CHAPTER 1
# Energy Crops: Introduction

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## 1.1 Introduction

Two major events that impacted significantly on the development of humankind involved the use of plants: our ability to make fire and our change from being hunter-gatherers to food-producers. The exact dates in which these advances first occurred are subject to debate but it is certain that they occurred in this order. Estimates suggest that agriculture arose some 10 000 years ago, whilst the control of fire may date back some 790 000 years.[1] As food production became more efficient, it became possible for larger numbers of people to live together. Human populations expanded and civilisations were born.[2] During this expansion, the requirement for plants to provide fuel was not in conflict with food production. Rather, this requirement diminished as alternative sources of energy were developed. As a result, twenty-five years ago, although plants were still being used for fuel in underdeveloped regions of the world, it was oil, coal, natural gas and nuclear power that together fulfilled most of the world's energy needs.[3]

Within a remarkably short timeframe, a major change then took place. The first steps of this process can be traced to the first oil crisis of the 1970s, when a sudden rise in the price of oil led to the first push for the development of renewable energies. In addition to food production, many governments supported the development of novel nonfood crops (see Chapters 11–18).

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These crops were harvested and combusted to produce heat and power, a contribution that continues today. However, a drop in oil prices in the 1990s stemmed enthusiasm and, other than the production of bioethanol in Brazil (see Chapter 5), bioenergy markets remained small.

A culmination of events then precipitated a "green energy" boom. Oil prices spiked and there was increasing concern over energy security. Moreover, numerous reports, particularly from the Intergovernmental Panel on Climate Change (IPCC)[4] and from Nicholas Stern,[5] focused attention on the substantial cost to humankind of *not* acting to reduce the current rate of increase in greenhouse gas (GHG) emissions. As the use of fossil fuels is a major contributor to climate change, the need for alternative sources of energy, which save carbon and are renewable, was placed quickly and firmly back at the top of global agendas.

There are many possible alternatives to fossil fuels, particularly for heat and power generation, *e.g.* wind, hydro, solar, as well as plant biomass, all of which are expected to play a role. However, there are few alternatives to replace transport fuels (*e.g.* electric, hydrogen). As the number of vehicles on the roads is continually rising, it is clear that, unless emissions from the transport sector can be curbed, they will counter any reductions achieved by other sectors. Combined with the desire of some nations to reduce their reliance on the fuel supplies of a few major producers, this resulted in a swift, strong push to increase the production of liquid transport fuels from crops and many food crops were exploited for this purpose (see Chapter 2–10). Simultaneously, the need for fossil-fuel substitutes for a whole range of products that currently rely on the refining of oil became apparent to the chemical industries.

As a consequence of these environmental and political drivers, three new markets have emerged for plants, all of which are potentially huge: bioenergy, biofuels and biorenewable materials (Figure 1.1). However, securing sufficient food for future populations remains a major challenge, particularly in the face of climate change. To balance all of these demands on plants will require little short of another revolution. One decade into this millennium, major challenges face humankind. "A Perfect Storm" were the words adopted by Professor Beddington, the UK government's chief scientific adviser, to draw attention to this recently.[6] He pointed specifically to research that indicated that by 2030 "a whole series of events come together": The world's population will rise from 6bn to 8bn (33%); demand for food will increase by 50%; demand for water will increase by 30% and; demand for energy will increase by 50%.[6]

Whilst crops certainly hold solutions to these challenges, they are also part of the problem. Agriculture is a major user of resource, including energy from fossil fuels, and is also another major contributor to GHG emissions. Research has drawn attention to the fact that producing energy from crops could have the opposite effect to what is intended, if the energy inputs exceed the carbon benefits and if the GHG emissions associated with any new cultivation for displaced food production are not taken into account.[7]

In this book, the potential contributions of different energy crops will be reviewed within the context of the different and sometimes conflicting

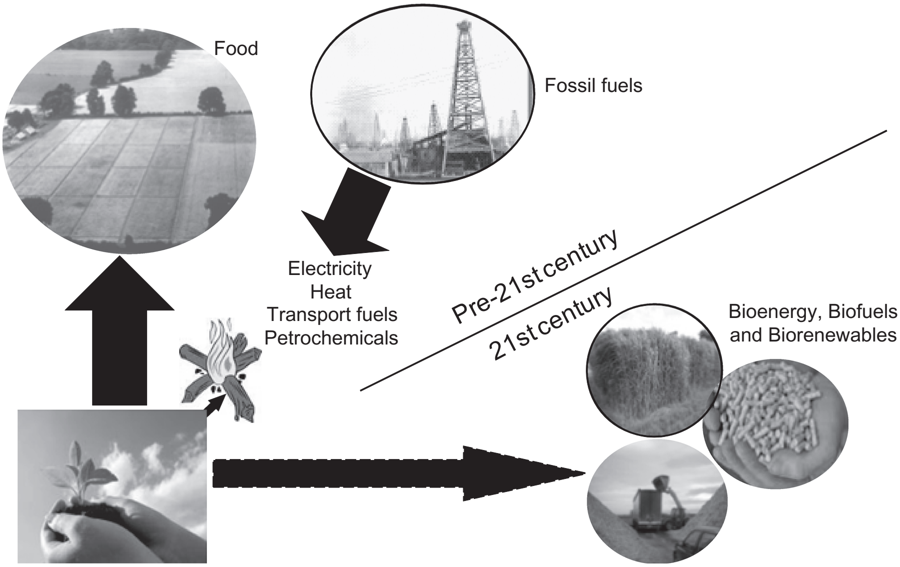


**Figure 1.1** Major challenges lie ahead. Until now, plants have predominantly provided food and although they have been used for fuel since early mankind, fossil fuels and nuclear power have increasingly supplied the world's energy needs. In the 21st century, crops will also be needed to supply raw materials for expanding bioenergy, biofuel and biorenewable markets.

challenges and drivers that are currently acting. By way of introduction, this chapter will introduce various bioenergy terms, outline how feedstock from energy crops can be converted into energy, briefly define the different types of energy crops and finally draw attention to the main components of the debate surrounding energy crop production. The principle aim will be to introduce the topics and not to comprehensively review them, as the subsequent chapters will provide the details.

## 1.2 Biorenewables, Bioenergy and Biofuel Definitions

''Biorenewables'' is an all-embracing term that covers the production of heat, power, transport fuel and other products from organic matter of recent (as distinct from fossil) origin. These converge in the ''biorefinery'' concept, which can be defined as the sustainable coproduction of a spectrum of biobased products (food, feed, materials, chemicals) and energy (fuels, power, heat) from biomass. However, not all biorenewable products are derived from biorefining *per se*. The need for more sustainable products with reduced carbon footprints has led to the development of many new supply chains from nonfood crops and wastes.

In this book we will confine our discussions to the production of renewable energy from biological materials, or ''bioenergy''. In practice, this term is sometimes used with reference only to renewable heat and power and sometimes also to include renewable transport fuels. Here, we adopt an earlier definition[8] and take it to mean the production of any renewable energy, reserving the use of the term "biofuels" for renewable liquid transport fuels only. Biofuels can be subdivided into "bioethanol" made from grain and sugar crops, which provides a substitute for petrol, and "biodiesel", made from vegetable oil, which is a substitute for diesel (see Sections 1.3.3 and 1.3.4).

Energy crops can be grouped on the basis of the main market their production is targeted at (*e.g.* "biofuel crops") and on the type of feedstock that they provide for conversion (*e.g.* "biomass crops"). This is then further qualified by taking into account the different conversion processes that can be applied and by virtue of the fact that more than one type of energy source can be obtained from the same crop.[8,9] Thus, the term "biomass crops" is most often used with reference to growing crops for the purpose of producing total biological mass as a feedstock, whilst "lignocellulosic crops" refers more specifically to use of the cell wall components of plants. "Bioethanol crops" and "biodiesel crops" refer to crops grown for production of bioethanol and biodiesel, respectively, and so on. There are also secondary classifications of "first" and "second" generation, depending upon whether conversion is based on simple sugars or more complex lignocelluloses as the energy source (see below). Whilst this book is not concerned with detailed descriptions of the conversion processes (a topic to be covered by another volume in this series), it is important to outline what they are in order to have clarity over the specific energy-crop system being referred to at any one time.

## 1.3 Converting Crops to Energy

There are four main routes to energy conversion that can be summarised as: direct combustion, thermal conversion (pyrolysis, gasification), biological conversion (anaerobic digestion, fermentation) and chemical conversion (transesterification).

### 1.3.1 Direct Combustion

Direct combustion is the oldest and still the most commonly used route for converting biomass to heat, power and combined heat and power (CHP). It is applicable at all scales from domestic to industrial, using boilers that range from small domestic stoves (1 to 10 kW) to the largest devices used in power and CHP plants ($>5$ MW). Biomass of many different forms can be used, including wood chip, pellets and different straws. The most efficient combustion is achieved when dedicated biomass boilers are used. However, solid biomass particles can also be mixed with coal in cofiring or cogeneration, enabling the large power-generation industries to reduce their carbon footprint by incorporating biomass as a percentage of their feedstock.

### 1.3.2 Thermal Conversion

In thermal conversion processes, high temperatures are used but energy is not produced directly from biomass. Instead, the biomass is converted to energy carriers such as synthetic gases, oil or methanol that have higher energy densities (and thus lower transport costs) and/or more predictable and improved combustion characteristics.[10] The two main thermochemical processes, pyrolysis and gasification, differ with respect to the presence/absence of oxygen.

Pyrolysis occurs in the complete absence of oxygen at temperatures in the range of 400–800 °C.[11,12] During this process, most of the cellulose and hemicellulose and part of the lignin, which together make up the lignocellulosic fraction, disintegrate and form gases. As these gases cool, some of the vapours condense to form bio-oil, which has potential as a substitute for fuel oil and as a feedstock for synthetic gasoline or diesel production. The remaining biomass, mostly comprised of lignin, forms charcoal.

Gasification requires partial oxidation and temperatures of around 800 °C. The biomass is partially burned to form "producer gas" and charcoal. The carbon dioxide ($CO_2$) and water ($H_2O$) in the producer gas are chemically reduced by the charcoal to form carbon monoxide (CO) and hydrogen ($H_2$). Producer gas contains 18–20% $H_2$, 18–20% CO, 8–10% $CO_2$, 2–3% methane ($CH_4$), trace amounts of higher hydrocarbons (*e.g.* methane and ethane), water, nitrogen (if air is used as the oxidising agent) and various contaminants such as small char particles, ash, tars and oils. The partial oxidation in the gasification process can be carried out using air, oxygen, steam or a mixture of these. When air is used, a low heating value gas is produced that is suitable for use in boilers, engines and turbines but not for transporting in pipelines, because of the low energy density. Gasification with oxygen or steam produces a medium heating value gas, which is suitable for limited pipeline distribution, as well as a synthesis gas or "syngas" (typically 40% CO, 40% $H_2$, 3% $CH_4$ and 17% $CO_2$, dry basis). Syngas can be used to make methanol, ammonia and diesel using Fischer–Tropsch synthesis,[10] first developed by F. Fischer and H. Tropsch in 1923.

### 1.3.3 Biological Conversion

There are two main forms of biological conversion: anaerobic digestion and fermentation. Both are well-developed technologies.

Anaerobic digestion (AD) is the breakdown of organic materials by bacteria in the absence of oxygen. Almost any organic material can be processed, including waste paper, grass cuttings, food waste, industrial effluents, sewage and animal waste. The result is a biogas made up of around 60% methane and 40% $CO_2$. Biogas can be burnt to generate heat or (once it is scrubbed) electricity. It can also be used as a biofuel. A solid and liquid residue called digestate is also produced, which can be used as a soil conditioner. The amount of biogas and the quality of digestates obtained vary according to the feedstock used. More biogas will be produced if the feedstock is putrescible, which means it is more liable to decompose. The use of sewage and manure produces less biogas as the animal that produced it has already removed some of the energy content.

Fermentation, followed by distillation, is the biological conversion process used for converting sugars to ethanol or, depending on the microbial strain, other low molecular weight alcohols. Most ethanol fermentation is based on Baker's yeast (*Saccharomyces cerevisiae*), which requires simple (monomeric) sugars as raw material. Conventional yeast fermentation produces 0.51 kg of ethanol from 1 kg of any of the C6 sugars, such as glucose and mannose, or sucrose. However, not all feedstocks contain simple sugars. Starch, for example, is a polymer and when starch is used a hydrolysis step is first required to break it down into simple sugars for fermentation. Bioethanol production from starch is now well established in the USA, with maize (Chapter 3) being the major raw material.

Polymeric carbohydrates are also present in all cell walls of the plant and potentially provide the most abundant source of carbon for bioenergy and biofuel production available on earth. However, in this form the sugars are not readily accessible, existing in the form of fibres, sometimes interlinked with lignin, and additional steps of pretreatment and hydrolysis are required to release the sugars for fermentation. The cell wall polymers of wheat are described in Chapter 2.

Fermentation and distillation to produce ethanol from sugar have been at the heart of the brewing and of the wine and spirit industries for a long time in human history. The same well-developed and efficient procedures have been used effectively to produce alcohols that can be used as fuels for internal combustion engines. This is well established in Brazil using sugar from sugarcane (Chapter 5), and is being developed in the USA using sweet sorghum (Chapter 4). When used as a biofuel, ethanol is blended with gasoline. The percentage blend depends on the engine type: a 10% blend (E10) can be used by most engines, whereas an 85% blend (E85) requires specialised flexifuel vehicles.

### 1.3.4 Chemical Conversion

The main chemical conversion process is transesterification which results in the production of biodiesel; effectively, biodiesel is the fatty acid methyl esters (FAME) produced from different oil-containing crops. In fact, lipids (*e.g.* from algae (Chapter 18)) and oils, either directly produced by crops or derived from processed vegetable oil from the food industry, can all be used as feedstock for conversion into biodiesel.

Biodiesel production begins with pressing the crop to produce a liquid oil fraction and an oil cake byproduct, which can be used as cattle feed. The liquid vegetable oils can be used directly as engine fuels, but this requires engine modification because of their very high viscosity, poor thermal and hydrolytic stability and less favourable ignition qualities. As a result, transesterification is used to transform the large, branched molecular structure of the oils into smaller, straight-chained molecules similar to those of standard diesel. There are three basic routes: (i) Base-catalysed transesterification; (ii) Direct, acid-catalysed transesterification; (iii) Conversion of the oil to its fatty acids and then to biodiesel. The base-catalysed method is the most commonly used because it uses low temperature (50–66 °C) and pressure (around 1.4 bar), has a high yield (98%) with minimal side reactions and reaction time, and it is a direct conversion to biodiesel with no intermediate compounds. The base catalyst is methoxide ($CH_3O^-$), which is generated by dissolving sodium hydroxide or potassium hydroxide in methanol. The process results in the formation of glycerol, a second byproduct, as well as the biodiesel that can be used as a substitute for, or additive to, petroleum-based diesel.

### 1.3.5 First-, Second- and Advanced-Generation Technologies

Biofuel production from crops in which the sugars/starches and oils are stored in forms that are easily accessible is often referred to as "first-generation" biofuel. This is because the fermentation of sugars and starches and transesterification of lipids and oils for biofuel production involves well-developed conversion technologies, the only real change being the use of the product for transport rather than human consumption.

In contrast, although cell wall polysaccharides represent an abundant potential source of sugars, their recalcitrance to breakdown presents a major challenge. The additional pretreatment and hydrolysis steps are currently inefficient, energy intensive and expensive to perform. Considerable optimisation of the enzymatic and physicochemical processes is needed to improve the efficiency of the conversion chain, or modification of the polysaccharides themselves through plant breeding or genetic modification, before biofuels can be cost-effectively produced in this way. As a result, the conversion of cell wall polysaccharides has become known as "second-generation" biofuel. The same is true for production of liquid fuel from gasification and pyrolysis. Although possible, large biomass volumes are required and considerable improvements in efficiency are needed for these to be truly commercially viable at the industrial scale.

In many ways, the terms first and second generation are misleading, since in practice there is a continuum of technological processes and numerous ways in which feedstocks and processes can be combined. This is also a very fast-changing field, and one into which considerable investment has been placed. Similarly, the distinction between second generation and more advanced generation technologies is often difficult to make.

One alternative that is also being explored is the use of fuel cells, which are devices that convert chemical energy directly into electrical energy. Ethanol or methanol produced from biomass by fermentation or chemical catalysis can be fed into the anode of a fuel cell and air or oxygen into the cathode. Electrolysis oxidises the ethanol or methanol to $CO_2$ and $H_2O$, generating an electrical current in the process that can be used to power electric motors. A challenge to this technology is that the membrane separating the anode and the cathode in the fuel cell is somewhat permeable to the alcohol fuels, which reduces efficiency. The ultimate advancement would be the use of hydrogen, instead of alcohols, to generate electrons in the fuel cell. Using hydrogen as a fuel in vehicles has attractions as it would generate only water as an emission. However, much further development is required and there are safety issues to be dealt with concerning hydrogen storage. At present, production of hydrogen from water is not yet feasible in practice but possible ways of using lignocelluloses for hydrogen generation are being developed.

## 1.4 Energy-Crop Types

In theory, any crop could be used as an energy crop. Over 80 are referred to in a recent handbook, for example.[13] In practice, however, issues relating to the availability of feedstock and the efficiency, cost effectiveness and sustainability of the whole chain, from field to fuel (see Section 1.5) restrict the choice. In this book, the major energy-crop types are covered by separate chapters and will simply be introduced here.

### 1.4.1 Grain and Seed Crops

The presence of wheat and barley seed in archaeological sites dating back to 6750 BC is testimony to the importance that cereals have played in the development of human societies. Today, maize, rice and wheat dominate world agricultural production and, together with a whole range of other grain and seed crops, provide the staple food of populations worldwide.[2]

Grain and seed crops have also traditionally been used in fermentation to produce beer, wine and spirits, because the stored carbohydrates (sucrose and starch) can be readily broken down by enzymatic systems. The adoption of this process to produce bioethanol for vehicles, however, has resulted in the use of food grain for nonfood purposes on an unprecedented scale. Maize (Chapter 3) and wheat (Chapter 2) currently make the largest contribution to biofuel production, matched only by that from sugarcane (Chapter 5) and oil palm (Chapter 10).[8] Maize is also used for biogas. In addition, the parts of cereal crops that are not used for food (*e.g.* wheat straw and corn stover) can be used as a source of biomass for thermal conversion and lignocellulose for second-generation biological conversion. Similarly, grain from sorghum as well as stalks of sweet sorghum (Chapter 4) can both be used for biofuels, whilst sorghum stovers could be used as a source of lignocellulose.

### 1.4.2 Sugar Crops

Sugars are transported in plant stems in normal development but some species can also store high concentrations. The main sugar crops used for bioenergy are sugarcane (Chapter 5), sugar beet (Chapter 6) and, as mentioned above, sweet sorghum (Chapter 4).

Bioethanol production from sugarcane is an extremely efficient and well-developed industry in Brazil (Chapter 5). Indeed, it is interesting to contemplate whether or not other biofuel crops would really be competitive if sugarcane could be cultivated throughout the world in the way that it can in the tropics and subtropics. Most certainly, it is among the most productive plants known and it is also able to store high concentrations of sucrose in the stem. In addition, sugarcane bagasse (the fibrous residue) is a primary fuel source, making most sugarcane mills extremely efficient. It could also be a source of lignocelluloses and the feasibility of producing ethanol from bagasse is currently under investigation. Sweet sorghum is adapted to both humid and tropical climates but can be grown in colder climates than sugarcane (Chapter 4). In cooler temperate climates, sugar beet (Chapter 6) can be used as a source of sugar for bioethanol.

### 1.4.3 Oil Crops

Oil palm (Chapter 10) is by far the largest producer of oil for biodiesel. However, a large range of alternative oil crops are grown in areas where the climate does not favour oil-palm production.[14] This includes soybean (particularly in the Americas) (Chapter 8) and oilseed rape (particularly in Europe and cooler temperate areas) (Chapter 7). More recently, Jatropha (Chapter 11) has been heralded as a promising biofuel crop for drought-prone environments, as well as other species, such as Pongamia (Chapter 12). Other oil crops, such as sunflower (Chapter 9), babassu palm, peanut and even olive are also used for biodiesel.

### 1.4.4 Dedicated Biomass Crops

As pointed out previously, biomass can be obtained from any crop. Indeed, practices such as using the whole wheat crop (grain included) for combustion are known to have been carried out (this probably exacerbates global warming through the production of nitrogen oxides, which are much more potent GHGs than $CO_2$). However, the term "dedicated biomass crops" refers to nonfood crops that are solely grown for biomass production. These comprise mostly perennial grasses and fast-growing trees. Dedicated biomass crops were first developed for combustion and thermal conversion technologies but, due to their potential to supply high yields of lignocelluloses, have become of interest for second-generation biofuels. Perennial grasses are also widely used for biogas, but wood chip is not suitable for this process.

An impressive number of perennial grasses are used as energy crops but, in this volume, coverage is restricted to the major ones; *Miscanthus*, (Chapter 15); switchgrass (Chapter 17) and reeds (Chapter 16).[12] Similarly, this volume covers two main fast growing trees: willows (Chapter 13) and poplars (Chapter 14).

### 1.4.5 Algae

Algae fall into two main types: microalgae (phytoplankton, microphytes or planktonic algae) and macroalgae (seaweed). Both are used for biofuel production, although microalgae have received most attention due to their ability to be grown in ponds and bioreactors. Macroalgae can be grown on ropes. As the photosynthetic efficiency of algae (6–8% on average) is higher than terrestrial plants (1.8–2.2% on average) they are able to accumulate biomass at faster rates. Other advantages are that they do not require the use of high-grade productive land and can utilise a wide range of water sources (fresh, brackish, saline and waste water) (Chapter 18).



## 1.5 The Energy-Crop Debate

Back in the 1970s, when oil prices first rose, the principle of growing crops for energy was encouraged without challenge. When biofuels first came along, they were heralded as "green gold" but, all too quickly, they became "a crime against humanity" and "food versus fuel" is a commonly heard phrase these days.

Two points remain clear: The challenges ahead are formidable (Figure 1.1) and energy crops have the potential to provide a source of renewable energy that can reduce GHG emissions and help combat climate change. However, put in very simple terms (which it most certainly is not), growing energy crops requires resources (land, water, energy) and using these resources for energy means that they are not available for food. Converting land use to energy crops may result in direct environmental impacts, for example on biodiversity, or water availability. Even if there is enough land to manage all these aspects favourably (a matter of much debate), the justification for energy crops becomes hard to defend if the energy inputs required from crop to fuel result in little or no carbon savings and GHG reductions.

The reason why little (if any) of these concerns were raised back in the 1970s and 80s is because the bioenergy system that was being encouraged was the use of dedicated biomass crops and crop wastes and the scale of land conversion was still relatively small. Out of a large potential number of species, a few perennial grasses and fast-growing trees were promoted because of their advantages as nonfood crops with the potential to produce high biomass yields with relatively low fertiliser inputs. Life-cycle analyses of biomass to heat and power produced in this way shows high carbon savings and GHG reductions. The use of first-generation food crops for biofuels is a different situation. Crops like maize and wheat require high nitrogen fertiliser inputs and the energy savings are therefore much lower, and (depending on the management) may even be negative. When only seed/grain is used there is also wastage and lower yield. Finally, there is direct competition with food production as the grain is diverted to an alternative use, although high-protein animal feed is a significant coproduct.

Much effort has been placed on improving the entire chain from crop to fuel, for all energy crops, and the calculation of energy balances is very much affected by the boundaries set on the system and the coproducts that are included. Nonetheless, there is general recognition that efficient second- and advanced-generation systems are needed, which access the cell wall polysaccharides in the nonedible parts of the plant. However, the biofuels debate took a more complicated turn with the publication of a paper in Science by Searchinger and colleagues.[7] They claimed that the increase in the use of maize for fuel would result in new plantings of maize around the world to make up the shortfall in food supply and that the GHG emissions resulting from this new land conversion would not only offset any savings but even result in a carbon debt. Although the assumptions made in the paper have been rigourously challenged, the outcome has been to slow down the pace of energy crops expansion and the message "proceed with caution" seems to sum up the situation now. These issues, only briefly touched on here, are covered in many of the chapters in relation to the crop being focused on.



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