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Biomass Pyrolysis Processes: Review of Scope, Control and Variability

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Review of Scope, Control and Variability

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Abstract

This review focuses on biomass pyrolysis processes for use in biochar systems. Objectives are to describe the scope, range of control and degree of variability of such processes.

Slow, intermediate and fast pyrolysis processes are reviewed. Product yield distributions change depending on feedstock composition and preparation, control of temperature and material flows. These allow some control over distribution of main products – char, liquids and gases. Typical mass yield ranges for slow pyrolysis are char 25-35%, liquid 20-50%, gas 20-50%; for intermediate pyrolysis, char 30-40%, liquid 35-45%, gas 20-30%; and for fast pyrolysis, char 10-25%, liquid 50-70%, gas 10-30%. Variability associated with char yield is estimated at ±5% (relative). Char yield should be considered an underlying, but minor source of variability in pyrolysis biochar systems.

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1. Introduction

Pyrolysis biochar systems offer one of the few available options for carbon-negative technology in the short term. Pyrolysis converts organic matter into a carbon-rich solid, char, and volatile products by heating in the absence of oxygen. Char from biomass, biochar, when produced and incorporated into soils under certain conditions may provide a stable storage for carbon over a long time scale. Through pyrolysis biochar systems carbon dioxide may be removed from the atmosphere, assimilated firstly by plant growth then stored as a stable form of carbon in the soil rather than returning to the atmosphere through decomposition. In addition, the volatile products of pyrolysis, bio-oil and syngas, are considered as carbon-neutral, renewable fuels and can be used to offset fossil fuel consumption in electricity generation or other fuel uses thereby avoiding carbon dioxide emissions.

Estimates of the potential for carbon sequestration using biochar are limited but suggest that the total global scale could be large, possibly on the gigatonne scale, with one suggesting sequestration potential could exceed existing emissions from fossil fuels (Lehmann et al, 2006). Such global estimates are necessarily based on numerous assumptions and are open to criticism. It has been suggested that the efficiency of biochar systems will be strongly dependent on case-specific factors and that it is difficult to assess the overall potential without much further study (Fowles, 2007).

In two recent publications aiming to quantify potential benefits of specific biochar systems (Gaunt and Lehmann, 2008; McCarl et al, 2009) it is notable that the performance parameters of the pyrolysis processes themselves were not considered as variables for sensitivity analysis and essentially single sets of data for the pyrolysis processes have been used. This is a surprising limitation as the pyrolysis process performance is likely to be one of the key factors affecting the efficiency of a pyrolysis biochar system.

Following a general introduction to the main processes for biomass pyrolysis, the present review describes the breadth of scope of these processes in terms of the range of control of process parameters and how this affects outputs. The degree of unintentional process variability that may occur, and its significance, is also considered.

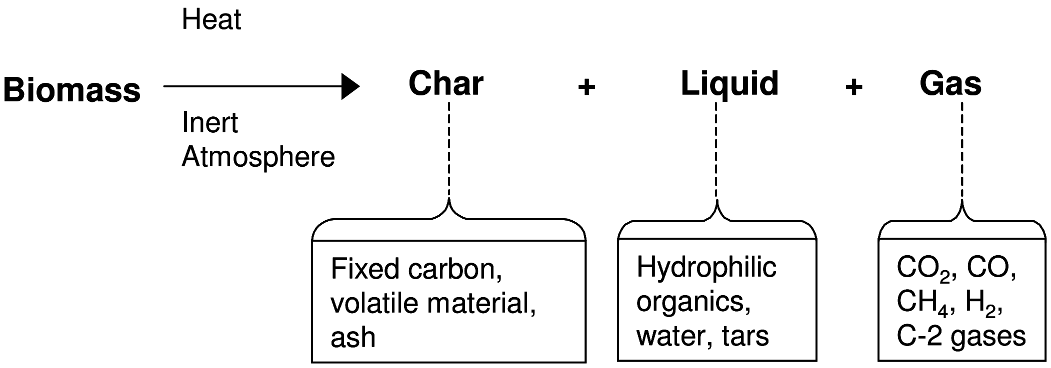
This review is based on work carried out for a MSc dissertation project (Brownsort, 2009) that also considered the influence of process parameters on benefits arising from biochar systems using a model study to compare examples of the main pyrolysis methods. This second aspect of the work will be published separately.

2. Biomass Pyrolysis Processes

2.1. Introduction

2.1.1. Definition

Pyrolysis is a thermo-chemical decomposition process in which organic material is converted into a carbon-rich solid and volatile matter by heating in the absence of oxygen (Demirbas and Arin, 2002). The solid, termed variously as char, biochar, charcoal or coke, is generally of high carbon content and may contain around half the total carbon of the original organic matter. The volatiles can be partly condensed to give a liquid fraction leaving a mixture of so-called 'non-condensable' gases. The process is represented simply in Equation 1. Each of the three product streams from pyrolysis, solid, liquid and gas, can have properties and uses that provide value from the process.



Equation 1. Simple Representation of Pyrolysis Process

2.1.2. Product Terminology

In this review the term char will be used generally to describe the solid product of pyrolysis, charcoal will be used for more traditional processes with wood as feedstock, biochar will be used where the intention is for the char to be used as a soil amendment. The term coke will not be used here being more generally used for coal-derived char. Char contains a varying carbon content, typically ranging 60-90% (Gaur and Reed, 1995). Some is 'fixed-carbon' in terms of its proximate analysis, some present in a remaining volatile portion; inorganic material in char is termed ash.

Liquid products from biomass pyrolysis are frequently termed bio-oil. However, this is a somewhat confusing term as the organic liquid product is generally hydrophilic containing many oxygenated compounds and is present, sometimes as a single aqueous phase, sometimes phase-separated, together with water produced in the pyrolysis reaction or remaining from the feedstock (Demirbas and Arin, 2002). In this report this is generally referred to simply as the liquid product and includes the water unless otherwise stated.

The gas product is termed synthesis gas, shortened to syngas. It is generally composed of carbon dioxide, carbon monoxide, methane, hydrogen and two-carbon hydrocarbons in varying proportions. In this report it is often referred to simply as the gas product.

2.1.3. Historical Context

Mankind has used pyrolysis and related processes for thousands of years. The earliest known example is the use of charcoal, produced as an unintentional residue from cooking fires, for cave drawings by Cro-Magnon man some 38,000 years ago (Antal and Grønli, 2003). In the Bronze Age intentionally produced charcoal was used for smelting metals and charcoal is still heavily used in metallurgy today. For thousands of years charcoal has been a preferred cooking fuel. Prior to the development of petrochemicals, pyrolysis, or 'wood distillation', was a source of many valuable organic compounds for industrial and medicinal uses; some high value liquid products, such as flavourings, are still produced by wood pyrolysis (Bridgwater and Peacocke, 2000). Pyrolysis and gasification processes have been used to extract liquid and gas products from coal since Victorian times and the technology for producing a synthetic crude oil from coal is well established. It is only more recently that biomass and organic wastes have become a focus as feeds for pyrolysis and related thermal treatment processes for energy recovery or bio-fuel production; the technologies are still relatively undeveloped (Mistry et al, 2008).

Char has also been used in agriculture for thousands of years. The fertile *terra preta* (dark earth) soils of the Amazonian region result from incorporation of char into otherwise poor soils. The resulting soils have long-lasting fertility that has been related to the stability of carbon in the soil (Lehmann et al, 2009). It is this observation coupled with the search for carbon sequestration techniques for climate change mitigation that has led to recent interest in pyrolysis-derived char, or biochar.

2.2. Pyrolysis Process Types

There are two main classes of process for biomass pyrolysis, introduced briefly below, plus a number of other related technologies. These sections are intended to give an overview of the technologies only; references to detailed published reviews are given.

2.2.1. Fast Pyrolysis

Fast pyrolysis is characterised by high heating rates and short vapour residence times. This generally requires a feedstock prepared as small particle sizes and a design that removes the vapours quickly from the presence of the hot solids. There are a number of different reactor configurations that can achieve this including ablative systems, fluidised beds, stirred or moving beds and vacuum pyrolysis systems. A moderate (in pyrolysis terms) temperature of around 500℃ is usually used. Development of fast pyrolysis progressed rapidly following the oil crises of the 1970's as a way of producing liquid fuel from an indigenous renewable resource, primarily wood, and the process is designed to give a high yield of bio-oil. There are several well-established commercial processes such as Ensyn Corporation's Rapid Thermal Process (Ensyn, 2009) or Dynamotive's Biotherm process (Dynamotive, 2009). The area has been extensively reviewed by Bridgwater (e.g. Bridgwater et al, 1999; Bridgwater and Peacocke, 2000).

2.2.2. Slow Pyrolysis

Slow pyrolysis can be divided into traditional charcoal making and more modern processes. It is characterised by slower heating rates, relatively long solid and vapour residence times and usually a lower temperature than fast pyrolysis, typically 400℃. The target product is often the char, but this will always be accompanied by liquid and gas products although these are not always recovered.

Traditional processes, using pits, mounds or kilns, generally involve some direct combustion of the biomass, usually wood, as heat source in the kiln. Liquid and gas products are often not collected but escape as smoke with consequent environmental issues. Developments through the late 19th and early 20th centuries led to industrial scale processes using large retorts operated in batch (e.g. Riechert process, VMR ovens) or continuous modes (e.g. Lambiotte process). These allow recovery of organic liquid products and recirculation of gases to provide process heat, either internally or externally (Antal and Grønli, 2003). Prior to the widespread availability of petrochemicals, such processes were used to generate important organic liquid products, in particular acetic acid and methanol. An excellent review of the science behind charcoal making is given by Antal and Grønli (2003).

Other developments in the later 20th century led to slow pyrolysis technologies of most interest for biochar production. These are generally based on a horizontal tubular kiln where the biomass is moved at a controlled rate through the kiln; these include agitated drum kilns, rotary kilns and screw pyrolysers (Brown, 2009). In several cases these have been adapted for biomass pyrolysis from original uses such as the coking of coal with production of 'towns gas' or the extraction of hydrocarbons from oil shale (e.g. Lurgi twin-screw pyrolyser, Henrich, 2007). Although some of these technologies have well-established commercial applications, there is as yet little commercial use with biomass in biochar production. Examples in this context include BEST Energies' process using an agitated drum kiln (BEST Energies, 2009; Downie et al, 2007) and Pro-Natura's Pyro-6 and Pyro-7 technology (Pro-Natura, 2008). No comprehensive review of modern slow pyrolysis techniques is available, however, Brown (2009) summarises them briefly together with other potential techniques for biochar production.

2.2.3. Other Technologies

This section covers a brief review of technologies other than slow and fast pyrolysis that may be used for thermal treatment of biomass and char production. Other than the first mentioned, they are not considered further in this report.

The term 'intermediate pyrolysis' has been used to describe biomass pyrolysis in a certain type of commercial screw-pyrolyser – the Haloclean reactor (Hornung et al, 2004; Hornung et al, 2006). This reactor was designed for waste disposal of electrical and electronic component residues by pyrolysis. When used for biomass it has performance similar to slow pyrolysis techniques, although somewhat quicker. Other than this application the term intermediate pyrolysis has been used occasionally but not consistently in the literature.

Very fast pyrolysis is sometimes referred to as 'flash pyrolysis' (Demirbas and Arin, 2002), usually in the context of laboratory studies involving rapid movement of substrate through a heated tube under gravity or in a gas flow. Higher temperatures and shorter residence times than fast pyrolysis are used, the main product distributions are similar to fast pyrolysis.

Flash carbonisation is a different process involving partial combustion of a packed bed of biomass in a pressurised reactor with a controlled air supply. A high yield of char and gas are reported with no liquid product formed under the reaction conditions (Antal et al, 2003). The technology is currently being commercialised by Carbon Diversion Incorporated (CDI, 2009).

Gasification is an alternative thermo-chemical conversion technology suitable for treatment of biomass or other organic matter including municipal solid wastes or hydrocarbons such as coal. It involves partial combustion of biomass in a gas flow containing a controlled level of oxygen at relatively high temperatures (500-800°C) yielding a main product of combustible syngas with some char. Although designed to produce gas, under some conditions gasifiers can produce reasonable yields of char and have been proposed as an alternative production route to pyrolysis for biochar (Brown, 2009).

Hydrothermal carbonisation is a completely different process involving the conversion of carbohydrate components of biomass (from cellulose) into carbon-rich solids in water at elevated temperature and pressure (Titirici et al, 2007). Under acidic conditions with catalysis by iron salts the reaction temperature may be as low as 200°. The process may be suitable for concentration of carbon from wet waste streams that would otherwise require drying before pyrolysis, making it complementary to pyrolysis and a potential alternative to anaerobic digestion for treatment of some wastes.

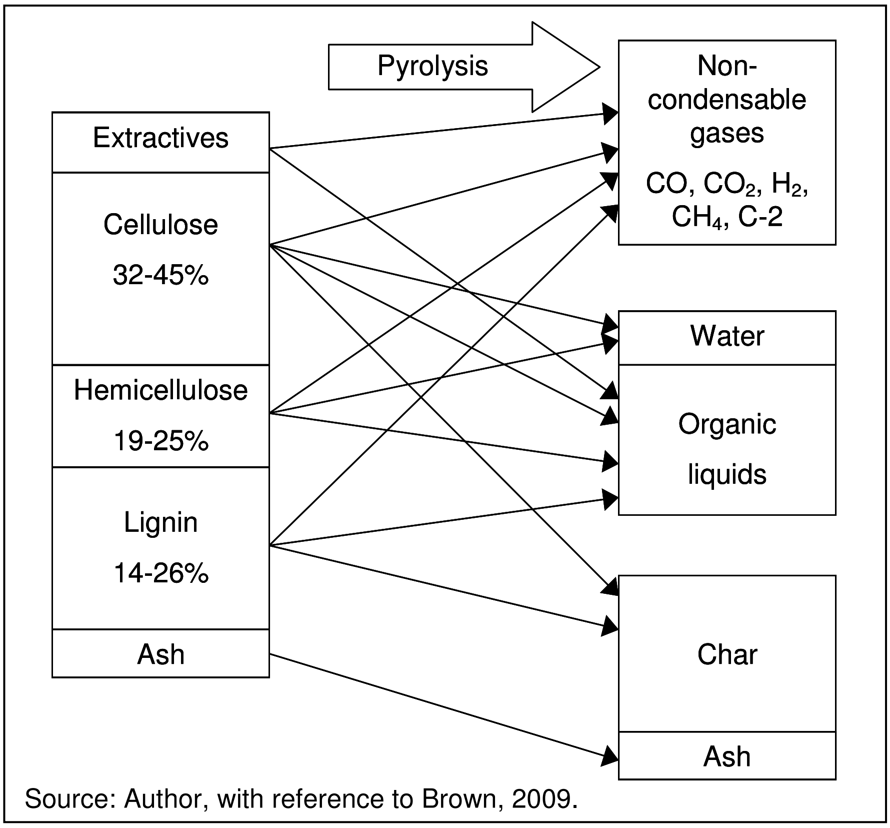
2.3. Effects of Feedstock and Main Process Parameters

This section describes the effect of the main controllable factors affecting the distribution of products from pyrolysis processes. The effect of feedstock composition and preparation is discussed first followed by the effects of process operating conditions. Slow, intermediate and fast pyrolysis are all affected in a related manner but the importance of factors and the effect of changes on product yield distribution differs between process types.

2.3.1. Feedstock Composition

Biomass is generally composed of three main groups of natural polymeric materials: cellulose, hemicellulose and lignin. Other typical components are grouped as ‘extractives’ (generally smaller organic molecules or polymers) and minerals (inorganic compounds). These are present in differing proportions in different biomass types and these proportions influence the product distributions on pyrolysis (Antal and Grønli, 2003; Brown, 2009; Mohan et al, 2006).

On heating to pyrolysis temperatures the main components contribute to product yields broadly as follows (Antal and Grønli, 2003). Primary products of hemicellulose and cellulose decomposition are condensable vapours (hence liquid products) and gas. Lignin decomposes to liquid, gas and solid char products. Extractives contribute to liquid and gas products either through simple volatilisation or decomposition. Minerals in general remain in the char where they are termed ash. This distribution of components into products is shown schematically in Figure 1.



Source: Author, with reference to Brown, 2009.

Figure 1. Simplified Representation of Biomass Pyrolysis

Vapours formed by primary decomposition of biomass components can be involved in secondary reactions in the gas phase, forming soot, or at hot surfaces, especially hot char surfaces where a secondary char is formed (Antal and Grønli, 2003). This is particularly important in understanding the differences between slow and fast pyrolysis and the factors affecting char yields and is discussed further in Section 2.3.4 below.

Minerals in biomass, particularly the alkali metals, can have a catalytic effect on pyrolysis reactions leading to increased char yields in some circumstances, in addition to the effect of ash contributing directly to char yield. Minerals also affect the reactivity and ignition properties of chars (Antal and Grønli, 2003).

2.3.2. Feedstock Preparation

Moisture content can have different effects on pyrolysis product yields depending on the conditions (Antal and Grønli, 2003). In traditional charcoal kilns heated internally by wood combustion, high moisture levels lead to reduced charcoal yields as a greater quantity of wood must be burnt to dry and heat the feed. For externally heated equipment the reported effect of steam on the yield of char varies depending on the conditions. Increased moisture present when pyrolysis reactions are performed under pressure has been shown to systematically increase char yields (Antal and Grønli, 2003).

Fast pyrolysis processes in general require a fairly dry feed, around 10% moisture (Bridgwater and Peacocke, 2000), so that the rate of temperature rise is not restricted by evaporation of water. Slow pyrolysis processes are more tolerant of moisture, the main issue being the effect on process energy requirement. For charcoal making, wood moisture contents of 15-20% are typical (Antal and Grønli, 2003). In all pyrolysis processes water is also a product and is usually collected together with other condensable vapours in the liquid product. Moisture in the reaction affects char properties and this has been used to produce activated carbons through pyrolysis of biomass (Zanzi et al, 2001).

Feed particle size can significantly affect the balance between char and liquid yields. Larger particle sizes tend to give more char by restricting the rate of disengagement of primary vapour products from the hot char particles, so increasing the scope for secondary char-forming reactions (discussed further in Section 2.3.4) (Antal and Grønli, 2003). Hence larger particles are beneficial in processes targeting char production and small particles are preferred to maximise liquid yields in fast pyrolysis.

2.3.3. Temperature Profile Control

The temperature profile is the most important aspect of operational control for pyrolysis processes. Material flow rates, both solid and gas phase, together with the reactor temperature control the key parameters of heating rate, peak temperature, residence time of solids and contact time between solid and gas phases. These factors affect the product distribution and the product properties.

For fast pyrolysis a rapid heating rate and a rapid rate for cooling primary vapours are required to minimise the extent of secondary reactions. These reactions not only reduce the liquid yield but also tend to reduce its quality, giving a more complex mixture, an increased degree of polymerisation and higher viscosity (Bridgwater and Peacocke, 2000). Conversely, in slow pyrolysis there is some evidence that slow heating leads to higher char yields, but this is not consistent (Antal and Grønli, 2003).

Peak temperature, however, has an unequivocal effect on char yields and properties. Higher temperatures lead to lower char yield in all pyrolysis reactions. This results from the main controlling variable of pyrolysis reaction kinetics being temperature (Antal and Grønli, 2003).

The effect can be thought of as more volatile material being forced out of the char at higher temperatures reducing yield but increasing the proportion of carbon in the char. Temperature also has an effect on char composition, chars produced at higher temperatures having higher carbon contents both total- and fixed-carbon (Antal and Grønli, 2003). This may have important implications for biochar stability in soils. Solid residence time is also important but to a lesser degree than peak temperature, longer time at temperature leading to lower char yield (Antal and Grønli, 2003).

The effect of temperature on liquid and gas yields is more complex. Liquid yields are higher with increased pyrolysis temperatures up to a maximum value, usually at 400-550°C but dependent on equipment and other conditions. Above this temperature secondary reactions causing vapour decomposition become more dominant and the condensed liquid yields are reduced. Gas yields are generally low with irregular dependency on temperature below the peak temperature for liquid yield; above this gas yields are increased strongly by higher temperatures, as the main products of vapour decomposition are gases. For fast pyrolysis the peak liquid yields are generally obtained at a temperature of around 500°C (Bridgwater et al, 1999). Peak liquid yields for slow pyrolysis are more variable. Demirbas (2001) reports peak liquid yields of 28-41% at temperatures between 377°C and 577°C, depending on feedstock, when using a laboratory slow pyrolysis technique. The Haloclean process yields a peak of 42-45% liquid at temperatures of 385-400° with different straw feeds (Hornung et al, 2006).

The effects of peak pyrolysis temperature are shown for fast and intermediate pyrolysis examples in Figure 2; the trends for typical slow pyrolysis processes are similar to intermediate pyrolysis.

2.3.4. Gas Environment

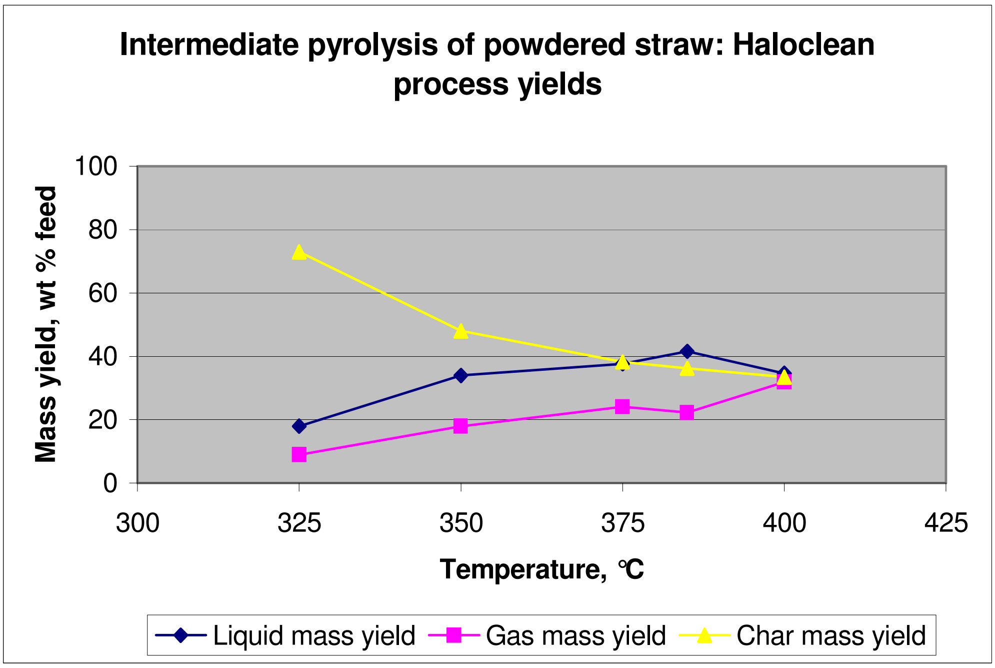
Conditions in the gas phase during pyrolysis have a profound influence on product distributions and on the thermodynamics of the reaction. Most of the effects can be understood by considering the secondary char-forming reactions between primary vapour products and hot-char. The area is discussed in detail and rationalised by Antal and Grønli (2003) in the context of charcoal making; the main points are summarised here.

Gas flow rate through the reactor affects the contact time between primary vapours and hot char and so affects the degree of secondary char formation. Low flows favour char yield and are preferred for slow pyrolysis; high gas flows are used in fast pyrolysis, effectively stripping off the vapours as soon as they are formed.

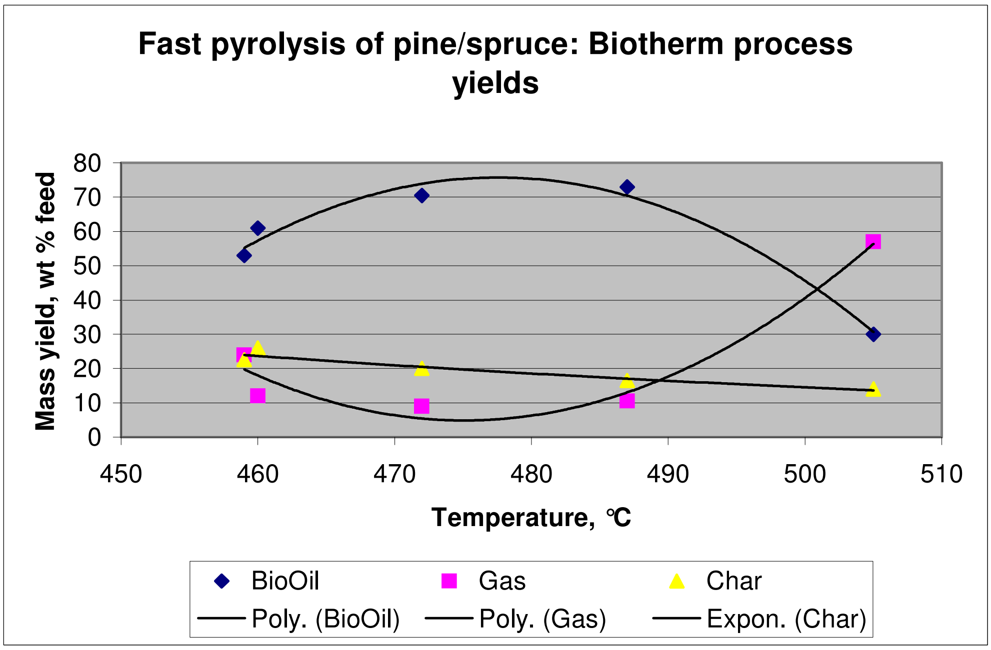
Pressure has a similar effect. Higher pressure increases the activity of vapours within and at the surfaces of char particles so increasing secondary char formation. The effect is most marked at pressures up to 0.5MPa. Conversely, pyrolysis under vacuum gives little char, favouring liquid products. For pyrolysis under pressure, moisture in the vapour phase can systematically increase the yield of char, believed to be due to an autocatalytic effect of water, reducing the activation energy for pyrolysis reactions.

The thermodynamics of pyrolysis are also influenced by gas environment. The reaction is more exothermic at higher pressures and low flow rates. This is rationalised as being due to the greater degree of secondary char-forming reaction occurring. Hence, higher char yields are associated with conditions where pyrolysis is exothermic; such conditions will favour the overall energy balance of processes targeting char as product.

In summary, any factor of pyrolysis conditions that increases the contact between primary vapours and hot char, including high pressure, low gas flow, large particles or slow heating is likely to favour char formation at the expense of liquid yield. Antal and Grønli (2003) provide data from their own work indicating that chars formed under low flow, high pressure conditions with consequent higher char yields also have higher fixed-carbon yields. This effect may be useful in maximising the carbon sequestration potential in biochars although there may be other changes in the char properties that are not immediately evident.



Source: Hornung, 2008.



Source: Dynamotive, 1999

Figure 2. Product Yield Trends with Pyrolysis Temperature

2.4. Carbon and Energy Flows on Pyrolysis

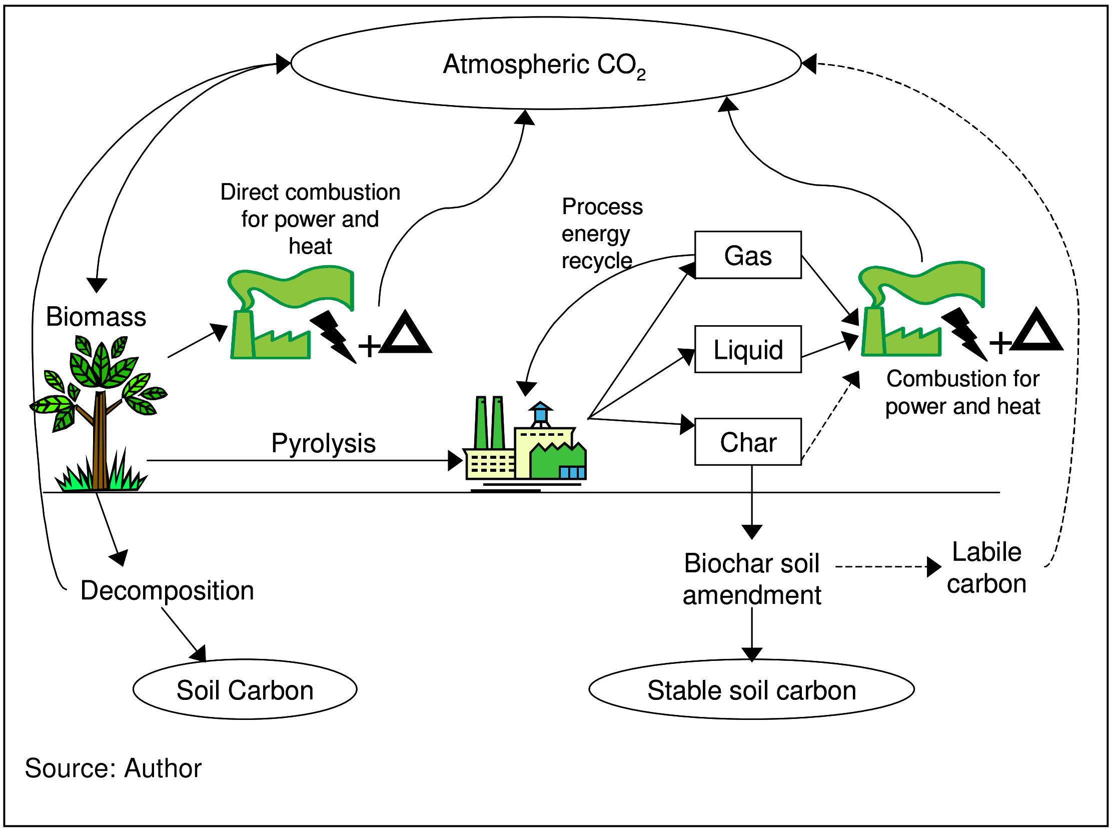
To determine how pyrolysis processes and biochar systems may benefit climate change, through their effect on emissions of greenhouse gases, an understanding of carbon and energy flows is required. This section gives a qualitative description of the main flows and considerations. A simple scheme showing the main carbon flows associated with biomass pyrolysis is given in Figure 3.

Carbon is drawn from the atmosphere as carbon dioxide by growing plants through photosynthesis and assimilated into biomass. Under natural processes of death and decomposition the carbon is released as carbon dioxide back to the atmosphere in a fairly short timescale. Biomass has an energy value roughly related to its carbon content (together with contributions from other elements and factors). This energy can be released through combustion and used for purposes such as electricity generation or heating. The carbon is thermo-chemically oxidised to carbon dioxide and returns to the atmosphere. In this manner the energy available from biomass is considered renewable and carbon neutral. If the usable energy so produced substitutes energy that would otherwise be obtained by burning fossil fuels, then the carbon dioxide emission associated with the fossil fuel combustion is avoided.

If biomass is pyrolysed, the carbon and the energy value are split between the three product streams: char, liquid and gas. The total mass of the products will be equal to the mass of the starting material, if properly accounted, and the total carbon content of the products will also equal that of the biomass. However, some energy is inevitably lost as heat from the process meaning the total energy value in the products is less than the starting material. Some energy is also required to run the pyrolysis process: to dry the feed, to heat to temperature, to drive equipment. In theory, all this can be supplied by recycle from the products, once the process has been started-up, with the effect that the product quantities available for use downstream of the pyrolysis process are reduced.

As with the biomass feed, the char and liquid products have energy values roughly related to their carbon contents. Release of this energy by combustion can again be considered as renewable and is largely carbon neutral (some emissions are associated with feedstock production and transport); the carbon returned to the atmosphere as carbon dioxide is the same as would otherwise have resulted from biomass decomposition. If the char product is not burnt, but retained in a way that the carbon in it is stable, then that carbon can be equated to carbon dioxide removed from the atmosphere and sequestered.

The gas product is typically a mixture of carbon dioxide (9-55% by volume), carbon monoxide (16-51%), hydrogen (2-43%), methane (4-11%) and small amounts of higher hydrocarbons (composition ranges from references cited in Appendix 2). The gases are usually present with nitrogen or other non-oxidising gas introduced to inert the pyrolysis equipment, this can be treated as a diluent and ignored for material balancing but will affect the heating value of the syngas. The carbon dioxide and nitrogen provide no energy value in combustion, the other gases are flammable and provide energy value in proportion to their individual properties. Again use of the energy in the gas can be considered as renewable and largely carbon neutral. No special consideration of the carbon dioxide in the pyrolysis gas is required as it is not additional to what would result from biomass decomposition.



Source: Author

Figure 3. Scheme Showing Main Carbon Flows Associated with Biomass Pyrolysis

As with biomass, any usable energy from combustion of the three pyrolysis products that substitutes for fossil fuel use is considered to avoid carbon dioxide emissions.

To summarise, from the point of view of carbon accounting and the effect on carbon dioxide in the atmosphere, carbon flows involved in biomass growth, decomposition and combustion, including the combustion of biomass pyrolysis products, can be considered as carbon neutral, having no effect on atmospheric carbon dioxide. Energy from biomass or its pyrolysis products used to substitute energy from fossil fuels leads to avoidance of carbon dioxide emissions compared to a reference case of fossil fuels use. Carbon stored in char is equated to carbon dioxide removed from the atmosphere. The sum of these last two effects gives the net effect on atmospheric carbon dioxide of biomass pyrolysis processes. There are clearly important considerations omitted from this simplification, a key one being the stability of carbon in char when used as biochar in soil amendment.

3. Biomass Pyrolysis: Review of Process Scope

3.1. Review Methodology

The aim of this study is to understand the scope of biomass pyrolysis processes appropriate for biochar production in terms of their range of feedstock, process and equipment type, operating conditions, product yields and energy values. A review of literature in the field was carried out covering charcoal making, laboratory-scale slow pyrolysis and a small number of reports on pilot or commercial scale 'modern' slow pyrolysis. Fast pyrolysis was covered to a limited extent focusing on pilot or commercial scale and laboratory-scale reports with good yield data. The review covered some sixty items and may be considered indicative but not comprehensive, there is much more published work on laboratory-scale processes and fast pyrolysis in particular. Summary information extracted from the review is given in Appendix 1 and discussed below.

3.2. Observations

There are a number of general observations that can be made on the literature reviewed.

Of the published work on slow pyrolysis most is focused on traditional charcoal making or is based on laboratory-scale studies, there is very little on the recent area of interest in producing biochar with co-products used for energy. The focus on charcoal means there is little available yield data for the liquid and gas co-products and even less where the energy values of the co-products are given. For fast pyrolysis processes, with their focus on conversion to energy products and greater degree of development, data coverage is better, but there are still very few reports giving sufficient data to construct complete energy and carbon balances over the process. Although many reports give a range of yields for varying conditions or feeds, few give data that shows reproducibility of results, a point that is taken up in Section 4.

3.3. Pyrolysis Process Scope

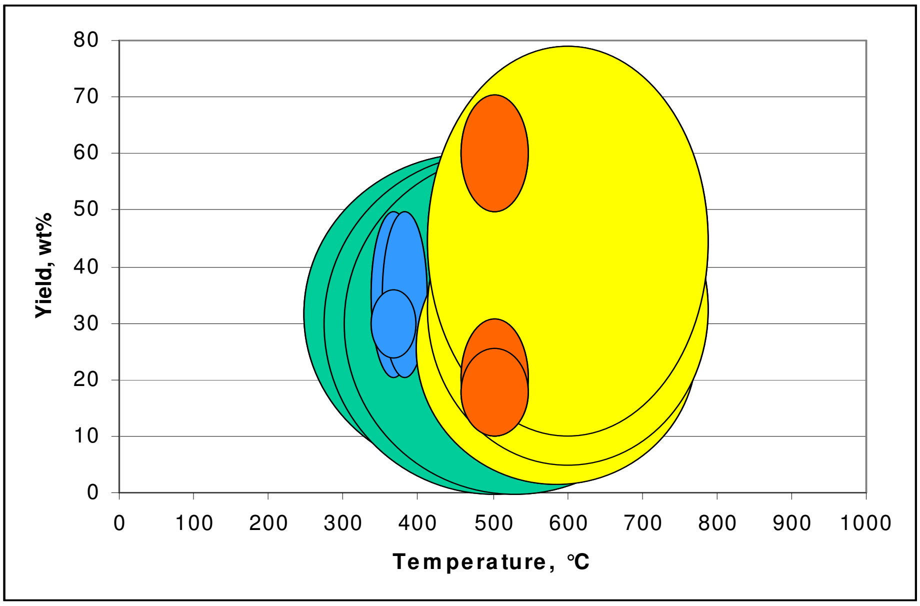
The total scope of pyrolysis processes reviewed, in terms of feedstock, operating conditions and product yields, is very wide. Pyrolysis of scores of different feedstocks has been reported, temperature and residence times varying over a wide range have been used and consequently yields of each of the three products also vary over wide ranges. Yield distributions are specific to individual sets of feed and process variables. However, typical ranges may be suggested from the review. Table 1 summarises the wider and typical ranges for key variables and product yields. Figure 4 attempts to give an idea of the process envelope in terms of temperature and product yields. It should be noted that the yields are interdependent and will always total 100% if fully accounted.

Although it is useful to summarise typical ranges of product yields for the main pyrolysis processes there will be many exceptions to these ranges. If comparing different processes or basing conclusions on a process output it is important that the key variables and the feedstock are defined, otherwise it is not possible to know whether conclusions are specific to that example or more generally applicable.

Table 1. Scope of Pyrolysis Process Control and Yield Ranges

		Slow Pyrolysis	Intermediate Pyrolysis	Fast Pyrolysis
Feed		Scores of feeds reported		
Temperature, °C	Range	250 - 750	320 - 500	400 - 750
	Typical	350 - 400	350 - 450	450 - 550
Time	Range	mins - days	1 - 15 mins	ms - s
	Typical	2 - 30 mins	4 mins	1 - 5 s
Yields, % wt on dry				
Char	Range	2 - 60	19 - 73	0 - 50
	Typical	25 - 35	30 - 40	10 - 25
Liquid	Range	0 - 60	18 - 60	10 - 80
	Typical	20 - 50	35 - 45	50 - 70
Gas	Range	0 - 60	9 - 32	5 - 60
	Typical	20 - 50	20 - 30	10 - 30

Source: References for literature review, see Appendix 1



Notes: The three large green ellipses indicate the total scope of operating range reported, in terms of temperature and yields, for the three products of slow pyrolysis, char, liquid and gas. The smaller blue ellipses show the typical ranges for slow pyrolysis, the smallest indicating char yield range for typical temperatures.
Yellow and orange ellipses give the same indications for fast pyrolysis; the higher yield ranges are for liquids.
Intermediate pyrolysis is not shown. Source: Author.

Figure 4. Pictorial Representation of Pyrolysis Process Scope

3.4. Example Pyrolysis Data

From the first level literature review of pyrolysis processes, reports on processes involving specific feedstocks were selected and more detailed information extracted. The feeds were selected as those most likely to be available for biochar production in the UK in collaboration with a project team studying the potential for biochar pyrolysis systems (Sohi et al, 2009, unpublished work). Selected feeds were spruce wood, miscanthus, wheat straw, willow, and chicken litter. Full extracted information is included in Appendix 2; a summary of the key data available is given in Table 2.

The data in Table 2 allow a very limited comparison of the effect of different process types on product distributions from the same feedstock, but the consistency of the process examples is poor making paired comparisons difficult. The broad differences and trade-off expected between yields of slow and fast pyrolysis for char and liquid products are evident, although they are confounded by high gas yields in some cases. One exception is the fast pyrolysis of chicken litter where the char yields are high and equal to or greater than the liquid yields; this is explained by very high ash contents in the feed (*ca.*20%) and char (*ca.*40-60%wt) (Kim et al, 2009). The data exemplifies the wide range of yields discussed in the previous section, for instance char yields from slow pyrolysis ranging 12 to 61%. There is very limited data available on energy values of the products, only the set for intermediate pyrolysis of straw allowing a full energy balance calculation.

3.5. Pyrolysis Process Scope: Conclusions

Taken as a whole, this review of pyrolysis process scope shows that for any given feedstock it is possible to vary the product distribution between char, liquid and gas, within limits, by choice of process type and operating conditions. Higher char yields are obtained by slow pyrolysis processes with lower temperatures and low flow rates; higher liquid yields arise from fast pyrolysis processes, specific temperatures and high flow rates. The gas yield is not usually the focus of slow or fast pyrolysis and is generally not actually measured but calculated by difference in mass balance. High gas yields would best be provided by gasification processes, not covered by this review.

Similarly, for any given process and equipment set-up, different product distributions will arise from different feedstocks depending on their composition. However, this should not be a major factor in choice of feedstock for pyrolysis, as controllable operating conditions, such as temperature, generally have a larger effect and could be changed to adjust product distributions. Choice of feedstock is more likely to be dependent on factors such as availability, cost and sustainability considerations.

The wide envelopes of process operation and product distribution for pyrolysis processes imply that choices over process type, operation or feedstock may give different outcomes in terms of effect on climate change mitigation, or other objectives.

Table 2. Summary of Pyrolysis Data for Selected Feedstocks

Feed	Process Type and Reference	Feed Moisture	Feed Energy	Pyrolysis Temp-erature	Char Yield	Char Energy	Char Energy Yield	Gas Yield	Gas Energy	Gas Energy Yield	Liquid Yield	Liquid Energy	Liquid Energy Yield
		%wt	MJ/kg	°C	%wt	MJ/kg	% feed energy	%wt	MJ/kg	% feed energy	%wt	MJ/kg	% feed energy
Spruce	Fast pyrolysis, Waterloo process, continuous shallow fluidised bed (Scott et al, 1999)	7		500	12			8			78		
Spruce	Fast pyrolysis, Lurgi-Ruhrgas twin-screw pyrolyser, (Henrich, 2007)	9	16	500	17			13			70		
Spruce	Fast vacuum pyrolysis, Pyrovac process, agitated vacuum tube, (Bridgwater and Peacocke, 2000)	15		450	24			12			64		
Spruce	Slow pyrolysis, laboratory, sealed tube, (Demirbas, 2001)		19.77	377	32.6	29.34	48	20.2			47.2		
Miscanthus	Fast pyrolysis with partial combustion, fluidised bed, (Rocha et al, 2002)	10-12	17.7	450-500	12-15	20-25	17	10-12			70-75		
Miscanthus	Slow pyrolysis, laboratory, rotary kiln, (Michel et al, 2006)	9.6		500	23,28	29		46,51			26		
Miscanthus	Slow pyrolysis with steam activation, laboratory, vertical tube packed bed, (Zanzi et al, 2001)	6.6		550	24			10			66		
Wheat Straw	Fast pyrolysis, Biotherm process, deep fluidised bed, (Scott et al, 1999; Radlein and Kingston, 2007)	1,8		440-550	18-30			18-24			49-58		
Wheat Straw	Intermediate pyrolysis, Haloclean process, rotary kiln with screw, (Hornung et al, 2006)		15.9	400	33-35	25	52-55	20-32	11	14-22	35-45	12	26-34
Wheat Straw pellets	Slow pyrolysis with steam activation, laboratory, vertical tube packed bed, (Zanzi et al, 2001)	6.9		550	25			12			63		
Willow	Slow pyrolysis, laboratory, horrizontal tube with silica, (Leivens et al, 2009)	10,12	16,14	350	61,55			<1			38,45	23	55,74
Willow	Slow pyrolysis with steam activation, laboratory, vertical tube packed bed, (Zanzi et al, 2001)	7.3		650	12			49			39		
Chicken Litter	Fast pyrolysis, bench scale fluidised bed, (Kim et al, 2009; Mante, 2008)	8-10	15	450,470	41,43			36,13			23,43	27,30	41,86

4. Variability in Pyrolysis Processes

4.1. *Introduction*

The previous section established that the product distributions of pyrolysis processes can fall within a wide envelope and that they can be selected, or controlled to a degree, by choice of feedstock, process type, and operating conditions. In this section the variability associated with a specific set of choices is examined. That is, how reproducible are product distributions for a given combination of process, feedstock and operating conditions? It is important to understand this to know how much credence to put on assessments of biochar systems where a single yield figure is used for char. If there is an inherent variability in char yield the benefits arising from biochar systems can also be expected to be variable. This section considers the sources, evidence and magnitude of yield variability. The sensitivity of system benefits to biochar yield variation in a number of literature case studies is also examined.

4.2. *Sources of Variability*

Sources of variability will relate to the main controlling parameters described in Section 2. Variation in biomass feedstock, even if nominally a single source, is likely to be one of the main causes of variability (Downie, 2009). The exact composition of a type of biomass will vary depending on many factors relating to when, where and how it was grown, for instance the weather, soil type and agricultural regime. Figures for carbon contents in nominally the same type of biomass may differ by as much as 10% relative (Gaur and Reed, 1995). The composition of a single supply of a particular biomass type should be more consistent but is not likely to be truly homogenous, except at small scale, unless special provisions for mixing and blending are made. Feedstock moisture content and particle size may vary within and between loads and affect process yields.

Temperature control is also likely to be an important cause of variability, particularly for slow pyrolysis. The lower heat fluxes and longer residence times of slow pyrolysis give scope for variation in heating rate and peak temperature. Yields from traditional charcoal kilns are known to be affected by weather conditions (Toole et al, 1961), due to the effect on temperature control and fuel-wood consumption. The BEST Energies slow pyrolysis demonstration plant is reported (Downie et al, 2007) to operate with a ±30°C temperature range under continuous steady-state conditions at 550°C and this is considered to be “a highly controlled process” (Downie, 2009). Reference to the charts in Section 2 suggests this temperature range would lead to detectable variation in yield.

Fast pyrolysis, at least fluidised bed and similar systems, might be expected to have less variability due to the need for tight control of material and heat flows and the engineering design measures to achieve this. However, limited evidence suggests variability is no less for fast than for slow pyrolysis.

4.3. *Evidence and Magnitude of Variability*

Literature on pyrolysis reviewed for this study generally gives yield data as single values or as a range relating to different operating conditions. For single values, there is rarely any indication of whether this is an average of several experiments or one result. However, five reports were found where multiple yield data were given from the same, or very similar conditions and feedstocks.

These include two studies of traditional charcoal making, one involving masonry block kilns (Toole et al, 1961), one a simple oil-drum kiln (Okimori et al, 2003); these studies gave yields for charcoal only. Information on the Haloclean intermediate pyrolysis process (Hornung et al, 2006) gives yield data for char, liquid and gas for three runs at different temperatures, but within a range representing typical operational variation (375-400°C). Similarly, data for the Biotherm fast pyrolysis process (Dynamotive, 1999) gives yields for different temperatures (459-490°C) close to or within the stated design range (470-490°C). Data for the GRTI fast pyrolysis pilot plant (abandoned in 1989) also relate to a narrow range of typical operating temperatures (499-524°C) (Bridgwater and Peacocke, 2000). These data are summarised in Table 3 where an average, absolute range, and percent relative standard deviation (%RSD) is given for each set.

Table 3. Summary of Pyrolysis Yield Variability Data

		Data points	Char			Liquid			Gas		
			Ave. Yield	Range	%RSD	Ave. Yield	Range	%RSD	Ave. Yield	Range	%RSD
Process and Reference	**Feed**	#	% wt	% wt	%	% wt	% wt	%	% wt	% wt	%
Traditional charcoal making, block kilns, various feeds, (Toole et al, 1961)	Oak, maple, other hardwoods	16	28.2	9	8.7						
Traditional charcoal making, block kilns, single feeds, (Toole et al, 1961)	Seasoned maple (ave. 31% moisture)	6	29.5	5	5.8						
	Unseasoned maple (ave. 58% moisture)	5	26	3	4.2						
Traditiona charcoal making, drum kilns, (Okimori et al, 2003)	Acacia	3	25.4	2.6	4.6						
Intermediate pyrolysis, Haloclean process, rotary kiln with screw, (Hornung et al, 2006)	Wheat straw	3	36	5	5.4	38	7	7.5	26.1	10	16.1
Fast pyrolysis, Biotherm process, (Dynamotive, 1999)	Wood, undefined	4	21.3	9.5	16.3	64.4	20	12.3	13.9	15	42.8
Fast pyrolysis, GTRI process, entrained flow tube, (Bridgwater and Peacocke, 2000)	Wood, undefined	5	11.9	13.6	41.5	53.8	11.9	7.2	34.4	20.4	21.6
Fast pyrolysis, bench scale continuous fluidised bed, (Yanik et al, 2007)	Oreganum stalk		23		8	39		8			
	Corncob		23		7	41		2			
	Straw		20		2	35		4			

A further report (Yanik et al, 2007) stating a degree of variation of char and liquid yields for given conditions is also summarised in Table 3. This study used fast pyrolysis with a bench-scale continuous fluidised bed reactor at a fixed temperature (500°) and three different feeds. In Table 3 the stated variation is taken as standard deviation and converted to %RSD, however, this may be an over-estimate as it is not clear from the report if standard deviation or range is given.

This data appears insufficient to be statistically significant but may justify an opinion that variability in char yields from intermediate pyrolysis or charcoal making, and by implication slow pyrolysis, is of the order of 5%RSD. This would imply a likely variability of ±1.5% absolute in a typical slow pyrolysis char yield of 30%.

The data for liquid yields support a similar estimate of an order of 5%RSD variability, with the exception of data for the Biotherm process. However, if the data points from temperatures outside the Biotherm design range are excluded, the variability in the two remaining points is within this estimate. The gas yields appear to vary to a greater degree but the data is insufficient to generalise. Greater variability in gas yields could be rationalised as due to difficulties in measurement or collection of gas product but it may simply arise arithmetically through the usual calculation of gas yields from the mass balance; absolute errors or variability in liquid and char yields will add to give larger absolute error in gas yield.

Variability in char yield from the GTRI fast pyrolysis process looks to be greater than other processes, this may be related to the low char yield. It is not possible to conclude a clear difference in variability between fast and other pyrolysis processes from this data, although an impression of greater variability in fast processes may be given.

The views of industry experts on the causes and degree of variability in pyrolysis process yields were sought to substantiate the conclusions drawn. Adriana Downie of BEST Energies gave the following comments on sources of variability (Downie, 2009).

> "Yields change dramatically due to feedstock… the heat and mass transfer of the feedstock changes with composition and particle size distribution. These are the greatest factors that will determine the yield variability in any system… more often than not, the variables in the process outputs will come directly from the variability in the feedstocks."

The estimate of magnitude of char yield variability is given support by comments from Cordner Peacocke (2009):

> "When I've performed fast pyrolysis experiments on clean softwoods, I can usually get the char yields to be very consistent, within a few percent of the measured value."

Although this presents a view of consistency, it accepts a variability in line with the conclusion drawn above of an order of 5%RSD variability in product yields.

4.4. Sensitivity of Biochar System Benefits to Yield Variability

The significance of this estimated char yield variability has been examined using simple sensitivity analysis of four literature case studies, three focusing on carbon abatement outcomes, one considering financial viability of pyrolysis processes. In each case the calculations made in the study were repeated using char yields 5%(relative) lower and higher than used in the original report and sensitivity to the change was determined.

4.4.1. Case Study 1

A study by Okimori et al (2003) investigated potential carbon dioxide emission reductions through carbonisation of forestry wastes from acacia plantations in Indonesia. The wastes would be converted to charcoal in small, local facilities using drum, pipe or brick kilns with no capture of liquid or gas products for energy use. The char could be re-applied to soils in forest re-plantation or in agriculture leading to sequestration of carbon, although a market for charcoal for combustion was also recognised. A potential for sequestration of *ca.*48,500 t-C/yr was estimated from this activity given an annual plantation area harvested of 10,750 ha.

Applying the estimated relative variability in char yield of ±5% in this case study gave a directly proportional change of ±5% in the resulting benefit, implying a range of *ca.*46,000-51,000 t-C/yr potential carbon sequestration. This is displayed in Figure 5.

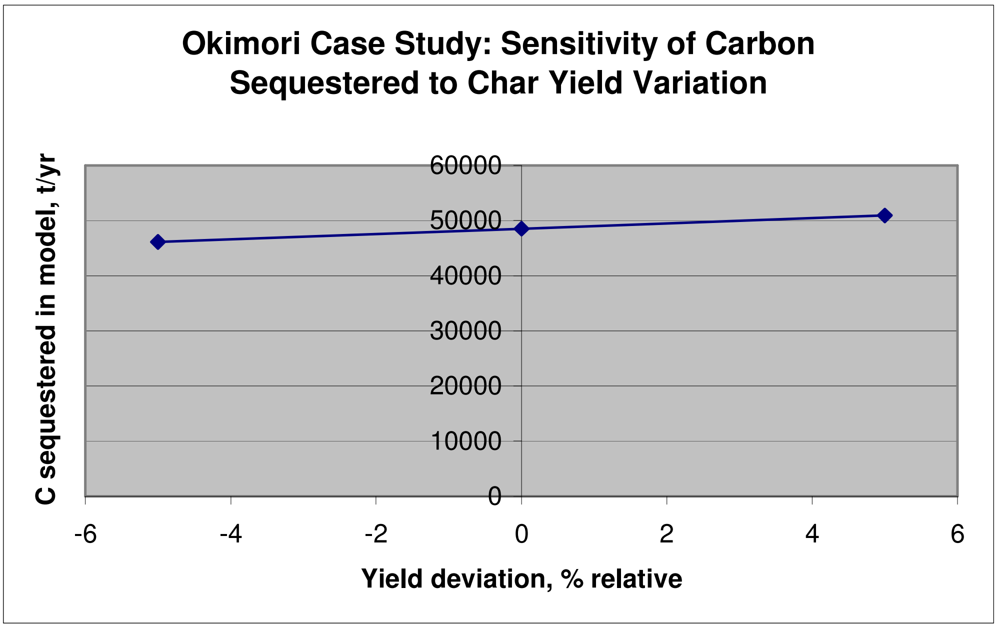


Figure 5. Okimori Case Study: Sensitivity of Carbon Sequestered to Char Yield Variation

4.4.2. Case Study 2

Ogawa et al. (2006) examined a number of cases for carbon sequestration through biomass carbonisation, two of which are considered here and in the following section. The first was based on acacia forestry in Indonesia, as above, but this time also combined with carbonisation of wastes from the associated pulp mill. The biochar produced would again be used for soil improvement in forestry and agriculture.

The total potential for carbon sequestration estimated in this case was 15,571 t-C/yr. Applying the ±5% char yield variability estimate to calculations in this study leads to a change of ±6% in benefit. The slightly exaggerated effect is due to an external fuel consumption allowed for in the calculation, assumed to be independent of char yield, and to the arithmetic effect of adding together the two halves of the case. The resulting range of benefit, 14,642-16,501 t-C/yr, is shown in Figure 6. This arises from a harvested forest area of 12,000 ha/yr, the lower benefit figure compared to the Okimori case described above is due to a lower assumed proportion of forest residues available for carbonisation.

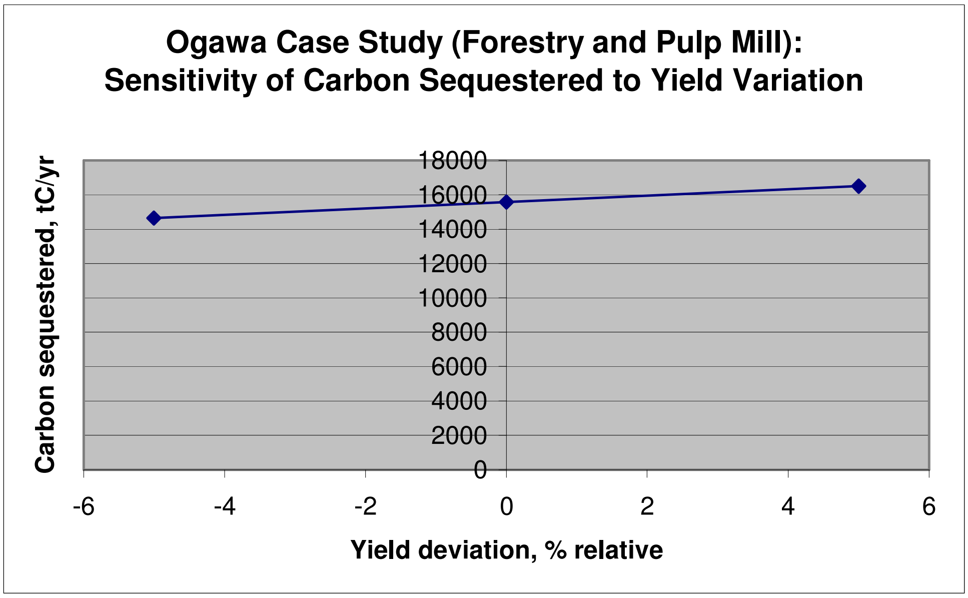


Figure 6. Ogawa Case Study (Forestry and Pulp Mill): Sensitivity of Carbon Sequestered to Char Yield Variation

4.4.3. Case Study 3

Another case studied by Ogawa et al (2006) involved mixing char produced from sawmill wastes with cattle manure to give a biochar compost used in agriculture in Japan on a small scale. This example combines benefits in waste disposal and carbon sequestration. Applying the same method as above gives a ±6% change in a projected benefit of 298 t-C/yr sequestered. The slightly exaggerated sensitivity compared to the ±5% yield variation is again due to a fuel use not proportional to char yield. The range of benefit, 280-316 t-C/yr, is shown in Figure 7.

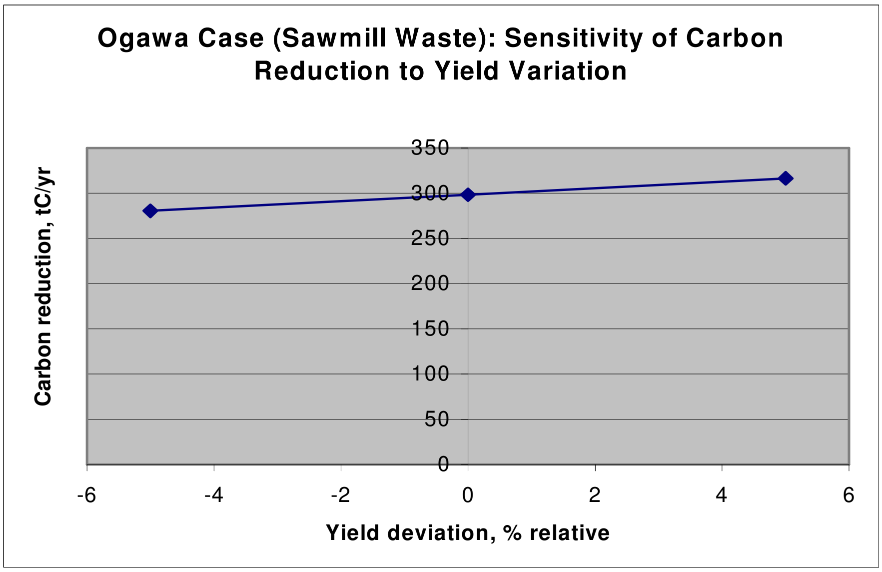


Figure 7. Ogawa Case Study (Sawmill Waste): Sensitivity of Carbon Sequestered to Char Yield Variation

4.4.4. Case Study 4

McCarl and co-authors (2009) present an economic analysis of the use of fast and slow pyrolysis for biochar production from maize stover (stalks and leaves) in the book *Biochar for Environmental Management* (Lehmann and Joseph, 2009). The analysis is based on data for the Biotherm fast pyrolysis process with estimates made to give corresponding information for an arbitrary slow pyrolysis process. The analysis assumes use of primary pyrolysis products as process energy source (all syngas and some char in the fast pyrolysis case) with all the liquid product converted to electricity. Excess char is available for soil amendment and is given a value in the analysis related to its greenhouse gas offset at contemporary prices. The use of about two thirds of the char product for process energy in the fast pyrolysis case, a feature of the Biotherm process (Dynamotive, 1999), leaves little available for greenhouse gas offset as soil amendment but maximises the liquid product availability for electrical generation.

The analysis considers capital and operating costs for the two processes balanced by revenue from electricity and biochar sales, and greenhouse gas offsets (McCarl et al, 2009). It predicts a negative net margin, or loss, in each case of –44.6 and –70.1 US$/t-feedstock for fast and slow pyrolysis respectively. Applying the estimated char yield variability of ±5% leads to only small changes in the estimated margins of ±0.8% for fast pyrolysis and ±1.2% for slow, as shown in Figure 8. The insensitivity of the net margin to biochar yield reflects the small proportion of the total represented by the biochar and greenhouse gas offset values compared to the value of electricity sales. The difference between fast and slow pyrolysis sensitivity is due to the greater availability of biochar product in the slow pyrolysis case.

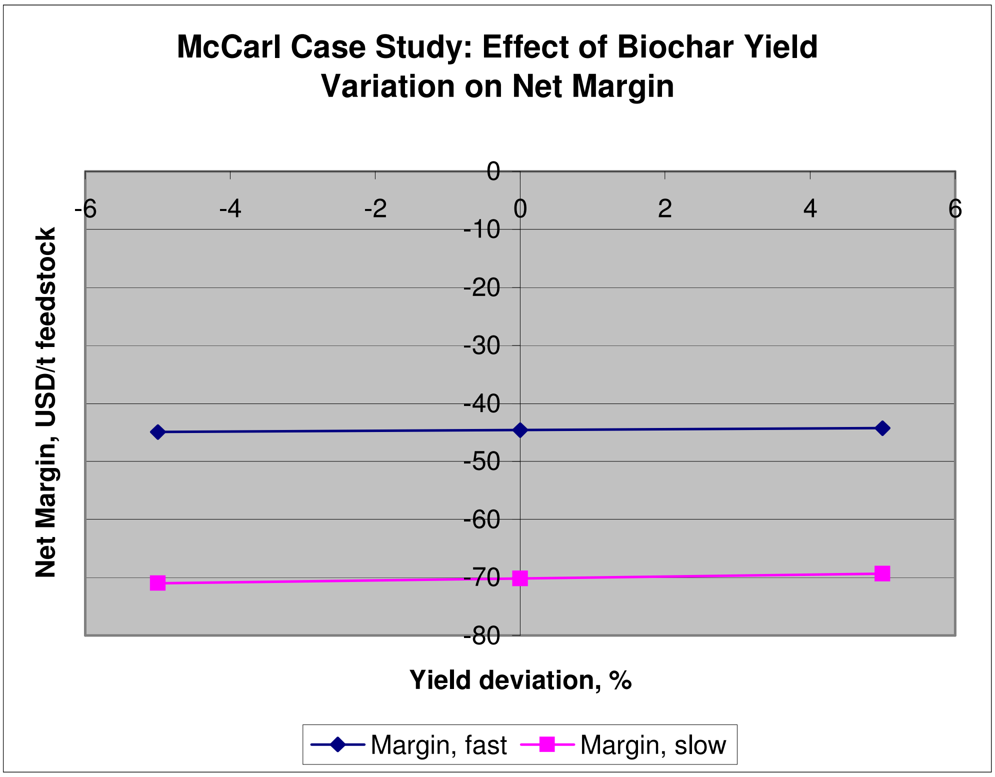


Figure 8. McCarl Case Study: Sensitivity of Financial Analysis to Char Yield Variation

4.5. Significance of Yield Variability

In any technology assessment or forecasting exercise, it is important to understand the accuracy that can be attached to a data set. The evidence for char yield variability in pyrolysis processes, while limited, suggests an order of ±5% RSD may be a reasonable estimate of variability. From the sensitivity analysis above it appears that variability in biochar system benefits may be exaggerated or diminished compared to the variability in char yield depending on the way in which biochar contributes in the benefit calculation. In the examples given where the effect is exaggerated, this is due to a subtractive factor independent of char yield reducing the net benefit while the absolute change in benefit with yield variation remains the same; hence the relative change is exaggerated. It should be expected that such exaggeration would be more significant for cases where the benefits of biochar systems are more marginal

In each of the case studies presented, several assumptions have been made to arrive at the projections of biochar system benefits. The variation in benefits arising from char yield variability is generally no greater, and often smaller than the effect of other assumptions made, but it remains as an underlying, if low level, cause of uncertainty.

5. Conclusions

This review has focussed on the performance of biomass pyrolysis processes for use in biochar systems. The objectives have been to understand the range of control achieved by these processes and the degree of variability that may be associated with reported data for product yields.

There are several technologies capable of converting biomass to solid char products that may be suitable for use as biochar, often with liquid and gas co-products that can be used as fuels. Two main process types, slow and fast pyrolysis, plus the related intermediate pyrolysis have been reviewed to establish the scope of their operational control and variability. The main factors affecting yield distributions and properties of the products are the biomass feedstock itself (its composition and preparation) and the control of temperature and material flows during the pyrolysis process. Key factors are the peak reaction temperature and the gas environment affecting contact between primary solid and gas-phase products.

Product yield distributions from pyrolysis vary widely depending on feedstock, process type, reaction conditions and equipment used. These factors allow a degree of control over which main product, char, liquid or gas, is delivered through biomass pyrolysis. Typical mass yield ranges for slow pyrolysis are char 25-35%, liquid 20-50%, gas 20-50%; for intermediate pyrolysis, char 30-40%, liquid 35-45%, gas 20-30%; and for fast pyrolysis, char 10-25%, liquid 50-70%, gas 10-30%. In general slow and intermediate pyrolysis give higher char yields while fast pyrolysis gives higher liquid yields. Care should be taken when using such generalisations as there are important exceptions. For any comparison of biochar systems or their potential benefits to be meaningful the feedstock, pyrolysis process and outputs assumed should be clearly specified.

The variability associated with a particular yield figure for char from slow or intermediate pyrolysis has been estimated at ±5% (relative). Some support for this order of variability has been given by industry experts. The variability for liquid and gas yields or for yields from fast pyrolysis is less clear but may be of a similar order. Analysis of sensitivity to this char yield variability has been carried out for some literature case studies of biochar systems. The effect is diminished or magnified depending on how char yield contributes to the calculation of system benefits. Char yield should be considered as an underlying source of variability in pyrolysis biochar systems although it is unlikely to be more significant than the effect of other uncertainties and assumptions.

The range of control of product distributions from biomass pyrolysis, through choice of feedstock, process and conditions, gives the potential to optimise the process to satisfy different objectives. The effect of these choices on the potential for mitigation of climate change through use of pyrolysis biochar systems with soil carbon storage has been the subject of a related study which is reported elsewhere (Brownsort, 2009; Brownsort et al, 2010, in preparation).

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APPENDIX 1

Pyrolysis Process Literature Review

The following pages hold spreadsheet prints with information and summary data from the literature review of pyrolysis processes.

Copies of the spreadsheet may be available from the author.

Process	Organisation	Source Ref	Pyrolysis Type	Process Temp, °C	Equipment Type	Status	Scale	Feed (data extracted)	Char Yield, %	Yield Basis	Oil Yield, %	Gas Yield, %	Comment
Lab-slow	CMK, Uni Hasselt, Belgium	Lievens et al, 2009	Slow	350	Static horrizontal tube	Lab	3g	Willow, leaves and branches, from contaminated land	54, 49.1	%w/w as fed (moist 12.3, 9.9%), including ash, 11.6, 3.4	33.9, 40.3, of which about 20 is water of reaction	<1	Low temp used to keep heavy metals in the char, but possibly not very charred at 350°C. High char yield includes ash, but if expressed on dry higher still - 61, 54.5% wt on dry
Lab-slow	RIT, Stockholm/ BAS, Sofia	Zanzi et al, 2001	Slow	550-750	Vertical tube of horrizontal rotating tube with sweep of inert, steam &/or co2	Lab	65g	Bagasse, miscanthus, olive waste, straw pellet, straw, salix, birch (Misc, Straw pel, salix)	24,25,12	%wt maf	66,63,39	10,12,49	Range of temps all high as trying to get activated carbon product. No energy values given. All done with activation gas sweep - steam in this paper. Other papers with inert gas Ar or N2, higher yields for char but little other data. Misc 30-45; straw 30-32.5%.
Lambiotte		Domac et al, 1985	Slow	Feed gas 900	Continuous vertical retort	Commercial	25000tpa Char	oak wood, <25% moisture and 10cm chunks	35	dry feed	some	?	Gas reused for process heat
Pyro-6F, Pyro-7 (Pro-Natura)	Pro-Natura	Pro-Natura, 2008 (Newsletter).	Slow	550	'Rotary Retort' (Horrizontal drum) - how driven?	Pilot, small 'commercial', few?	4-5 t char per day, (~500kg/h cont feed)	Mixed ag or for waste	30-45	on <15% moist feed (I.e. higher if expressed on dry)			Gas/vapours most consumed with excess of 120-150kW heat value for other uses. Need to search acedemia for more data.
Rectangular kilns		Rocha et al, 2002	Slow		Mechanical mat handling, vapour recovery	Trad	100t/month	wood	35-37	dry feed	small, 15-50 kg/month		Oil yield seems too low, Tonnes per month?
Reichert Retort	Aston, and Namibia Investment Centre	Domac et al, 1985; Honsbein, 2005	Slow	Feed gas 600-700	Semi/continuous vertical retort	Commercial	600 lt/40min	African woods	33-40	?	some	?	Gas reused, high-ish fixed-C implies a real high yield.
Research, slow py	Uni of Metz	Michel et al, 2006	Slow	400-600	Rotary kiln	Lab	10-30g bx	Miscanthus (M straw and pellets)	16-29	on dry	24-34	46-51	Gives variation for final temp (500,600), form (straw or pellet) heating rate (2.5-15 K/min). Oil yield includes water. No data on (non systematic) variability other than unexpected trend with particle size (larger->less char) which could be variability??
Rotary hearth		Domac et al, 1985	Slow	900-1000	Rotary hearth	Commercial	2-5000tpa char	fine wood or ag waste	25	dry feed	?	?	Gas and vapours burned for process heat or power
Rotary kilns	Terra Humana, Hungary	Someus, 1993 (US Patent)	Slow	up to 850	Rotary kiln	Commercial	100-250kg/h	any biomass, low grade coal					No yields given in patent or TH website. Link from //terrapreta.bioenergylists.org/company
Scientific Carbons	Scientific Carbons/Eprida /NREL	Yeboah et al, 2003	Slow	?	?	Based on Scientific Carbons Inc existing facility	Full scale ? 225kg/h of pyrolysis vapours, 50kg/h biomass pilot	Peanut shells	32	on dry feed (?)	31	5	Yields at pyrolysis output stage, plus water 32%. Output fed to reformer -> H2 57%, CO2 26%, CO 12%, CH4 5%.
Stennau	Uni of Tubingen	Bridgwater, Peacocke, 2000	Slow	'fairly low'	Rotary kiln	?	1t/d (41 kg/h)	MSW	56	daf???	30.9	71m3/t feed	solid yield seems high for true char yield on daf basis, maybe includes ash?
Tubingen	Uni of Tubingen	Bridgwater, Peacocke, 2000	Slow	300-350	Various: cone screw, rotary furnace, F-Bed, transport belt	commercialised	up to 400kg/h	sewage, msw, ag waste	50-60		18-27		Gives ele anal for char as 51% 'others' confirming high ash in this yield
VMR oven	eg Crarbo Group	Antal and Gronli, 2003	Slow		Twin cannisters	Established, eg Carbo Group	up to 11000tpa	various woods	30-32	?			Vapour/gas used for feed drying and process heat, Reumerman 2002 gives yield on dry of 41%.
Flash Carbonisation	Carbon Diversion Technologies	Antal et al, 2003	Pressure Slow	400-800	Pressurised reactor	Commercial	1t or 3.5t	any biomass	29.5-40	dry feed	*	*	Pressurised with an air input, ignition of biomass, but yield still approaching theoretical, off gas not flammable, ie the combustion is of gas/vapour, no oil recovered in Antal 2003 paper, but CDI show oil as a product. Yields from paper, CDI site quotes no yield.
ALTEN	Alten (KTI/ Italenergie)	Bridgwater, Peacocke, 2000	Intermediate	500	Fluidised/stirred bed	Pilot	500 kg/h	Wood/ ag waste	20.5	daf	20.5		But quotes 25% of each char and oil in text, gas yield 100/141 total mass input basis. P.11 of review
ALTEN	Uni of Thessaloniki / Italenegie	Zabaniotou and Karabelas, 1999	Intermediate	400	Fluidised bed	Pilot	9-1200kg/h dry feed	Forest res	15-20; 18	on dry feed			Plant uses air to fluidise and partial combustion for heat input. Oil and Gas yields not defined. Char separation poor and much ended up in the oil.
ALTEN		Zabaniotou and Karabelas, 1999	Intermediate						31.5	on dry feed	28.5	25	Zab quote of figures for Avezzano plant, 15% missing ?Water?

Process	**Organisation**	**Source Ref**	**Pyrolysis Type**	**Process Temp, °C**	**Equipment Type**	**Status**	**Scale**	**Feed** (data extracted)	**Char Yield, %**	**Yield Basis**	**Oil Yield, %**	**Gas Yield, %**	**Comment**
Haloclean	Aston, BioEnergy Research Group	Hornung, 2007and 2008 (unpublished presentations)	Intermediate	325-400	Tubular kiln, internal screw with steel balls		Pilots 50kg/h or 500kg/h ?	Detailed in pres	73-34	on dry feed (?)	18-42-35	9-32	Lowest temp may not be highly carbonised. Varies 48-34 over 350-400 °C.Note probable typo giving 50% Char yield at 450° noted in other table (2005), corrected in 2008b.
Haloclean	Aston, BioEnergy Research Group	Hornung, 2008	Intermediate	450-550	Tubular kiln, internal screw with steel balls		Pilots 50kg/h or 500kg/h ?	Detailed in pres	15-41	on dry feed (?)	38-57	10-42	Pairs of results showing up to 18% variation in char yield for 50 °C temp difference. Also gives charts with variation by feed form for straw - powder 38% pellets 45% at 375 °C. Also pellets 45-35% for 375-400 °C - so quite sensitive - useful data sets?
Haloclean	Sea Marconi, Italy	Sea Marconi, 2009	Intermediate	450-500	Tubular kiln, internal screw with steel balls	Commercialised, large scale for tyre also WEEE pyrolysis	2 tph biomass plant constructed (12000tpa)	Ag and For wastes	20-30	?	50-60	?	
Haloclean	FZK	Mai et al, 2008	Intermediate	450-500	Tubular kiln, internal screw with steel balls		Pilot 50kg/h	rape, rice, straw	20-40	on dry feed (?)	40-60	10-20	Possibly same work as Hornung reports. Yields from a chart - unclear. Quotes a 'water' yield which I think is really an aqueous organic fraction which is combustible in their engine.
Pyrovac	Pyrovac Inst. Inc.	Bridgwater, Peacocke, 2000	Fast-vacuum	450	Agitated tube, vac	commercialised	?	biomass, industrial and MS wastes (Fir/spruce bark, spruce wood)	34,24	dry feed	35,47	11,12	egs given for fir/spruce bark vs spruce wood. Integrated process burns char for elec and gas for process heat
ABRI/ROI	ABRI Inc and Renewable Oil International	Badger and Fransham, 2006	Fast?	?	Screw pyrolyser	Pilot and small commercial	50tpd (feed?)	wood, chicken manure	25	dry feed	60	15	Based on figures for wood in patent. Char from chicken manure 45% yield. ROI call process Fast Py. Patent saved not printed.
Ablative plate	Uni of Aston	Bridgwater, Peacocke, 2000	Fast	550-600	Hot plate, rotating blades	pilot	3kg/h	wood eg poplar	13.8-15.7	? Dry	74-80.8	6.2-10.4	Oil includes reaction water. Four runs given 550-602 °C - perhaps less variable?
Bioware	Uni of Campinas	Rocha et al, 2002	Fast	450-650	Fluidised bed	Large pilot	100kg/h	Various biomass	5-15	dry feed	70-75	15-20	
GTRI	GTRI	Bridgwater, Peacocke, 2000	Fast	500	entrained flow tube	Pilot dormant	~60kg/h	wood	7.6-21.2	daf	48.1-60.0	27.9-44.3	five runs quoted, reactor temps 499-524, showing variation, these were later runs once plant optimised, so indicative of variability
Lab-fast	Uni of Thessaloniki / CPRI	Ioannidou et al, 2009	Fast	360-730	Captive sample heated rapidly, no sweep gas?	Lab	0.3g	Corn cob and stalk	50-15	%wt as fed (?)	10-30	10-63	Neither of these set-ups seem very representative of large scale fast or slow processes
Lab-fast	Virginia Tech	Kim et al, 2009	Fast	450-550	Bubling FB	Bench scale	200g	Chicken and turkey litters, bedding material	22-44	%wt as fed (?)	15-29	32-61	
Lab-fast	Virginia Tech	Mante, 2008	Fast	450 (470)	Bubling FB	Bench scale	300g	Chicken litter, pine and oak shavings	43	%wt on dry	43	14	Pine:22,63,15. Same group as Kim 2007
Lab-fast	FZK	Yanik et al, 2007	Fast	500	Continuous FB	Bench scale	100g	Corncob, oregano stalk, straw	23,23,20	dry feed	39,41,35,	32,30,39	Plus 6% water in each case. Gives errors of +/- 1.9,1.4,0.4 on char yields. Residence times 1-2s.
Lurgi	FZK	Henrich, 2007	Fast	500	Twin screw pyrolyser	Large scale commercial for coal/shale /waste etc		straw, wood	20-30 straw, 15-20 wood	dry feed	50-60; 60-70		Aiming for oil for BTL process, although char included in the slurry for gasification. paper saved not printed
Rotating cone	BTG/ Uni of Twente	Bridgwater, Peacocke, 2000	Fast	600	Rotating cone	pilot	50-200kg/h	wood waste	15	?	60	25	BTG has/is scaling up
RTI Process/ BioTherm Process	Waterloo/RTI/ Dynamotive	Bridgwater, Peacocke, 2000	Fast										Not noted in detail as have other sources but does have some yield egs if needed
RTI Process/ BioTherm Process	Waterloo/RTI/ Dynamotive	Dynamotive, 1999; Radlein and Kingston, 2007	Fast	450-500	Continuous deep FB	Commercial	up to 200tpd	Wood; Bagasse	15;26	as fed (<10% moist)	72;62	13; 12	Gives good set of comparison and variance data. Char yield variability at design conditions ranges 4%, oil and gas ranges higher at low temps.
RTI Process/ BioTherm Process	Waterloo/RTI/ Dynamotive	Scott et al, 1999	Fast	475-525	Continuous deep FB	Commercial	up to 200tpd	Various biomass	12.5-30	dry feed	49-74	10-20	Gives data for hardwood sawdust, wheat straw, bagasse. Key to RTI process is discovery that longer vapour residence times don't adversely affect the oil yields in bubbling FBs.
RTP (Rapid Thermal Processing)	Ensyn	Bridgwater, Peacocke, 2000; Ensyn website	Fast	490	Transported bed updraft	Commercial	350t/d (14t/h)	eg woody	0		75 (Ensyn) up to 83		gas and char recycled for heat
Waterloo FPP	Union Fenosa, Sp	Bridgwater, Peacocke, 2000	Fast		Bubling FB	commercial	?2-4t/h	Eucalyptus, oak pine	15-20	dry feed	up to 70		gas recirculated
Waterloo/ Hamburg	BFH/IWC	Bridgwater, Peacocke, 2000	Fast	400-525 (475)	Continuous FB	Pilot	5kg/h	Contaminated wood	14.35	dry feed	72.4	13.25	
Wellman	Wellman Process Engineering	Bridgwater, Peacocke, 2000	Fast		Continuous bubbling FB	?Demonstration constructed 1999	250kg/h	Biomass	0		>70		Bridgwater consults for them?? Not sure of status. Char and ?gas consumed.
WFPP		Piskorz et al, 1996 (RTI Patent)	Fast	425	Continuous shallow FB			Hardwood sawdust	30.5	?	59.6	5.9	RTI Patent gives 'poorer looking' data from WFPP for comparison.
WFPP	Uni of Waterloo	Scott et al, 1985	Fast	450-650	Continuous shallow FB		Bench	Wood, ag and for wastes. Data for corn stover	45.7-19	as fed (9%moist, 11% ash)	21-32	11-14	Gives various other yield data in charts for other feeds. Char yields 25-35 at 400-450 °C, but oil optimum temp 500-550. Might be worth getting the Canadian patent for WFPP

APPENDIX 2

Pyrolysis Process Information: Data Extracted for Selected Feeds

The following pages hold spreadsheet prints with data extracted from literature for the selected feedstocks: chicken litter, corn cob, corn stalk, miscanthus, pine, spruce, wheat straw, and willow. Data for the BEST Energies process using an undefined green-waste is also included.

Copies of the spreadsheet may be available from the author.

Pyrolysis Process Information: Data Extracted for Selected Feeds							Update:	24.06.09	(references later)						
Reference				**Feedstock**											
Process	**Source Ref**	**Organisation**	**Country**	Type	Source	Moisture	Volatiles	Fixed-C	C	H	N	O	Other info	Particle size	Energy
						wt% wet	wt% wet	wt% wet	wt% on dry	wt% on dry	wt% on dry	wt% on dry		mm	MJ/kg
Lab-fast	Kim et al, 2009	Virginia Tech	USA	Chicken litter	Shenendoah valley, Virginia	22.81			37.15	5.3	3.13	34.67	Ash 22.8%	#20 mesh	15.14
Lab-fast	Mante, 2008	Virginia Tech	USA	Chicken litter	Shenendoah valley, Virginia	8-10			29.15	4.1	6.42	36.56	Ash 23.53%wtmf; S 0.36; Cl 0.62	1	14.79
Lab-fast	Ioannidou et al, 2009	Uni of Thessaloniki / CPRI	Greece	Corn cob	Orestiada, Greece	7.57	84.37		43.77	6.2		50	Ash 8.06%wt	<1	18.25
Lab-slow	Ioannidou et al, 2009	Uni of Thessaloniki / CPRI	Greece	Corn cob	Orestiada, Greece	7.57	84.37		43.77	6.2		50	Ash 8.06%wt	<1	18.25
Lab-fast	Ioannidou et al, 2009	Uni of Thessaloniki / CPRI	Greece	Corn stalk	Orestiada, Greece	6.44	91.26		43.8	6.4		49.78	Ash 2.3%wt	<1	18.17
Lab-slow	Ioannidou et al, 2009	Uni of Thessaloniki / CPRI	Greece	Corn stalk	Orestiada, Greece	6.44	91.26		43.8	6.4		49.78	Ash 2.3%wt	<1	18.17
Bio-Alternative	Birdgwater, Peacocke, 2000	Bio-Alternative	Switzerland, Spain	Fir wood (and others)		10-15							Dried and comminuted		
Pyrovac	Birdgwater, Peacocke, 2000	Pyrovac Inst. Inc.	Canada	Fir/Spruce bark		15							Dried and shredded		
Lab-slow	Zanzi et al, 2001	RIT, Stockholm/ BAS, Sofia	Sweeden/ Bulgaria	Miscanthus		6.6			48.9	4.6	0.4	46.7	Ash 2.69 %wtmf	1-3.2	
Bioware	Rocha et al, 2002	Uni of Campinas	Brazil	Miscanthus or other Elephant grass - not specified		10-12							Ash 11%wt on dry	2-4	
Bioware	Rocha et al, 2002	Uni of Campinas	Brazil	Miscanthus or other Elephant grass - not specified		10-12							Ash 11%wt on dry	2-4	
Research, slow py	Michel et al, 2006	Uni of Metz	France	Miscanthus pellets	Germany 2005	9.6	80		47.1	5.4	0.44	44.6	Ash 2.3; S 0.06; Cl 0.074. Cell 45; hemicell 30; lignin 21.	dia 6; length 10-30	17.744
Research, slow py	Michel et al, 2006	Uni of Metz	France	Miscanthus straw	Germany 2005	9.6	80		47.1	5.4	0.44	44.6	Ash 2.3; S 0.06; Cl 0.074. Cell 45; hemicell 30; lignin 21.		17.744
RTI Process/ BioTherm Process	Dynamotive, 1999	Waterloo/RTI/ Dynamotive	Canada	Pine 85%, spruce 15% mix	Local (Vancouver)	5							Ash 0.25%wt	<1.2	
Fixed bed	Ryu et al, 2007	Uni of Sheffield	UK	Pinewood		8.9	78.8	12.1	52	7		41		cube 20	17.8
Lab-fast	Mante, 2008	Virginia Tech	USA	Pinewood shavings	Shenendoah valley, Virginia	8-10			46.53	5.9	<0.5	42.31	Ash 1.95%wtmf; S <0.05; Cl 180ppm	1	18.02
WFPP	Scott et al, 1999	Uni of Waterloo	Canada	Spruce sawdust		7							Ash 0.46 (%wtmf)	1	
Lurgi	Henrich, 2007	FZK	Germany	Spruce wood		8.9							Ash 1%		16.2
Haloclean	Hornung, 2008	Aston, BioEnergy Research Group/FZK	Germany/UK	Wheat straw pellets											
Lab-slow	Zanzi et al, 2003	RIT, Stockholm/ BAS, Sofia	Sweeden/ Bulgaria	Wheat straw pellets		6.9			47	6.1	0.5	46.4	Ash 6.34 %wtmf	1-3.4	
Haloclean	Hornung et al, 2006	Aston, BioEnergy Research Group/FZK	Germany/UK	Wheat straw powdered											
Lab-slow	Lievens et al, 2009	CMK, Uni Hasselt, Belgium	Belgium	Willow (branches)	Limberg, contaminated land	10			45.5	6.1	0.7	44	Ash 3.4% wt on dry, CL- 150ppm	<2	16
Lab-slow	Lievens et al, 2009	CMK, Uni Hasselt, Belgium	Belgium	Willow (leaves)	Limberg, contaminated land	12			41.9	5.7	2.1	37.8	Ash 12% wt on dry, S 0.9; Cl- 4650 ppm	<2	14
Lab-slow	Zanzi et al, 2002	RIT, Stockholm/ BAS, Sofia	Sweeden/ Bulgaria	Willow (salix)		7.3			48.8	6.2	1	43.4	Ash 0.75 %wtmf	1-3.3	
BEST Energies	Downie et al, 2007	BEST Pyrolysis Inc	Australia	'Greenwaste'		38			45.6	5.3	0.15	38.4	Ash 3.5% on dry; S 0.06%.		

Pyrolysis Process Information: Data Extracted for Selected Feeds								
Reference			**Process**				**Conditions**	
Process	**Source Ref**	Type	Equipment	Scale	Temperature	Pressure	Heating rate	Residence time
					℃	Mpa	℃/min	?
Lab-fast	Kim et al, 2009	Fast	Bubling FB	Bench - 200g/h here	450		fast	0.5-5
Lab-fast	Mante, 2008	Fast	Bubling FB	Bench - 300-350g/h here	469		fast	
Lab-fast	Ioannidou et al, 2009	Lab fast	Captive sample heated rapidly, low He sweep gas rate	0.3g	520	0.1	52℃/sec	?
Lab-slow	Ioannidou et al, 2009	Lab slow	Fixed bed, sample blown onto preheated beads, higher N2 sweep gas.	1.5g	500	0.1	Contact with preheated beads	>15min
Lab-fast	Ioannidou et al, 2009	Lab fast	Captive sample heated rapidly, low He sweep gas rate	0.3g	520	0.1	45℃/sec	?
Lab-slow	Ioannidou et al, 2009	Lab slow	Fixed bed, sample blown onto preheated beads, higher N2 sweep gas.	1.5g	500	0.1	Contact with preheated beads	>15min
Bio-Alternative	Birdgwater, Peacocke, 2000	Conventional carbonisation	Counter current updraft gasifier	50-2000kg/h	?	0.1		
Pyrovac	Birdgwater, Peacocke, 2000	Fast-vacuum	Agitated tube, vac	2880 kg/h dried (15%) biomass	450	0.015		
Lab-slow	Zanzi et al, 2001	Lab slow pyrolysis with carbon activation by steam	Vertical tube in furnace - packed bed?	65g	550		25	60min
Bioware	Rocha et al, 2002	Fast with partial combustion	Fluidised bed	Large pilot 100kg/h	450-500			
Bioware	Rocha et al, 2002	Fast with partial combustion	Fluidised bed	Large pilot 100kg/h	550-650			
Research, slow py	Michel et al, 2006	Lab slow pyrolysis	Rotary kiln under argon	10-30g	500	0.1	5	? >60min
Research, slow py	Michel et al, 2006	Lab slow pyrolysis	Rotary kiln under argon	10-30g	500	0.1	15	? >60min
RTI Process/ BioTherm Process	Dynamotive, 1999	Fast	Continuous deep FB	Now to 200tpd, but data from ?pilot	472			
Fixed bed	Ryu et al, 2007	Large lab slow pyrolysis	Packed bed in reactor, within furnace.	150-300g (up to 1kg)	400	0.1	10	heat up + 60min
Lab-fast	Mante, 2008	Fast	Bubling FB	Bench - 300-350g/h here	421		fast	
WFPP	Scott et al, 1999	Fast	Continuous shallow FB	5tpd demonstrator, data from ?	500		fast	0.5
Lurgi	Henrich, 2007	Fast	Lurgi-Ruhrgas twin-screw pyrolyser	20kg/h pilot, scaling up to 500kg/h	500	0.1	fast	few seconds
Lurgi	Henrich, 2007	Fast	Lurgi-Ruhrgas twin-screw pyrolyser	20kg/h pilot, scaling up to 500kg/h	500	0.1	fast	few seconds
Haloclean	Hornung, 2008	Intermediate pyrolysis	Rotary kiln, internal screw with steel balls	Pilot 50kg/h, 15t processed	400	0.1	?	2 min
Lab-slow	Zanzi et al, 2003	Lab slow pyrolysis with carbon activation by steam	Vertical tube in furnace - packed bed?	65g	550		25	60min
Haloclean	Hornung et al, 2006	Intermediate pyrolysis	Rotary kiln, internal screw with steel balls	Pilot 50kg/h, 15t processed	400	0.1	?	2 min
Lab-slow	Lievens et al, 2009	Lab slow pyrolysis	Static horrizontal tube with silica heat carrier	3g	350		10	
Lab-slow	Lievens et al, 2009	Lab slow pyrolysis	Static horrizontal tube with silica heat carrier	3g	350		10	
Lab-slow	Zanzi et al, 2002	Lab slow pyrolysis with carbon activation by steam	Vertical tube in furnace - packed bed?	65g	650		25	60min
BEST Energies	Downie et al, 2007	Slow pyrolysis	Drum kiln, agitated	300kg/h dry basis	550+/-30		5-10	

Pyrolysis Process Information: Data Extracted for Selected Feeds														
Reference		**Char**								**Gas**				
Process	**Source Ref**	Yield		Moisture	Volatiles	Fixed-C	Carbon%	Carbon yield	Energy, HHV	Yield		Composition	Energy, HHV	
		%	?basis	%	%	%	%	%	MJ/kg	%	?basis		MJ/kg	MJ/Nm3
Lab-fast	Kim et al, 2009	40.63	%wt			ash				35.88	%wt			
Lab-fast	Mante, 2008	43.1	%wt dry feed							13.6	%wt dry feed			
Lab-fast	Ioannidou et al, 2009	31	%wt as fed (?)			CHO	67.62	20.832	24.27	26	%wt as fed (?)	Vol% CO 51; H 32; CH4 9; CO2 9.	13	
Lab-slow	Ioannidou et al, 2009	37.31	%wt as fed (?)							16.16	%wt as fed (?)	Vol% CO2 51.69; CO 38.21; CH4 4.08; H2 1.82; +C2-C6	8.5	
Lab-fast	Ioannidou et al, 2009	22	%wt as fed (?)			CHO	62.18	13.6796	19.13	45	%wt as fed (?)	Vol% CO 46; H 28; CH4 10; CO2 17.	15	
Lab-slow	Ioannidou et al, 2009	32.67	%wt as fed (?)							14.47	%wt as fed (?)	Vol% CO2 52.36; CO 34.77; CH4 5.49; H2 2.42; +C2-C6	8	
Bio-Alternative	Birdgwater, Peacocke, 2000	30	%wt dry wood		12-18				30			Vol%: H2 7.9; CO 16.3; CO2 13.2; N2 48.4; O and H-C 14.7		3.8-5.5
Pyrovac	Birdgwater, Peacocke, 2000	34	%wt dry wood		20.3	72.1		24.514	30.4	11	%wt dry wood	Vol%: H2 6.6; CH4 10.0; CO 32.0; CO2 41.5; C-2-5 6.4; MeOH 0.4; Others 3.1	10.9	
Lab-slow	Zanzi et al, 2001	24	%wt maf	7.5						10	%wt maf	Vol% N2 free: CO2 52.9; CO 27.9; H2 10; CH4 7.6; C-2 1.6.		
Bioware	Rocha et al, 2002	12-15	%wt dry basis			40-45	52.5	7.0875	20-25	10-12	%wt			
Bioware	Rocha et al, 2002	<10	%wt dry basis			CHON ash	52.5	5.25		15-20	%wt			
Research, slow py	Michel et al, 2006	23	%wt fraction of total						29.083	51	%wt fraction of total	CO2, CO, CH4 not quantified		
Research, slow py	Michel et al, 2006	28	%wt fraction of total							46	%wt fraction of total	CO2, CO, CH4 not quantified		
RTI Process/ BioTherm Process	Dynamotive, 1999	20	%wt as fed							9	%wt as fed			
Fixed bed	Ryu et al, 2007	30	%mass yield		35	63	79.8	23.94	32	34	%mass yield by diff	CO2, CO, CH4, H2, C3H8 not quantified		
Lab-fast	Mante, 2008	22.4	%wt dry feed							14.88	%wt dry feed			
WFPP	Scott et al, 1999	12.2	%wt maf							7.8	%wt maf			
Lurgi	Henrich, 2007	17	?							13	?	CO>CO2>CH4>H2~C2-C5		
Pyrovac	Birdgwater, Peacocke, 2000	24	%wt dry wood							12	%wt dry wood			
Lab - slow	Demirbas, 2001	32.6	?			CHON ash	77	25.102	29.34	20.2	?	na	na	
Lab-fast	Yanik et al, 2007	20	%wt						19 kcal/kg	39	%wt			
RTI Process/ BioTherm Process	Scott et al, 1999	30.2	%wt moisture free feed							21.1	%wt moisture free feed			
RTI Process/ BioTherm Process	Radlein and Kingston, 2007	18	%wt							24	%wt			
WFPP	Scott et al, 1999	24.5	%wt maf							17.8	%wt maf			
Lurgi	Henrich, 2007	28	?							18	?	CO2>CO>CH4>C2-C5>H2		
Haloclean	Hornung, 2008	35	?						25	20	?			
Lab-slow	Zanzi et al, 2003	25	%wt maf	2.5						12	%wt maf	Vol% N2 free: CO2 55.4; CO 21.9; H2 10; CH4 10.9; C-2 1.8.		
Haloclean	Hornung et al, 2006	33.5	?						25	31.9	?			
Lab-slow	Lievens et al, 2009	49.1	%wt as fed							<1				
Lab-slow	Lievens et al, 2009	54	%wt as fed							<1				
Lab-slow	Zanzi et al, 2002	12	%wt maf	2.1						49	%wt maf	Vol% N2 free: CO2 18.5; CO 33.1; H2 43.1; CH4 4.7; C-2 0.6.		
BEST Energies	Downie et al, 2007	40	%wt dry feed			CHNO-Ash	72.3	28.92				Vol%: N2 38; CO 20; CO2 16; H2 16; CH4 8.5; C-2 <1		

Pyrolysis Process Information: Data Extracted for Selected Feeds							
Reference		**Liquid**					**Notes**
Process	**Source Ref**	Oil Yield	Water Yield		Moisture	Energy, HHV	
		%	%	?basis	%	MJ/kg	
Lab-fast	Kim et al, 2009	23.49	included	%wt		27.49	Uncertain yield basis, might be as fed, as liquid yield is just condensates as far as can tell. Mante specifies yields on dry basyis though.
Lab-fast	Mante, 2008	43.25	included	%wt dry feed		29.7	
Lab-fast	Ioannidou et al, 2009	30	included	%wt as fed (?)			Neither of these set-ups seem very representative of large scale fast or slow processes. This 'fast' process seems more like a slow for yield distribution. 520 result picked as 360/380 look anomalous.
Lab-slow	Ioannidou et al, 2009	40.22	included	%wt as fed (?)			Neither of these set-ups seem very representative of large scale fast or slow processes. This 'slow' process has anomalous char yield pattern, highest at 600 (54%). 500 picked as more data given for this.
Lab-fast	Ioannidou et al, 2009	20	included	%wt as fed (?)			Neither of these set-ups seem very representative of large scale fast or slow processes. This 'fast' process seems more like a slow for yield distribution. 520 result picked as 360/380 look anomalous.
Lab-slow	Ioannidou et al, 2009	42.22	included	%wt as fed (?)			Neither of these set-ups seem very representative of large scale fast or slow processes. This 'slow' process has anomalous char yield pattern, highest at 600 (40%). 500 picked as more data given for this.
Bio-Alternative	Birdgwater, Peacocke, 2000	15-20		%wt on feed	4.5	22.2	Gas burnt 'in a boiler' or after drying in an engine. Oil used in a hospital boiler. Char desired product.
Pyrovac	Birdgwater, Peacocke, 2000	35	20	%wt dry wood	23	23	Char burnt for steam -> turbine 5.5MWe; flue gas -> drying; syngas and some biooil -> process heat; biooil -> CC gas turbine 8.5MWe; flue gas -> drying
Lab-slow	Zanzi et al, 2001	66		%wt maf			Yield basis probably % wt mf not maf - otherwise doesn't balance
Bioware	Rocha et al, 2002						
Bioware	Rocha et al, 2002	70-75	inc	%wt			
Research, slow py	Michel et al, 2006	26	included	%wt fraction of total			Char yields higher for slower heating, higher for lower final temp, higher for straw vs pellets - not expected, thin explanation.
Research, slow py	Michel et al, 2006	26	included	%wt fraction of total			Paper gives variation of yields with heating rate and physical form, but data patchy.
RTI Process/ BioTherm Process	Dynamotive, 1999	71		%wt as fed			Data picked from charts, other data for T=459,460,487,505 - good set for variability. Energy data: total heat requirement 2.5MJ/kg, when gases recycled to reactor require 1MJ/kg of external heat input eg nat gas, this at 'six barrels per day plant' scale. No figures for drying requirement. The gas input said to be 5% of 'total CV' of oil yield at max yield.
Fixed bed	Ryu et al, 2007	35	included	%mass yield			Paper gives profiles for yields at five final temperatures, also for GCV, energy yield, char analyses. Data not tabulated - picked off charts so approximate.
Lab-fast	Mante, 2008	62.69	included	%wt dry feed		25.64	
WFPP	Scott et al, 1999	66.5	11.6	%wt maf			
Lurgi	Henrich, 2007	70	included	?			Figures approx, taken off charts, to search for published data
Pyrovac	Birdgwater, Peacocke, 2000	47	17	%wt dry wood			
Lab - slow	Demirbas, 2001	47.2		?			Paper gives good profiles for yields at range of seven final temperatures, but not very representative technique. Five other feeds tested.
Lab-fast	Yanik et al, 2007	35	6	%wt	4.68		
RTI Process/ BioTherm Process	Scott et al, 1999	48.7	?	%wt moisture free feed			Scott paper gives very little data for RTI process, mostly for WFPP comparison. Discussion of RTI mostly on easier design requirements.
RTI Process/ BioTherm Process	Radlein and Kingston, 2007	58		%wt		16.5	
WFPP	Scott et al, 1999	44.7	8.1	%wt maf			Scott, 1985 gives similar data for wheat straw but only as a chart. At 500℃, however, char 35-40%, gas 15-17, total liquid 43-44. Data for two runs.
Lurgi	Henrich, 2007	54	included	?			Figures approx, taken off charts, to search for published data
Haloclean	Hornung, 2008	45	included	?		21	Data in presentations very patchy. Hoping for more detail from Horning, but not arrived yet.
Lab-slow	Zanzi et al, 2003	63		%wt maf			Yield basis probably % wt mf not maf - otherwise doesn't balance
Haloclean	Hornung et al, 2006	34.6	included	?		21	Data in presentations very patchy. Hoping for more detail from Horning, but not arrived yet.
Lab-slow	Lievens et al, 2009	18	22.3	% wt as fed		23-24	Low temp used to keep heavy metals in the char, but possibly not very charred at 350℃. High char yield includes ash, but if expressed on dry higher still - 61, 54.5% wt on dry. Earlier paper has data for higher temps, usual profile of falling yield of char - data on charts.
Lab-slow	Lievens et al, 2009	14.7	19.2	% wt as fed		20-25	Low temp used to keep heavy metals in the char, but possibly not very charred at 350℃. High char yield includes ash, but if expressed on dry higher still - 61, 54.5% wt on dry. Earlier paper has data for higher temps, usual profile of falling yield of char - data on charts.
Lab-slow	Zanzi et al, 2002	39		%wt maf			Yield basis probably % wt mf not maf - otherwise doesn't balance
BEST Energies	Downie et al, 2007	0					No oil product so balance of yield should be gas - 60% by wt. And from carbon analyses given can conclude 37% of C ends up in gas, so should be able to deduce gas quantity and energy from analysis.

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