A mini review on renewable sources for biofuel

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Abstract

Rapid growth in both global energy demand and carbon dioxide emissions associated with the use of fossil fuels has driven the search for alternative sources which are renewable and have a lower environmental impact. This paper reviews the availability and bioenergy potentials of the current biomass feedstocks. These include (i) food crops such as sugarcane, corn and vegetable oils, classified as the first generation feedstocks, and (ii) lignocellulosic biomass derived from agricultural and forestry residues and municipal waste, as second generation feedstocks. The environmental and socioeconomic limitations of the first generation feedstocks have placed greater emphasis on the lingocellulosic biomass, of which the conversion technologies still faces major constraints to full commercial deployment. Key technical challenges and opportunities of the lignocellulosic biomass-to-bioernegy production are discussed in comparison with the first generation technologies. The potential of the emerging third generation biofuel from algal biomass is also reviewed.

Keywords: Bioenergy; Agricultural residues; Organic wastes; Biomass; Energy crops.

1. Introduction

As global demand for energy continues to rise, carbon dioxide emissions are expected to reach new record high, increasing from 31 Gt in 2011 to approximately 37 Gt in 2035 (IPCC, 2013). The need for climate change adaptation and the growing concerns over energy security are the main drivers behind the policies of many countries (belonging to the Organisation for Economic Co-operation and Development (OECD)) that encourage the growth of renewable energy. Today, renewable energy contributes 13% of the total global energy consumption, in which bioenergy accounts for approximately 10% (Figure 1). Bioenergy refers to the energy content in solid, liquid and gaseous products derived from biological raw materials (biomass) (IEA, 2010). This includes biofuels for transport (e.g. bioethanol and biodiesel), products to produce electricity and heat (e.g. wood chips and pellets), as well as biogas (e.g. biomethane and biohydrogen) produced from processing of biological materials from municipal and industrial waste (IEA, 2013).

Figure 1

Biofuels for transport represent the major fraction of bioenergy production worldwide. Biofuels are primarily produced from food crops with high content of sugar and starch, such as corn and sugarcane to produce ethanol, and oil seeds to produce biodiesel (IEA, 2010). These first generation technologies have been the first significant step of transition away from the traditional fossil fuels. It has then moved forward to the next generations of biofuels produced from non-food biomass, including residues of crops or forestry production (e.g. forest thinning, sawdust, etc.), dedicated energy crops (e.g. switchgrass, poplar, and miscanthus), lignocellulosic fraction of municipal and industrial solid waste, and algal biomass (Gupta et al., 2014; Sims et al., 2010).

More than two-thirds of bioenergy comes from the first generation land-based feedstocks (Figure 1), leading to growing concerns over competition for land and water for food and fibre production and other environmental issues related to land-use changes (Gasparatos et al., 2013; IEA, 2010). Therefore, the use of residues and wastes for bioenergy production has attracted more interest as they are often readily and locally available in most of the countries. Potential of lignocellulosic biomass varies and depends on the type, abundance and cost of biomass feedstocks, efficiency of the available processing technologies, and the pattern of energy demand. This paper reviews different existing and potential biomass sources with emphasis on lignocellulosic biomass, and identifies the challenges in the deployment of second generation technologies to meet future energy targets.

2. Biomass resources and their bioenergy potential

2.1. First generation feedstocks

Biofuel production has been increasing rapidly in the last decade and currently supplies 3.4% of global road transport fuel requirements, with a considerable share in Brazil (21%), and an increasing share in the United State (US; 4%) and the European Union

(EU; 3%) (IEA, 2013). Around 40 million gross hectares (2.5% of global cropland) (FAOSTAT, 2011) are used for bioenergy crops, mainly for biofuel production as bioethanol and biodiesel, and biogas, all involving arable food crops. The traditional feedstocks for first generation biofuels can be categorised as starch and sugar crops (for bioethanol), and oil seeds (for biodiesel).

2.1.1. Starch/sugar crops for bioethanol

The first generation bioethanol is produced by fermentation of crops high in sugar (e.g. sugarcane, sugar beet, and sweet sorghum) or by a series of hydrolysis/fermentation steps for starchy crops (e.g. corn, wheat, and cassava). Corn-based ethanol is dominating the global market with approximately 60 billion litres produced in 2012 with the US being the largest supplier, followed by sugarcane-based ethanol at 20 billion litres produced mainly by Brazil (REN21, 2013). Other marginal feedstocks that are used to produce bioethanol include but are not limited to sugar beet (EU), maize, sweet sorghum (China, US, Brazil), cereal (Canada, EU), and cassava (Nigeria, Brazil, Thailand, and Indonesia) (Table 1).

Table 1

The process to convert sugar-based biomass to ethanol is rather simple, involving the fermentation of C_6 sugars (mostly glucose) using yeast species such as *Saccharomyces cerevisiae* or *Zymomonas mobilis* (Lin & Tanaka, 2006). Fermentation of starch is more complex than fermentation of sugars because starch must first be hydrolysed to fermentable sugars with the aid of enzymes (α-amylase) (Lin & Tanaka, 2006). As a result, the energy requirement for starch-based ethanol is significantly greater than that for sugar-based ethanol. The by-products of ethanol conversion processes, such as dried distillers' grains and solubles (DDGS), can be used as protein-rich sources for animal feed, adding to the overall profitability of the whole process.

There are about 650 ethanol plants operating globally, together providing a total annual capacity of 100 billion litres (REN21, 2013). A litre of ethanol contains approximately 66% of the energy that provided by a litre of petrol (Wang et al., 1999). Ethanol can be burned directly or blended with petrol to improve fuel combustion in vehicles, resulting in lower CO_2 emission, reduction in petroleum use as well as fossil energy use. In particular, the use of E10, a commercial product having 10% ethanol blended with regular petrol, achieves 6% reduction in petroleum use, 2% reduction in GHG emissions, and 3% reduction in fossil energy use (Wang et al., 1999).

2.1.2. Oil crops for biodiesel

Biodiesel can be produced by combining oil extracted from seeds and oil-rich nuts with an alcohol through a chemical process known as transesterification (Balat & Balat, 2010). The most common oil crops are rapeseed in EU, soybean in US and Latin America, and palm and coconut oil in tropical Asian countries (such as Malaysia and Indonesia). The oil content in rapeseed and soybean is 35% and 21%, respectively (Ramos et al., 2009). Palm oil with 40% of oil content has the highest oil yield per area (~5 tons per ha) as compared to other oilseeds (e.g. 1 ton/ha for rapeseed and 0.52 tons/ha for soybean) (Balat & Balat, 2010). Additionally, beef tallow and used cooking oil can also be used as feedstocks for biodiesel conversion. Global biodiesel production in 2012 was 22.5 billion litres, with the EU (led by Germany) accounted for 41% of total production, followed by the US (16%), Argentina, Brazil and China (>10% each) (REN21, 2013).

The major difference between various oil feedstocks is the types of fatty acids attached in the triacylglycerols (TAG), which determine degree of saturation/unsaturation and molecular structure (Ramos et al., 2009). All these factors, in turn, affect production processes, quality and costs of the biodiesel products (Ramos et al., 2009). The transesterification of oil to biodiesel is a stepwise reaction of TAG with an alcohol (mostly methanol) to form esters and glycerol in the presence of catalyst (Balat & Balat, 2010). Thus, the majority of biodiesel can be produced using alkali-catalysed transesterification process as it is the most economical option, requiring low processing temperature and pressure while achieving a 98% conversion yield (Balat & Balat, 2010). On the other hand, Enzyme-catalysed processes are gaining interest due to low energy consumption, reduced soap formation and high purity of glycerol (Christopher et al., 2014). However, high enzyme cost and low reaction rate are two main obstacles to the commercialisation of these processes. The conversion process typically yields valuable by-products such as glycerol for food and pharmaceutical uses and crushed bean ‘cake’ as animal feed.

Similar to bioethanol, biodiesel can be used as pure fuel or blended with petroleum-based diesel for use by compression-ignition diesel engines. The most common biodiesel blended products are B2 (2% biodiesel and 98% petroleum diesel), B5 (5% biodiesel and 95% petroleum diesel), and B20 (20% biodiesel and 80% petroleum diesel). Biodiesel is not currently cost competitive with petroleum-based diesel due to the increasing prices of the vegetable oils (made up 45-70% of overall production cost). Hence, improving process efficiency and increasing use of the by-products can reduce the production cost.

2.1.3 Sustainability issues of the first generation feedstocks

The production of biomass feedstocks and its conversion to bioenergy have numerous socio-economic and environmental impacts. Although the first generation biofuels have been commercialised worldwide with mature technologies and markets, its sustainability has been questioned based on the competition with food crops and the effects on the environment and climate change (Gasparatos et al., 2013). Biofuel use represents an increasingly important share of global cereal, sugar and vegetable oil production. By 2020, bioethanol share will increase to 13% of annual global corn production compared to 11% on the average over the 2008-2010 period, and 35% of global sugarcane production compared to 21% over the baseline period of 2008-2010 (OECD-FAO, 2011). The share of vegetable oil to be used for biodiesel production at the global level is expected to reach 16% compared to 9% over the baseline period of 2008-2010 (OECD-FAO, 2011). The outlook of OECD-FAO certainly raises concerns about the impact of biofuel on food prices and food supply. A study of Fischer et al. (2009) predicted that biofuel expansion may further increase the price of agricultural commodities by 8-34% (cereals), 9-27% (other crops), and 1-6% (livestock) by 2020.

Furthermore, reduction in water and soil quality due to intensive use of fertilisers and agrochemicals has also been linked to the increased biofuel production, in particular to the expansion of sugarcane-ethanol in Brazil and palm oil-biodiesel in Southeast Asia (Gasparatos et al., 2013). Therefore, increased biofuels production also reduces water availability to food production, and add more pressure on water resources in countries facing increased risk of water scarcity such as India (OECD-FAO, 2011). Other impacts of biofuel production and use include greenhouse gases (GHG) emissions, air pollution, biodiversity loss, deforestation and rural development, among several others (Cherubini

& Strømman, 2011; Gasparatos et al., 2013; Popp et al., 2014). The cumulative environmental and social impacts of biofuel production derived from food crops have stimulated an interest toward less expensive and readily available biomass such as forest, agricultural, and municipal wastes.

2.2. Second generation feedstocks

Under the pressure of food security versus elevating global energy demand, lignocellulosic biomass is expected to be a major player in the transition toward low-carbon economies. The second generation feedstocks comprise of non-food lignocellulosic materials which can be divided into three main groups: (i) homogeneous, such as wood chips from energy crops with a price value of US$100-120/ton, (ii) quasi-homogeneous, such as agricultural and forest residues estimated at US$60-80/ton, and (iii) non-homogeneous, including low-valued municipal and industrial solid wastes between US$0-60/ton (Lee & Lavoie, 2013). In the past few years, there have been extensive research on potential feedstocks and significant progresses for improving the second generation technologies (Balat & Balat, 2010; Christopher et al., 2014; Gupta et al., 2014; Sims et al., 2010). However, several technical and economic hurdles still need to be addressed before they can be widely deployed. In 2012, about one-third of total bioenergy production was derived from agricultural and forestry residues (REN21, 2013). In particular, China has produced 3 million litres of ethanol from corn cobs and used in blends with gasoline; US has also made progress on advanced biofuels with the production in 2012 reaching 2 million litres, and projected to 36 million litres in 2013, partly for the military use (REN21, 2013). Several demonstration plants have been built in Europe with small capacities in operation.

2.2.1. Dedicated energy crops

Energy crops, developed and grown specifically for fuel, include perennial grasses (such as miscanthus, switchgrass and reed canary) and short rotation forestry (such as willows and poplar). These crops can be grown on poor or degraded soils while providing higher energy yields (Table 2) and a steady supply stream, avoiding costly storage of large biomass volumes between harvests.

Table 2

a. Perennial grasses

Switchgrass which originated from North America and miscanthus from Southeast Asia are among the best choices in terms of low input bioenergy production in the US and EU because of their tolerance for cool temperature, relatively low water and nutrition requirements, and their ability to grow on a broad range of land types using conventional farming practices (Lewandowski et al., 2003). Switchgrass usually require 3 years to reach productive maturity and produce dry matter yields reportedly between 5-19 tons/ha/year, corresponding to 0.8-3.0 toe (ton of oil equivalent) per ton (Heaton et al., 2004). Similarly, Miscanthus take 2-3 years to obtain full production and requires rhizome cuttings, resulted in additional costs associated with propagation. The established stands, however, can maintain productivity for at least 14 years with high biomass yields ranging from 5 to 43 tons/ha/year (Cadoux et al., 2012). Crop yields of perennial grasses strongly depend on local conditions, e.g. climate and land quality, and management system, e.g. irrigation and fertilisation.

Other potential herbaceous crops include reed canary grass, giant reed and alfalfa adapted to temperate regions, banagrass, napiergrass, and johnsongrass in tropical and subtropical regions (Prochnow et al., 2009; Ra et al., 2012). These perennial grasses are also effective for carbon sequestration and soil stabilisation, thus helping reduce erosion, and improving water quality and wildlife habitat (Lewandowski et al., 2003). Intercropping of perennial crops and annual food crops such as alfalfa and corn has been demonstrated to increase crop yields and to improve land-use efficiency (Zhang et al., 2011).

b. Short rotation wood crops

Some fast growing trees have also shown promise for biofuel production because of their high yield, wide geographical distribution, low costs, and less labour consuming comparing to annual crops (Hauk et al., 2014). Among the species, poplar, willow (abundant in temperate regions) and eucalyptus (mostly in tropical regions) are most frequently mentioned. Willow and poplar are used in short rotation of about 3-4 years and the yield can reach up to 8-10 tons dry matter/ha/year, whereas the rotation cycles for eucalyptus are 4-6 years with an average of 12 tons/ha/year (Hauk et al., 2014).

While the advantages of short rotation forestry and perennial grasses over annual agricultural crops are clear, these dedicated energy crops are still land-based, and thus not entirely escaping the food versus fuel debate. Only where food and fibre crops are not feasible would potential energy crops be the most beneficial.

c. *Jatropha*

Jatropha (*Jatropha curcas*) has been seen as an ideal crop for cheap biodiesel production. Jatropha, native in tropical America, is a multi-purpose drought resistant tree that grows well on degraded or marginal land, and has seeds with high oil content (~40%) (Koh & Mohd. Ghazi, 2011). Therefore, it benefits semi-arid and remote areas of developing countries. In the last 5-7 years, approximately 1.5 to 2 million hectares of Jatropha have been planted each year, resulted in a total of approximately 13 million hectares by 2015, distributed across India (73%), South-East Asia (21%), and Africa (6%) (Carriquiry et al., 2010). Jatropha oil can be used locally for fuel vehicles, diesel generators, or cooking stoves without a transesterification into biodiesel (Koh & Mohd. Ghazi, 2011). Some other species with biodiesel potential include pongamia, mahua, castor and linseed. Their potential seed and biofuel yields are summarised in Table 3.

Table 3

2.2.2. Agricultural/forestry residues

Agricultural and forestry residues represent a tremendous source of readily available biomass for biofuel production without the need for additional land cultivation. Agricultural residues include wheat straw, corn stove (leaves, stalks, and cobs), and bagasse (sugarcane waste), while forestry residues are comprised of logging residues, fuel wood extracted from forestlands, and primary and secondary wood-processing mill residues. It is estimated that annually around 5.1 billion dry tons of agricultural residues and 501 million of forestry residues are produced globally (IEA, 2010). However, only 10-25% of these could be used for bioenergy production. The technical potential from available annual supplies, therefore, has been estimated in terms of energy at over 100 EJ/year, with costs in the range of USD$2-3/GJ (IEA, 2010).

Biomass residues differ significantly in their properties and chemical composition (Table 4), consisting mainly of polysaccharides cellulose (hexose sugars, 35-50%), hemicellulose (a mix of hexose and pentose sugars, 20-35%) and lignin (Singh et al., 2010). These components are more resistant to being broken down than starch, sugar and oils in the conventional food crops, making the conversion processes more complicated, and more expensive.

Table 4

2.2.3. Municipal and industrial wastes

Approximately 1.3 billion tonnes of municipal solid waste (MSW) comprising primarily of putrescibles, papers, cardboards and plastics has been produced in 2012 (IEA Bioenergy, 2013). While the composition of MSW is highly variable, its major fraction is biodegradable with a significant calorific (heat) value and makes it suitable to energy recovery operation. It is estimated that a tonne of MSW produces approximately 8-12 GJ, one-third of the calorific value of coal and generate about 600 kWh of electricity (Chang et al., 1997). In addition, the food and paper industries also produce a large number of residues and by-products that can be used as biomass for bioenergy production. Industrial solid wastes include but are not limited to peelings and scraps from fruit and vegetables, meat and poultry waste, pulp and fibre from sugar and starch extraction, coffee grounds, etc., and all can be utilised as an energy source. The waste-to-energy approach is closely linked to the recent waste management practices which have moved away from disposal towards recovery, reuse, recycling and reduction. It offers numerous bioenergy applications replacing fossil fuels with the potential environmental benefits such as landfill space savings, and reduction in GHG emission.

2.2.1. Technological routes for bioenergy production

While lignocellulosic biomass is the most abundant and renewable resource available for human exploitation their variable compositions and recalcitrance contents represent some technical and economic challenges. The conversion process of lignocellulosic biomass can be divided into two main routes, namely bio-chemical and thermo-chemical routes (Figure 2). Before hydrolysis, lignocellulosic materials need to be pretreated to remove the recalcitrance (i.e. lignin) and to increase accessibility of the cellulose (and hemicellulose) to hydrolysis. Several pretreatment options are available, varying from physical (e.g. mechanical comminution, milling and ultrasound), chemical (e.g. ammonia fibre explosion, acid or alkali addition) to biological (e.g. enzyme addition) processes, each having different temperatures and reaction times (Gupta et al., 2014; Sims et al., 2010). The pretreatment process is the major cost component of the overall biofuel conversion process (Nichols et al., 2010; Sims et al., 2010), and selection of the suitable method depends on the characteristics of the residue biomass.

Figure 2

In the bio-chemical route, saccharification of cellulose and hemicelluloses components is a process of hydrolysis through which the polymeric carbohydrates release monomeric sugars, and subsequently fermented to ethanol. Saccharification can be achieved either chemically by acid hydrolysis with sulphuric acid or biochemically by the use of cellulase and xylanase enzyme systems of bacteria and fungi (Lee & Lavoie, 2013). While the acid hydrolysis approach is comparatively cheap, its application is limited due to low yields and unfavourable environmental issues involved with the use of strong acids. On the other hand, the enzymatic hydrolysis has the advantages of high yields, high selectivity, and producing less or no by-products to dispose of at the end of the process; however, the cost of cellulose may account for up to 15% of the cost of biofuel production (Klein-Marcuschamer et al., 2012). Although there has already been significant improvement to the cost of enzymes, reported in the range of US$0.1-0.4 per gallon of ethanol produced (Klein-Marcuschamer et al., 2012; Lennartsson et al., 2014), a further reduction is required to make it more cost competitive to the first generation enzymes for hydrolysis of starch, which remains around US$0.04/gal (Lee & Lavoie, 2013).

The thermo-chemical route covers specific thermal processes known as pyrolysis (550-750 ^{o}C) and gasification (750-1200 ^{o}C) in which biomass is heated and converted into different types of liquid (bio oil) and gaseous fuel (syngas) (Lee & Lavoie, 2013).. Bio oil requires further treatment via hydro-processing to produce hydrocarbon fuels and other by-products, whereas syngas can be used as a fuel for heat supply, or as a feed to manufacture a wide range of long carbon chain biofuels, such as synthetic diesel, aviation fuel, or methanol via the Gas-to-Liquid (GTL) platform (Sims et al., 2010). While potential exists on both large and small scales for GTL, this technology faces a number of challenges including high technical complexity, high capital costs, and financial risks associated with the process reliability, and natural gas and crude oil price volatility (Yue et al., 2014). In general, when compared with biochemical route which focuses primarily on the conversion of polysaccharides, the thermo-chemical processes can essentially convert all the organic components of the biomass into a range of products. Both conversion routes can potentially convert 1 tonne of dry biomass (heating value of 19.5 GJ/t) to around 6.5 GJ/t of energy carrier in the form of biofuels, which is equivalent to a biomass to biofuel conversion ratio of 1:3 (Mabee et al., 2006).

The economics of the existing processes could be enhanced when surplus heat-power (syngas) and co-product generation (bio-oil and long-chain hydrocarbons) are included in an integrated biorefinery system. Biorefinery is the sustainable processing of biomass into a spectrum of marketable products (e.g. food, feed, materials, and chemicals) and bioenergy (e.g. fuels, power and heat) (IEA Bioenergy, 2013). As a result, the biorefinery approach can maximise biomass conversion efficiency, minimise raw material requirements, while at the same time enhance the economic values of various market sectors (e.g. agriculture, forestry, chemical and energy) (IEA Bioenergy, 2013). The new concepts of biorefineries such as Whole Crop, Lignocellulosic Feedstock, and Thermo Chemical Biorefineries which are still in R&D stage involve producing a broader range of materials and chemicals by employing several conversion technologies and types of feedstocks. As a result, these facilities offer high processing flexibility and reduce the risk of investment (Gnansounou & Dauriat, 2010).

In this context, biomethane (biogas) is another important co-product during the conversion of lignocellulosic biomass to bioenergy. Biomethane is a versatile energy source which can be used for heating of residential and industrial facilities, for production of electricity with co-generators and combined heat and power (CHP) units to generate electricity with efficiency up to 42% and productive heat with a thermal efficiency of up to 50%. Biomethane can also be applied as vehicle fuel if it is compressed (compressed natural gas, CNG) or liquefied (liquefied natural gas, LNG) with energy content of approximately 10 kWh, corresponding to one litre of petrol. The market for natural gas vehicles (NGVs) has been increasing in many countries due to a combination of low-cost natural gas and higher prices for gasoline and diesel. At the end of 2012, there were about 16.7 million NGVs operating globally in all classes of vehicles including motorcycles, cars, buses and trucks (NGV Global, 2014).

2.2.1. Technical and economic challenges for commercialisation

Substantial progress has been made over recent years for the core technologies (e.g. enhanced hydrolytic enzymes, fermentation strains, and process integration). Some larger scale advanced biofuels plants are in operation and the first commercial scale plants in the US and EU were recently commissioned (REN21, 2013). However, the progress of commercialising advanced biofuels produced from lignocellulosic feedstocks has been slower than previously projected. The main obstacle for its deployment is high investment requirements (35-50% of the total cost) combined with several operational and political/policy uncertainties (Yue et al., 2014). The capital cost for a commercial scale plant is estimated to be in the order of $300-600 million, which is 2-3 times higher than the investment cost for a corn-ethanol plant (Popp et al., 2014).

In addition, feedstock supply chain and technology are yet proven at large-scale, representing major operational risks. Challenges remain for feedstocks production, supply and logistics, including seasonal nature and annual variability of biomass, their spatial distribution, and costs associated with preprocessing, storage and transport. A combination of high production cost (estimated above US$0.8/L of gasoline equivalent (IEA, 2010)) and the lack of supporting policies and mandates has limited market acceptance and competition for the second generation biofuels at the current stage.

2.3. Third generation feedstocks

The potential of algae to provide biomass for biofuel production has been widely accepted. Algae are aquatic photosynthetic microorganisms that grow rapidly on saline water, coastal seawater, municipal wastewater or on land unsuitable for agriculture and farming (Chen et al., 2011; Pittman et al., 2011). They are capable of converting light and carbon dioxide through cellular activities to produce a variety of chemicals including carbohydrates, proteins, lipids, vitamins, and pigments that have numerous applications in chemical and pharmaceutical industries, cosmetics, health food and feed supplements (Costa & de Morais, 2011; Ugwu et al., 2008). Microalgal species accumulate mostly lipids (e.g. TAG). Species such as *Botryococcus* and *Chlorella* have high lipid content (50-80%) which is adequate for biodiesel production (Costa & de Morais, 2011). Macroalgae and cyanobacteria such as *Chamydomonas* sp., *Cyanothece* sp. and *Spirulina platensis* accumulate mostly carbohydrates, thereby producing bioethanol when fermented (Costa & de Morais, 2011).

Algae can double their biomass in 2-5 days, which is a significant advantage when compared with other feedstocks harvested once or twice a year (Costa & de Morais, 2011). They produce a high dry weight biomass yield up to 60 tonnes/ha/year (*Pleurochrysis carterae*), from which approximately 20 tonnes of oil could be extracted (Moheimani & Borowitzka, 2006). This productivity from algae is five times higher than that achieved from oil palm, the highest yielding oil crop plant (Day et al., 2012). In addition, algae have no lignin and low hemicellulose levels, resulting in an increased hydrolysis efficiency, higher fermentation yields and thus reduced cost (Li et al., 2014). Algal biomass can be used to produce different types of renewable biofuels other than biodiesel and bioethanol. Biohydrogen is another a popular product which can be used in fuel cells whereas biomethane produced as a part of integrated processes can be used for transportation, electricity generation or for heating purposes (Costa & de Morais, 2011).

There are still many challenges associated with algal-biofuel production which involves the following key processes: algal cultivation, production modes, photobioreactor design, and downstream treatment processes (Chen et al., 2011). Cultivation of microalgae is considered as one of the major constraints to commercial development. Generally, cultivation can be done either on open bonds requiring low capital costs but having low biomass yield, or in closed bioreactors or hybrid systems with high capital costs and high yield (Chen et al., 2011; Costa & de Morais, 2011). Therefore, there is a trade-off between investment cost and algal biomass productivity. In addition, algal species and strains vary greatly in terms of growth rate, productivity, photosynthetic efficiency, nutrient requirements, and ability to adapt to adverse conditions (John et al., 2011). When screening algal strains for commercial biofuel production, high biomass yield with high carbohydrate and lipid contents are the desirable criteria. However, in order to maximise the production of lipids, cells growth and photosynthesis are often compromised, resulted in a decrease in overall productivity (Day et al., 2012; John et al., 2011). Addressing this problem might require intensive fundamental research on genetic modification and manipulation of lipids and cellulose synthesis pathways to enhance productivity. Furthermore, improving the efficiency of downstream processing, conversion and extraction techniques would enhance the commercial viability of algal biofuels.

3. Future outlook

Bioenergy is certainly becoming a greater part of the global energy mix and is projected to contribute up to 20-30% of the overall primary energy worldwide by 2035 (IEA, 2013). Biofuel production for transport has, and will, exhibited the most rapid growth, fostered by government support. In order to meet the ambitious targets in the New

Policies Scenario, the supply of all types of biomass will need to increase several folds, posing major challenges for agriculture and forestry activities and raising concerns over the potential environmental and social-economic impacts. Although the production of first generation bioenergy is in an advanced state with mature technologies, available infrastructure and markets, it is criticised for its land use implications on food prices and production. In the New Policies Scenario, the share of traditional biomass (sugar/starch crops and oil seeds) in total primary energy demand is expected to drop from 5.7% 3.9% between 2011 and 2035 (IEA, 2013).

On the other hand, the advanced biofuels derived from lignocellulosic and algal biomass offers the prospect of increasing biofuels supply with less land requirement while enhancing green-house gas mitigation. At the current stage, the second generation technologies are relatively mature, with a few commercial scale units and around 100 plants at pilot and demonstration scale worldwide whereas the third generation technologies are still under research and development. In the New Policies Scenario, although advanced biofuels are expected to gain market share after 2020 and reach 20% of biofuel supply in 2035 (IEA, 2013), there are still some technical and policy barriers to overcome before the technologies can be commercialised worldwide. High investment expenditure and high unit production cost make lignocellulosic biofuels less competitive to fossil fuel or many first generation products. Integrating second generation processes to already existing first generation infrastructures could be a practical option to reduce the investment costs and technological risks. To achieve lower production costs, a consistent and sustainable supply of cheap raw materials is essential. Furthermore, all components of the biomass including intermediates and by-products should also be considered and utilised in a biorefinery system to enhance the economic viability of the process.

4. Conclusion

To meet strong demand growth in the New Policies Scenario, the bioenergy supply chain cannot rely solely on one source but a combination of different biomass feedstocks including both food and non-food crops. Widespread development of the second and third generation technologies will require lower costs achieved via further technological progress and a continual policy support. The transition toward next generation biofuels will offer medium- to long-term solutions to the depletion of fossil fuels and global climate change.

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Table 2. Biomass and biofuel yields of different energy crops

Crop	Establishment time (years)	Biomass yield (ton/ha/year)[a]	Biofuel yield (toe/ton)[b]	References
Willow	3+	5 – 11	0.7 – 1.8	(Aylott et al., 2008)
Poplar	3+	2 – 10	0.4 – 1.5	(Aylott et al., 2008)
Eucalyptus	4+	10 - 12	0.2 – 1.2	(Romanelli et al., 2012)
Miscanthus	3+	5 - 43	0.8 – 6.9	(Cadoux et al., 2012)
Switchgrass	2 – 3	5 – 19	0.7 – 3.0	(Heaton et al., 2004)
Reed canary grass	1 – 2	2 – 10	0.3 – 1.2	(Singh et al., 2010)
Alfalfa	1 – 2	1 – 17	0.1 – 1.5	(Gallego et al., 2011)
Fibre sorghum	1 – 2	16 - 43	2.1 – 5.7	(Barbanti et al., 2006)

[a] yields are expressed in dry matter

[b] toe = tons of oil equivalent

Table 3. Oil content and production of non-edible oil seeds

Species	Oil fraction (%)	Seed yield ($x10^6$ tons/year)	Oil yield (tons/ha/year)
Jatropha	40 – 60	0.20	2.0 – 3.0
Mahua	35 – 40	0.20	1.0 – 4.0
Pongamia (Karanja)	30 – 40	0.06	2.0 – 4.0
Castor	45 – 60	0.25	0.5 – 1.0
Linseed	35 – 45	0.1	0.5 – 1.0

Source: Koh and Mohd. Ghazi (2011)

Table 4. Composition and yield of different feedstocks (based on dry mass (DM))

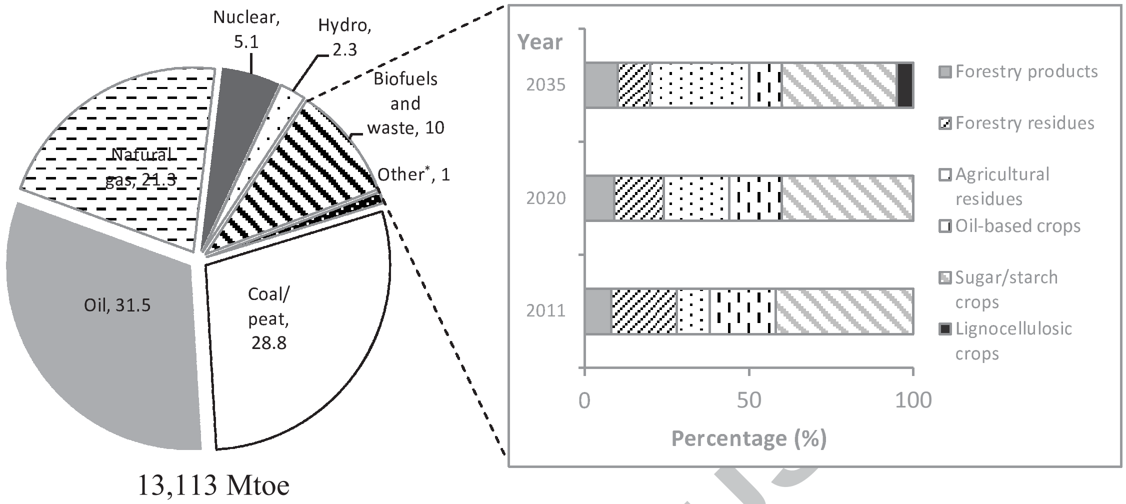
Feedstocks	Residue/ crop ratio	Dry matter (%)	Cl. (%)	Hc. (%)	Lg. (%)	Heating value (GJ/ton)	Biofuel yield (L/ton)
Forest residues							
Black locust	-	-	42	18	27	19.5	390
Hybrid poplar	-	-	45	19	26	19.6	416
Eucalyptus	-	-	50	13	28	19.5	411
Spruce	-	-	43	26	29	19.5	417
Pine	-	-	45	20	29	19.6	436
Agricultural residues							
Barley straw	1.2	88.7	43	30	7	18.9	367
Corn stover	1.0	86.2	46	35	19	18.0	503
Rice straw	1.4	88.6	40	18	7	18.2	392
Sorghum straw	1.3	89.0	44	35	15	18.6	199
Wheat straw	1.3	89.1	40	28	16	19.0	410
Bagasse	0.6	26.0	33	30	29	19.4	3,133
Solid waste							
Processed paper		-	47	25	12	16.3	-
Plastics		-	65	15	7.5	34	-
Food waste		-	45	5.3	13	18.6	-
Poultry waste		-	11	16	4	17.5	-
Solid cattle manure		-	2.7	2.3	4.5	17.1	-

Sources: Chang et al. (1997), Singh et al. (2010), Carriquiry et al. (2010), and Choi et al. (2014).

FIGURE CAPTIONS AND FIGURES

Figure 1 World primary energy demand in 2011 (left; IEA, 2013) and share of solid biomass supply for biofuels and power generation by feedstocks in 2011 and in the New Policies Scenario (right; WEO, 2012).

Figure 2 Conversion pathways from different biomass feedstocks to intermediates and to final biofuel production (Modified from Yue et al. (2014)).



* Other includes geothermal, solar, wind, heat, etc.

Figure 1

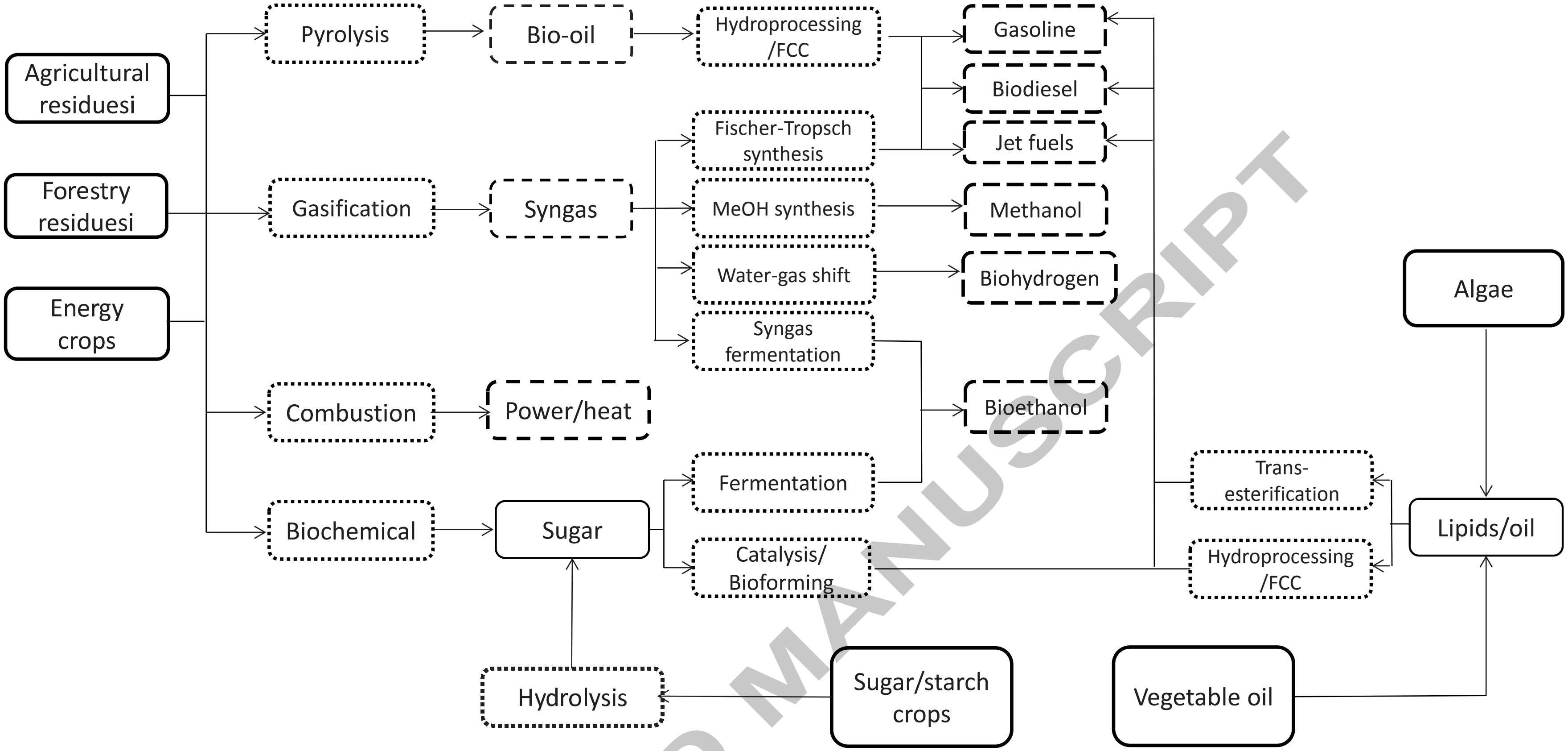

Agricultural residuesi
Forestry residuesi
Energy crops
Pyrolysis
Bio-oil
Hydroprocessing /FCC
Gasoline
Biodiesel
Jet fuels
Gasification
Syngas
Fischer-Tropsch synthesis
MeOH synthesis
Methanol
Water-gas shift
Biohydrogen
Syngas fermentation
Algae
Combustion
Power/heat
Bioethanol
Fermentation
Trans-esterification
Biochemical
Sugar
Catalysis/ Bioforming
Hydroprocessing /FCC
Lipids/oil
Hydrolysis
Sugar/starch crops
Vegetable oil

Figure 2

Highlights

- The use of food-crop related biomass for 1st generation biofuel is unsustainable
- 2nd generation lignocellulosic biomass are ready for full commercial exploitation
- 3rd generation algal biomass represents potential renewable source
- A combination of three generations will need to be met growing energy demand