran K., Ganesh A.: *Heating value of biomass and biomass pyrolysis products.* Fuel **75**(1996), 15, 1715–1720.

[8] Demirbas A.: *Effect of initial moisture content on the yields of oily products from pyrolysis of biomass.* J. Anal. Appl. Pyrol. **71**(2004), 803–815.

[9] Onay O., Mete Kockar O.: *Slow, fast and flash pyrolysis of rapeseed.* Renew. Energy **28**(2003), 2417–2433.

[10] Varhegyi G., Antal M., Jr.: *Charcoal, carbons and charcoal-type fuels from biomass wastes.* Ecol. Chem. Eng. **9**(2002), 1, 21–31.

[11] Prins M., Ptasinski K., Janssen F.: *Torrefaction of wood: Part 1. Weight loss kinetics*. J. Anal. Appl. Pyrol. **77**(2006), 28–34.

[12] Prins M., Ptasinski K., Janssen F.: *Torrefaction of wood: Part 2. Analysis of products*. J. Anal. Appl. Pyrol. **77**(2006), 35–40.

[13] Prins M., Ptasinski K., Janssen F.: *More efficient biomass gasification via torrefaction*. Energy **31**(2006), 3458–3470.

[14] Prins M., Ptasinski K., Janssen F.: *From coal to biomass gasification: Comparison of thermodynamic efficiency*. Energy **32**(2007), 1248–1259.

[15] Yoder J., Galinato S., Granatstein D., Garcia-Perez M.: *Economic tradeoff between biochar and bio-oil production via pyrolysis*. Biomass Bioenergy **35**(2011), 1851–1862.

[16] Lehmann J., Rillig M., Thies J., Masiello C., Hockaday W., Crowley D.: *Biochar effects on soil biota — A review*, Soil Biol. Biochem. **43**(2011), 1812–1836.

[17] Chew J., Doshi V.: *Recent advances in biomass pretreatment — Torrefaction fundamentals and technology*. Renew. Sust. Energy Rev. **15**(2011), 4212–4222.

[18] Neves D., Thunman H., Matos A., Tarelho L., Gomez-Barea A.: *Characterization and prediction of biomass pyrolysis products*. Prog. Energy Comb. Sci. **37**(2011), 611–630.

[19] Mann M., Spath P.: *A life cycle assessment of biomass cofiring in a coal-fired power plant*. Clean Prod. Process. **3**(2001), 81–91.

[20] Bolan N., Kunhikrishnan A., Choppala G., Thangarajan R., Chung J.: *Stabilization of carbon in compost and biochars in relation to carbon sequestration and soil fertility*. Sci. Total Environ. **424**(2012), 264–270.

[21] Sevilla M., Marcia-Agullo J., Fuertes A.: *Hydrothermal carbonization of biomass as a route for the sequestration of CO_2: Chemical and structural properties of the carbonized products*. Biomass Bioenergy **35**(2011), 3152–3159.

[22] Kobyłecki R., Bis Z., Borecki R.: *Poligeneracja dla szklarni*. Rynek Gazu (2012), 151–160 (in Polish).

[23] Kacprzak A., Kobyłecki R., Bis Z.: *Clean energy from a carbon fuel cell*. Arch. Thermodyn. **32**(2011), 3,145–157.

[24] Kobyłecki R., Bis Z.: *Autotermiczna termoliza jako efektywna technologia produkcji czystych i wysokoenergetycznych paliw*. Arch. Spalania **6**(2006), 1-4, 114–119 (in Polish).

[25] Kacprzak A., Kobyłecki R., Bis Z.: *Influence of temperature and composition of NaOH-KOH and NaOH-LiOH electrolytes on the performance of a direct carbon fuel cell*. J. Power Sour. **239**(2013), 409–414, DOI: 10.1016/j.jpowsour.2013.03.159.

[26] Xiu S., Shahbazi A.: *Bio-oil production and upgrading research: A review*. Renew. Sust. Energy Rev. **16** (2012), 4406–4414.

[27] Delrue F., Li-Beisson Y., Setier P.-A., Sahut C., Roubaud A., Froment A.-K., Peltier G.: *Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria*. Bioresource Technol. **136** (2013), 205–212.

[28] Parshetti G., Kent Hoekman G., Balasubramanian R.: *Chemical, structural and combustion characteristics of carbonaceous products obtained by hydrothermal carbonization of palm empty fruit bunches*. Bioresource Technol. **135** (2013), 683–689.

[29] Kruse A., FunkeA., Titirici M.-M.: *Hydrothermal conversion of biomass to fuels and energetic materials*. Curr. Opin. Chem. Biol. **17**(2013), 515–521.

[30] Akhtar J., Amin N.: *A review on operating parameters for optimum liquid oil yield in biomass pyrolysis*. Renew. Sust. Energy Rev. **16**(2012), 5101–5109.

[31] Goyal H.B., Seal D., Saxena R.C.: *Bio-fuels from thermochemical conversion of renewable resources: A review*. Renew. Sust. Energy Revi. **12** (2008), 504–517.

[32] Lehmann J., Joseph S. (Eds.): *Biochar for Environmental Management*. Earthscan, 2009.