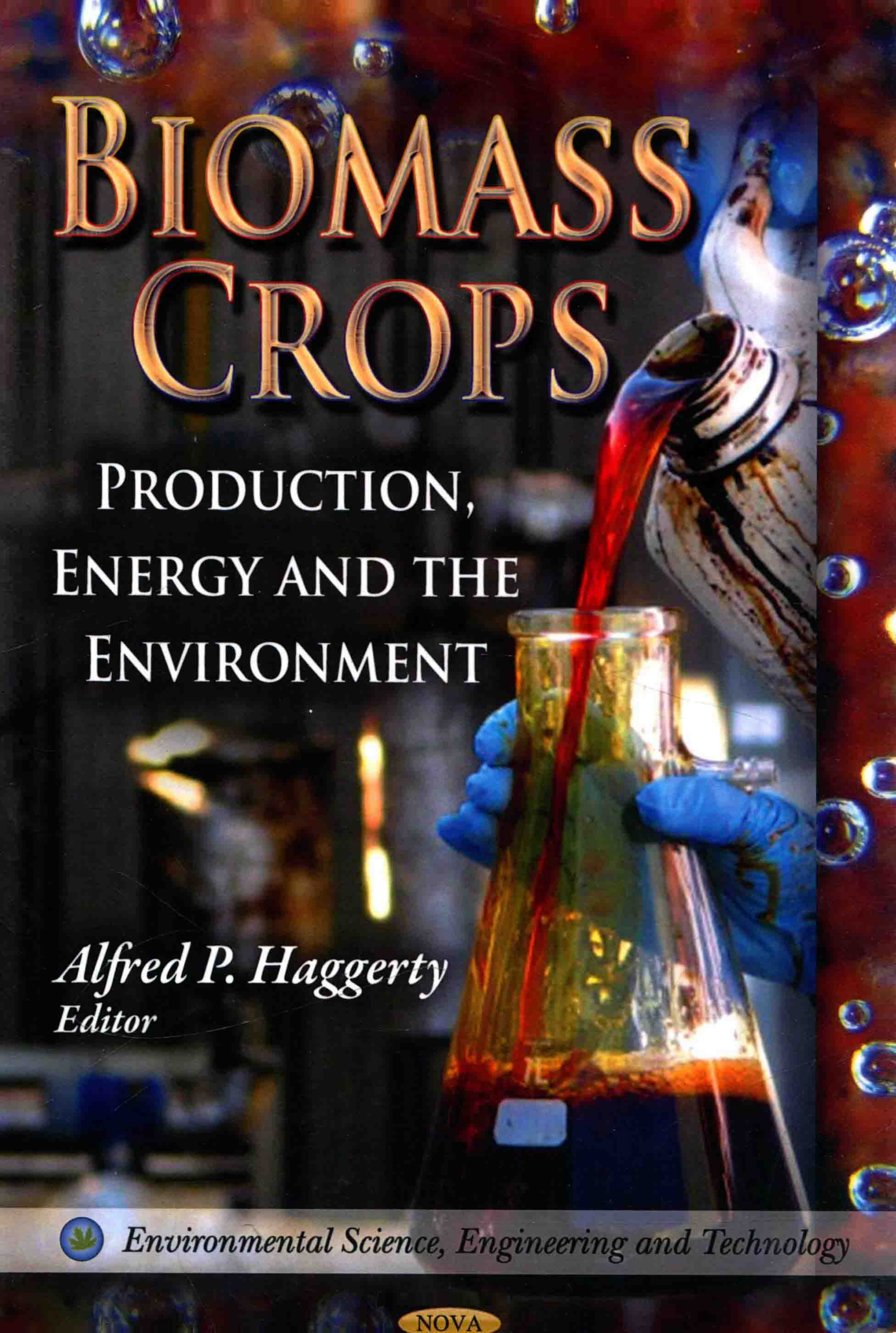

Biomass Crops

Production, Energy and the Environment

Alfred P. Haggerty
Editor

Environmental Science, Engineering and Technology

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ENVIRONMENTAL SCIENCE, ENGINEERING AND TECHNOLOGY

BIOMASS CROPS: PRODUCTION, ENERGY AND THE ENVIRONMENT

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PREFACE

In the energy industry, biomass refers to biological material which can be used as fuel or for industrial production. Biomass includes plant matter grown for use as biofuel, as well as plant or animal matter used for production of fibres, chemicals or heat. This new book presents current research in the study of biomass crops, including the conversion of wood into liquid fuels; alfalfa biomass production; gasification of biomass in aqueous media and biofuel production potential.

Chapter 1 - Statistics show that energy consumption has increased exponentially since the Industrial Revolution. Around 495 EJ of primary energy were consumed in the world in 2008, of which over 81% were met by combustion of fossil fuels (IEA, 2009). Considering a global population of 6.8 billion, this represents on average the equivalent of approximately 2 tons of petroleum per person and year. Projections for the coming decades reveal an average annual growth above 2.0%, owing primarily to an increase in world population and the rapid development of emerging economies like China, India and Brazil (IEA, 2009). At this rate, global energy demand is expected to double and global electricity demand will triple between 2008 and 2050 (EIA, 2010).

Chapter 2 - The looming energy challenges around the world will have to be tackled with a portfolio of different raw materials and technologies. Biomass is a widely available renewable carbon source and includes organic wastes and energy crops, which can be used for the production of biofuels to contribute to the reinvigoration of the biomass industry, among others. Energy crops have to be produced in a cheap and environmentally benign way in order to be utilized for the sustainable production of biofuels. Energy crops include mainly three categories, namely oil-rich crops, sugar crops, which contain sugars directly available for biofuel production, and lignocellulosic crops, which contain tightly bound cellulose, hemicellulose and lignin.

In this Chapter focus is given on fermentative biofuel production from sugar-rich and lignocellulosic biomass. Ethanol production from energy crops has been studied in the literature since the 1980s, but in the last decade significant research efforts have been addressed towards biological hydrogen production. Therefore, ethanol and hydrogen are considered two representative options for short- and long-term biofuel production, respectively. In particular, biofuel production from lignocellulosic crops or agricultural residues is more intensively discussed, given the higher degree of complexity of the utilization of these raw materials for biofuel production. Various pretreatment methods can be applied to enhance the accessibility of lignocellulosic carbohydrates for enzymatic hydrolysis and the production of fermentable substrates. The efficiency of ethanol/hydrogen production from these substrates is dependent on their quality, which largely depends, in turn, on the amount of degradation products which act as inhibitors in the fermentations. Therefore, significant discussion is dedicated to the key aspects of the role of pretreatment of biomass on the efficiency of biofuel production.

The development of dedicated pretreatment techniques which are tuned to special characteristics of different energy crops is discussed. Sweet sorghum and sugar beet are regarded as two energy crops that can be instrumental in the promising field of biofuels. Sweet sorghum is interesting because it constitutes a highly productive sugar crop which, after sucrose extraction, provides a yet not well studied lignocellulosic residue, sweet sorghum bagasse. Sweet sorghum bagasse is currently unexploited, poses a disposal problem and its usage as fodder for animals is not a sufficiently viable solution. Similarly, sugar beet constitutes a traditional sugar crop, which can provide the biofuel industry with innovative raw materials with no competition with food production. From the viewpoint of sustainability, it is necessary to simultaneously assess the impact of the aforementioned biomass and biofuels on the environment and the economic growth. In principle, the use of organic wastes can be a win-win solution; however, biomass crops can present peculiar advantages for their potential in protecting/reclaiming vulnerable and marginal soils, sequestering CO_2, bio-depurating wastewater and enhancing biodiversity and wildlife.

Chapter 3 - Increasing atmospheric CO_2 results in enhanced photosynthesis in C_3 plants like alfalfa. However, after long-term exposure, the photosynthetic rate decreases. This phenomenon, often described as down-regulation, is explained by most authors as the consequence of the disappearance of strong plant sinks leading to leaf carbohydrate accumulation and thus resulting in a photosynthetic decrease. The initial photosynthesis response to elevated CO_2 induces plant growth and enhanced yield production. After long term CO_2 exposure, when photosynthesis is acclimated, increased plant biomass is also shown due to the initial enhancement of plant dry matter. Management of alfalfa as a forage crop entails periodic cutting of shoots. In this situation, photosynthetic down-regulation is avoided and the alfalfa taproot is the main source organ that provides C and N compounds to new growing shoots. This source and sink organ role inversion allows us to study alfalfa biomass production before and one month after cutting (regrowth). Alfalfa is used as a forage crop for animal feeding as a source of protein and amino acids; therefore not only is the quantity of crop production important but also the biochemical composition of shoots is a key factor. During the present study, elevated CO_2 reduced leaf protein concentration probably due to the dilution effect derived from starch accumulation in these conditions. Forage plants may also be the primary source of antioxidants. Elevated CO_2 altered reactive oxygen species (ROS) production in leaves, reducing their production, and resulted in the relaxation of the antioxidant system, which may induce changes in the antioxidant value of forage biomass.

Chapter 4 - Phytochemical induction of monoterpenes following herbivory by insects and mechanical damage, was studied in *Minthostachys mollis* (Lamiaceae), a plant native to Central Argentina with medicinal and aromatic uses in the region. The monoterpenes pulegone and menthone were analyzed in *M. mollis* 24 and 48 h after leaves were mechanically damaged or exposed to insects with different feeding habits (chewing, scraping, sap-sucking, and puncturing). Essential oil composition and emission of volatiles were assessed. Mechanical damage resulted in an increase of pulegone and menthone concentration in *M. mollis* essential oil during the first 24h. Menthone content generally decreased whereas pulegone concentration increased in all treatments where insects were involved. The changes observed after insect feeding occurred also in the adjacent undamaged leaves, but induced changes after mechanical wounding were restricted to the damaged site, suggesting that an elicitor related to the insects may be required for a systemic response to be induced.

Changes in the volatiles released from *M. mollis* damaged leaves were also detected, most noticeably showing an increase in the emission of pulegone. Inducible chemical changes in aromatic plants might be common and widespread, affecting the specific compounds on which commercial exploitation is based.

Chapter 5 - The lignocellulosic biomass materials are abundant, cheap and renewable feedstocks suitable for biofuel and biochemical production. They can be derived from forestry wastes such as residues of the trees and shrubs, energy crops like maize, sorghum, miscanthus, kenaf, switchgrass, jatropha, corn, sugarcane and any agricultural residues such as corn stovers, wheat straw etc. The use of biofuels derived from lignocellulosic biomass does not cause additional increase in the carbon dioxide level in the earth's atmosphere. The release of carbon dioxide during biofuel utilization is balanced by the carbon dioxide consumed in biomass growth.

In many cases, because of large water content and high drying cost, biomass is not a suitable feedstock for conventional thermochemical gasification technologies. Thermochemical gasification techniques such as biomass gasification and pyrolysis are energy intensive processes and produce relatively high amounts of char and tar with low conversion of biomass into gas. Among other various conversion methods, hydrothermal gasification, using super- or sub-critical water as the reaction medium, is seen as a promising way to produce hydrogen from biomass with high efficiency. These processes can be applied to the conversion of biomass with high moisture content without drying. While processes applied in sub- and super-critical water around 250-400°C, methane and carbondioxide are the major products in addition to the target gas hydrogen but the formation of these major side products can be minimized by using appropriate catalysts and adjusting processing temperature and pressure conditions.

Aqueous phase reforming (APR) process is a rather new evolving technology involving decomposition of the oxygenated hydrocarbons to produce hydrogen-rich gas. The main advantage of APR is its relatively low gasification temperature where CO concentration within the hydrogen stream is rather low. The process produces high yield of hydrogen gas with low CO byproduct due to the water-gas shift reaction ($CO + H_2O \leftrightarrow H_2 + CO_2$) which is effective at the processing temperature. APR of carbohydrates take place at considerably lower temperatures compared to conventional alkane steam reforming process. A lower temperature reduces unwanted decomposition reactions that normally observed when carbohydrates are heated to elevated temperatures. Carbohydrates such as sugars (e.g., glucose) and polyols (e.g., ethylene glycol, glycerol) can be efficiently converted in the aqueous phase over appropriate heterogeneous catalysts at relatively mild processing conditions to produce hydrogen rich gas mixture. Lignocellulosic materials containing high level of polysaccharides are potential biomass sources for the APR gasification provided that, by using ecological pre-treatment techniques, the water-insoluble polysaccharides are hydrolyzed into relatively smaller carbohydrates which are soluble in water. This chapter will focus on APR and summarize the relevant research and development activities including the authors' work on conversion of lignocellulosics.

Chapter 6 - The biofuels are ecologically acceptable energy sources resulting in reduction in release of large quantities of CO_2 and other harmful greenhouse gases into the atmosphere causing global warming and climate change. Biofuels like biodiesel and bioethanol are the most important transportation fuels either used alone or as an additive to fossil fuels. The production technologies such as transesterification and fermentation are used for biodiesel and bioethanol respectively. The biofuel strategy should focus on use of biomass for blending ethanol with gasoline and non-edible oilseeds for production of biodiesel for blending with petro-diesel. Besides providing relief against local air pollution and global environmental change problems such diversification could also be useful in managing interruptions of fossil fuel supply, volatility of its prices and thus ensuring sustainable economic development.

Chapter 7 - There are many farmlands that have been contaminated with heavy metal (HM) in central Taiwan resulted from the irrigation using river water contaminated with HMs. According to the Soil and Groundwater Pollution Remediation Act (SGWPR Act) of Taiwan, these lands cannot plant edible crops until suitable techniques are conducted to decrease the total concentration of HM in soils to conform to the Soil Control Standard (SCS). However, some of the foliar crops still accumulated a high concentration of HM in the edible parts; even the concentration of HM of the remediated sites is below the SCS. Planting suitable crop species is especially important in this situation and these contaminated sites after remediation can be reused. Soybean, a biomass crop further used to produce biodiesel, seems feasible to plant in the farmlands in this situation. This manuscript reports previous results that used pot experiments to investigate the accumulation of HM by various parts of soybean planted in the artificially cadmium- (Cd-), copper- (Cu-), or zinc (Zn-) contaminated soils with different concentrations. The aim is to assess the feasibility of planting soybean in the HM-contaminated soils to produce biodiesel.

Chapter 8 - Declining soil fertility is a critical agricultural challenge facing smallholders in central Kenya. A study to improve soil fertility and farm productivity in the area was carried out during the period 2003 to 2007. Problem-solving tools were used to build the broad conceptual and methodological approaches needed to address farming constraints. The study identified farming systems constraints and disseminated "best-bet" integrated soil fertility management (ISFM) interventions using participatory methods and mutual collaborative action. This paper describes processes in the participatory approaches, project milestones and joint experiences that were gained. The participatory approaches included Participatory Rural Appraisal (PRA), Mother-baby approach (M-B approach), Farmer training groups (FTGs), Annual stakeholder planning meetings, Village training workshops, Cross-site visits and Participatory Monitoring and Evaluation (PM & E). Food shortage was the main problem identified by farmers resulting from low crop yields. The causes of poor yields were biophysical factors, but several socio-economic factors influenced farmer ability to manipulate farm productivity. Village training workshops attracted a 20% higher farmer turnout than mother trial field days. Farmer and experimental evaluations showed that the most favoured technologies were tithonia, manure, manure-fertilizer combinations, and tree legumes while the most effective dissemination pathways included demonstrations, farmer training grounds, field days and farmers' groups. Using PM& E procedures, farmers developed indicators that they used to monitor progress, and annual ISFM milestones were achieved, leading to the achievement of overall project objectives. Innovative adjustments to ISFM technology dissemination were proposed by both farmers and scientists.

CONTENTS

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Chapter 1

CONVERSION OF WOOD INTO LIQUID FUELS: A REVIEW OF THE SCIENCE AND TECHNOLOGY BEHIND THE FAST PYROLYSIS OF BIOMASS

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1. INTRODUCTION TO BIOMASS ENERGY

1.1. The Current Energy System

Statistics show that energy consumption has increased exponentially since the Industrial Revolution. Around 495 EJ of primary energy were consumed in the world in 2008, of which over 81% were met by combustion of fossil fuels (IEA, 2009). Considering a global population of 6.8 billion, this represents on average the equivalent of approximately 2 tons of petroleum per person and year. Projections for the coming decades reveal an average annual growth above 2.0%, owing primarily to an increase in world population and the rapid development of emerging economies like China, India and Brazil (IEA, 2009). At this rate, global energy demand is expected to double and global electricity demand will triple between 2008 and 2050 (EIA, 2010).

It becomes evident that this trend is unsustainable. From an environmental perspective, the massive combustion of fossil fuels has been held responsible for irreversible changes to the global climate, with profound consequences to the planet and our way of life (IPCC, 2007). With regard to the economy, the imbalance between increasing demand and the ongoing depletion of finite natural resources will push the price of fossil fuels up in the medium term. Unless the use of alternative energy sources is sufficiently widespread, this scenario will lead to international conflicts and severe contraction of the global economy with detrimental consequences to the standard of living of most people. The solution to this situation rests on two pillars: on the one hand, a reduction in the overall consumption of primary energy that should be achieved through implementation of energy efficiency measures and technologies. On the other, the promotion of locally available and less carbon intensive alternative energy sources that should progressively replace fossil fuels (Stern, 2006; IPCC, 2007; Demirbas et al., 2009).

At present, renewable sources collectively supply 14.0% of all the primary energy consumed in the world. The largest contribution comes from biomass, accounting for almost 10% of the global energy supply. Most of this bioenergy (87%) is obtained by direct combustion of wood for heat generation in domestic, agricultural, farming or small scale production activities. Biomass energy prevails, primarily in less industrialized economies owing to its use in domestic activities and also in environmentally conscious countries with abundant natural resources like Scandinavian countries and Brazil (IEA Bioenergy, 2002 and 2010).

Owing to the environmental and strategic benefits associated with the use of renewable energy sources, most governments have drafted programs with ambitious objectives intended to facilitate a smooth transition into this new energy model. A clear example is the "Energy-Climate Legislative Package" approved in 2009 by the Council of the European Union. This document requires Member States to meet the following targets by 2020: reduce greenhouse gas emissions by 20% of 1990 levels; increase the contribution of renewable energy sources to 20% of the total; and reduce primary energy consumption by 20% through implementation of improved efficiency technologies and strategies. The European Directive 2009/28/EC on the promotion of renewable energy has recently established additional objectives, including a 10% share of renewable energy in the transport sector by 2020.

Biomass will certainly have a significant role to play in the development of this sustainable energy model. Biomass contains chemical energy that has been captured from the sun radiation through photosynthesis. As illustrated in Figure 1, this energy can be made available by the application of different technologies, which are usually classified in two categories: biological such as anaerobic digestion and fermentation; and thermochemical like combustion, gasification and pyrolysis. This paper deals with advanced thermochemical routes and their potential in the efficient transformation of biomass feedstocks into valuable energy and chemical products.

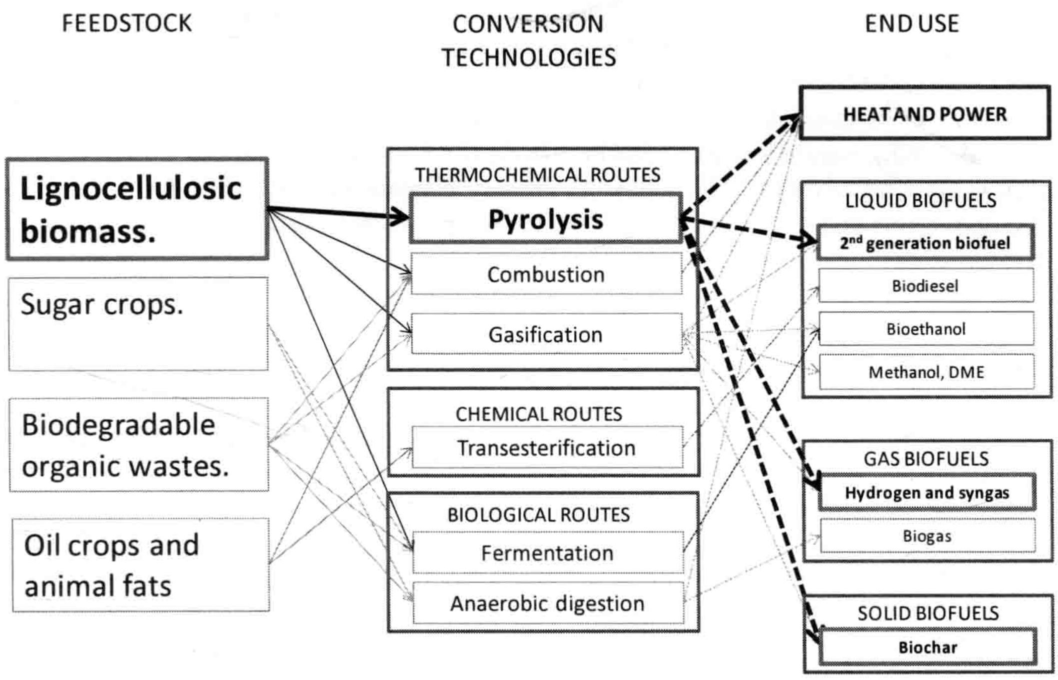

Figure 1. Alternative biological and thermochemical routes for the energy valorization of biomass.

1.2. Conventional Thermochemical Technologies: Biomass Combustion

Combustion of wood for heat generation is a well established technology, commonly associated with agricultural and industrial activities that produce biomass as a by-product (such as wood processing, paper making, forest management and food production and processing like olive oil, cereals and nuts). Around 83% of the solid biomass consumed in Europe is dedicated to heat production and only 17% to power generation. However, the latter is expanding rapidly, primarily in Northern Europe, North America and Brazil owing to favorable policies and abundant resources (IEA Bioenergy, 2002; Van Loo and Koppejan, 2008; Eurobserver, 2010).

Due to the low energy density and high transportation costs of biomass fuel, dedicated biomass power plants are usually smaller (5-25 MWe) than those using conventional fossil fuels, resulting in lower energy conversion efficiencies (typically between 20-25% depending on plant size and technology) and higher investment costs (2000-4000€/kW). Biomass combustion plants also require expensive maintenance programs due to corrosion, fouling and slagging caused by inorganic elements present in the biomass fuel (Cl, K, Na, Ca, Mg) (Jenkins et al., 1998; Demirbas, 2005). Economic risks are also higher than in conventional power plants owing to seasonal and yearly variability in the production and quality of the biomass feedstocks, their scattered geographical distribution and high transportation costs (Caputo et al., 2005).

As a result, the production of electricity from biomass remains expensive in most cases and highly dependent on public subsidies (Badcock and Lenzen, 2010; San Miguel et al., 2010). Electricity costs have been calculated to range between US$20/MWh for the co-firing of a locally available charge-free biomass feedstock to a more realistic $30-$50/MWh for medium size (10-25 MWe) dedicated power plants using conventional biomass at a standard cost of US$3-US$3.5/GJ (Caputo et al., 2005). This compares unfavorably with electricity generation costs calculated for more conventional energy sources like hydroelectric power (15 US$/MWh), natural gas in a combined cycle (25 US$/MWh), coal (26 US$/MWh) and nuclear (16 US$/MWh) (CNE, 2008). At present, biomass only accounts for 1.3% of the electricity generated in the world, 3.7% in the European Union and 3.4% in the USA (IEA Bioenergy, 2010; EIA, 2009).

1.3. Advanced Thermochemical Technologies: Gasification and Pyrolysis

The increase of scale in the consumption of biomass fuels expected in the following years will definitely require the development of innovative technologies capable of providing greater energy efficiency, improved cost effectiveness and a higher overall environmental performance. Gasification and pyrolysis are two thermochemical technologies that have the potential to contribute in this direction and play a key role in the expansion of bioenergy. As shown in Table 1, the former involves the transformation of a carbonaceous feedstock into a gas, usually called syngas or producer gas, by exposure to high temperatures (850-1000°C) under mildly oxidizing conditions (usually substoichiometric oxygen or/and steam). Gasification was developed in the early 19th century for the transformation of mineral coal into town gas that was used for lighting and domestic energy applications. It was subsequently adapted for the treatment of organic wastes, petroleum fractions and biomass. Syngas can be used with higher energy efficiency than the original feedstock in burners, engines and turbines for the generation of heat and electricity. After necessary processing and upgrading, syngas may also be used as a chemical feedstock for the synthesis of ammonia, methanol, synthetic liquid fuels or purified hydrogen.

Biomass gasification has already passed the demonstration stage and can be regarded as a young commercial technology, with plants of varying scale operating around the world. However, it is also true that the penetration of this technology in the energy market is still limited due to technical problems associated with the formation of tars and the fuel quality of the resulting gases (Knoef, 2005; Badeau et al., 2009).

Pyrolysis is another thermochemical technology capable of transforming lignocellulosic biomass into high value products. The term *pyrolysis* is very self explanatory in its root, deriving from the Ancient Greek words *pyro* (πρ) meaning heat and lysis (λύσις) meaning rupture. Pyrolysis is mainly associated with thermal decomposition of organic compounds, as they are heated in the absence of oxygen or any other reactive element. The pyrolysis of lignocellulosic biomass gives rise to its transformation into a non-condensable gas, condensable oil and a solid char, which can be used for their energy content or as a chemical feedstock. As will be explained throughout this paper, this technology is highly versatile, with product yields and characteristics highly dependent not only on biomass feedstock but also processing conditions. As shown in Table 1, pyrolysis processes are usually classified in two categories depending on the target product: solid charcoal in slow pyrolysis and liquid oils in fast pyrolysis.

Table 1. Typical product yields, reaction conditions and enthalpy in the pyrolysis of biomass, compared against combustion and gasification technologies

Process		Product yields (wt%)			Conditions	Enthalpy
		Liquid	Char	Gas		
Pyrolysis	Slow	15-25	30-40	30-40	Low temperature (300-600°C). Long vapor residence time (> 1 min) Inert atmosphere	Endothermic/ Exothermic
	Fast	60-75	10-15	15-30	Moderate temperature (450-500°C). Short vapor residence time (< 2 sec) Inert atmosphere	Slightly endothermic
Gasification		0-5	5-10	85-95	Very high temperature (850-1000°C). Mildly oxidizing conditions	Endothermic
Combustion		0	0-5	95-100	High temperatures (700-850°C). Highly oxidizing conditions.	Highly exothermic

Slow pyrolysis or carbonization is a traditional technology that has been used for centuries in rural societies for the production of charcoal (Lehmann and Joseph, 2009). Charcoal is more stable and has a higher energy density that the original biomass, which allows for storage for longer periods of time and produces higher temperatures upon combustion. Slow pyrolysis involves heating the wood slowly to temperatures around 300-600°C in the absence of oxygen over long periods of time. The process results in the thermal decomposition of the feedstock into a volatile fraction and a solid char. The resulting vapors are allowed very long residence times inside the reaction chamber in order to maximize recombination and polymerization reactions, leading to the formation of the solid char (30-40 wt%). The anoxic conditions were traditionally achieved by covering the piles of wood with turf or moistened clay. At present, the process is conducted in kilns and retorts which achieve higher carbon efficiencies and reduce processing times. The vapors generated in slow pyrolysis processes are usually condensed in order to reduce emissions into the atmosphere. This condensate, called pyroligneous oil, amounts to 15-25 wt% of the original biomass feedstock and consists of a mixture of water, methanol, acetic acid, phenols and other insoluble organic tars (Strezov et al., 2007; Lehmann and Joseph, 2009).

Fast pyrolysis is based on the same principles as carbonization, but relies on the careful control of the process conditions in order to maximize the formation of condensable compounds at the expense of other gas or solid fractions. In short, the production of high oil yields requires very rapid thermal degradation of the biomass feedstock followed by very rapid removal of the volatile products in order to minimize secondary reactions. This objective is achieved using reactors that allow efficient heat transfer into the biomass particle, small particle size of the feedstock, fine control of the reaction temperature (usually between 450°C and 500°C) and reduced residence time of the pyrolysis vapors in the reaction chamber (usually below 2 seconds). Oil yields up to 85 wt% have been reported in the literature, although typical values in optimized plants usually range between 60-75 wt%.

Bio-oils produced through fast pyrolysis have significantly higher energy density (around 19-22 GJ/m^3, compared to 4-5 GJ/m^3 in the original biomass and 38-40 GJ/m^3 of petroleum derived fuels) and more homogeneous characteristics than the original material. Therefore, they can be handled, stored, transported and processed more effectively than the original biomass feedstock. Pyrolysis oil is intended to serve as a secondary energy carrier for subsequent conversion into heat, electricity, chemicals or transport fuels.

The vision expressed in numerous communications describes an energy system in which bio-oil is produced in distributed pyrolysis units close to the sources of generation and then transported to centralized plants for energy generation or to bio-refineries for subsequent processing into advanced fuels and high-value chemicals (Bridgwater et al., 1999; Czernik and Bridgwater, 2004; Mohan et al., 2006; Demirbas and Balat, 2006; Babu, 2008; Badger and Fransham, 2006; Venderbosch and Prins, 2010). This model benefits from the improved economy of scale of large energy generation and processing plants. Unlike first generation bio-fuels (bio-ethanol and biodiesel), which only make use of a small fraction of the biomass (sugars and fats, respectively), fast pyrolysis processes make use of all the organic matter present in the biomass feedstock. This results in higher overall energy efficiencies and greater greenhouse gas abatement potential.

The basis of modern, fast pyrolysis was established in the early 1980´s with pioneering work conducted at the University of Waterloo (Canada). This was followed by numerous research institutions and companies that contributed in different areas like fast pyrolysis process design, characterization of pyrolysis oils and development of energy applications. The most renowned of these research groups include Aston University (United Kingdom), VTT Technical Research Centre (Finland), the University of Western Ontario (Canada), the National Renewable Energy Laboratory (USA) and the University of Twente (Netherlands), while the most active private companies in this field include Biomass Technology Group (BTG, The Netherlands), Envergent Technologies (USA), Dynamotive Energy Systems (Canada) and Ensyn Technologies (Canada). Interest in this technology is evidenced by the large number of technical documents published in the last two decades including numerous scientific reviews (Graham et al., 1984; Elliot et al., 1991; Maschio et al., 1992; Freel et al., 1993; Scott et al., 1999; Bridgwater, 1999; Bridgwater et al., 1999; Meier and Faix, 1999; Oasmaa and Czernik, 1999; Bridgwater and Peacocke, 2000; Bridgwater, 2003; Czernik and Bridgwater, 2004; Yaman, 2004; Mohan et al., 2006; Demirbas and Balat, 2006; Zhang et al., 2007; Babu, 2008; Goyal et al., 2008; Qiang et al., 2009; Zhang et al., 2010; Venderbosch and Prins, 2010), manuals (Bridgwater et al., 1999; Bridgwater 2002 and 2005) and compilations (Bridgwater, 2001, 2003, 2008 and 2009; Bridgwater and Boocock, 2006). The intense activity in this field of international scientific networks and organizations like ThermalNet (www.thermalnet.co.uk), PyNe (http://www.pyne.co.uk) and IEA Bioenergy (www.ieabioenergy.com) is also noteworthy.

Despite the considerable scientific and technical progress achieved in the last few decades, fast pyrolysis of biomass is not a complete reality yet. The production of bio-oil is not particularly expensive but there is limited acceptance of this novel fuel in the energy and chemical markets. Existing plants operate intermittently, usually in association with research