SYMPOSIA

Development Perspectives Of The Biobased Economy: A Review

J. W. A. Langeveld,* J. Dixon, and J. F. Jaworski

ABSTRACT

This paper provides an outline of the biobased economy, its perspectives for agriculture and, more particularly, for development purposes. Possibilities of development of biobased products, advanced biofuels, and viable and efficient biorefinery concepts are explored. The paper lists non-fuel bioproducts (e.g., chemicals, pharmaceuticals, biopolymers) and presents basic principles and development options for biorefineries that can be used to generate them alongside biofuels, power, and by-products. One of the main challenges is to capture more value from existing crops without compromising the needs and possibilities of small-scale, less endowed farmers. Biobased products offer the most development perspectives, combining large market volumes with medium to high price levels. Consequently, the most can be expected from products like fine chemicals, lubricants, and solvents. In addition, biosolar cells can help to relax pressures on biomass production systems while decentralized production chains can serve local needs for energy, materials, and nutrients as their requirement for viable economic development are linked to larger markets. Research challenges include development of such production and market chains, and of biosolar cells and selection of model crops that offer perspectives for less favored producers and underdeveloped rural areas.

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Abbreviations: 1,3 PDO, 1,3-Propanediol; DDGS, Distillers Dried Grains with Solubles; DME, Dimethylether; EU, European Union; GAP, Good Agricultural Practices; GHG, Greenhouse gas; MDG, Millennium Development Goal; MFC, Microbial Fuel Cell; PET, Polyethylene terephthalate; PHA, Polyhydroxyalkanoate; PLA, Polylactic acid; R&D, Research and development.

With the adoption of the Millennium Declaration, the realization of poverty alleviation and sustainable development received renewed attention and support. The Millennium Development Goals (MDGs) were subsequently formulated. The most important of these goals for the CGIAR system is the halving of hunger and poverty by 2015 in developing countries strongly linked to agriculture. Modest progress toward MDGs is occurring in a dynamic context characterized by changes in demography, markets and prices, institutions and culture, policies, agricultural and environmental resources, and technological development.

The discussion of agricultural futures in a biobased economy in this article is framed by the commitments underpinning the MDGs. This assumes that agricultural production to meet the new demands, which will emerge in a biobased economy, will be complementary to basic agricultural products and services required to meet the basic requirements of mankind echoed in the MDGs, especially those related to food, health, and environment.

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Agriculture still underpins key livelihoods for most people living in rural areas. In addition to the provision of food, fiber, and energy, agriculture also contributes to poverty reduction and economic development by providing employment in and income from value chains. Diversification, defined as an increased number of activities generating farm output or added value for the farm household, can be defined at different levels (e.g., field, farm, region, or country) of aggregation.

The development of a biobased economy will take place in an uncertain context, contributed to by climate change, production of biofuels, fossil fuel price, global financial systems, and the nexus with food security. Between 1970 and 2004, greenhouse gas (GHG) emissions increased by 70%. By 2015 the world will need to provide extra food for an additional 750 million people. Land use management, agronomy and livestock sciences, and technological development are key factors determining the net outcome of these processes. Proper agricultural management can contribute to increasing carbon soil sinks (Govaerts et al., 2009), reducing GHG emissions and providing feedstocks for bioenergy. Industrial production technologies can provide new uses for agricultural feedstocks.

The potential of the bioeconomy extends well beyond bioenergy. While a small share of fossil oil is used for chemical production and the remainder for fuel and energy, the economic value of the food and chemistry sectors is approximately equal. A long term and sustainable market can be envisaged for technologies that produce chemicals, materials, and pharmaceuticals from plant-based feedstocks (Sanders et al., 2007), which will supplement the emerging demand for bioenergy feedstocks and the still growing demand for food and other agricultural products.

Such a development will need to be supported by processing steps that are energy efficient and cost-effective. Biorefineries provide sufficient opportunities to allow such a development. The development of the bioeconomy has often been portrayed as sustainable or environmentally friendly, but there are key resource-related concerns that need to be addressed as biobased systems evolve. These include non-renewable energy use, renewable energy and land use efficiency, carbon emissions and sequestration, soil fertility and erosion, water quality and quantity, wildlife habitat, invasive species, and crop pests (Anex, 2007).

This article explores possibilities of biomass application for development purposes—in particular, biofuels, biobased products, and biorefineries. It provides an overview of non-fuel products, including chemicals, pharmaceuticals, and biopolymers, and discusses basic principles and development options for biorefineries that can be used to generate both fuels and products. Furthermore, it discusses development opportunities and research requirements in light of developing a biobased economy that offers opportunities for small-scale farmers in less developed areas.

BIOBASED PRODUCTS

Facing a future shortage of petrochemicals, biomass is expected to be the main future feedstock for chemicals. The use of vegetable oils, crop starch, residual proteins (from biofuel production), and cellulose (from straw and wood) to produce polymers, lubricants, solvents, surfactants, and specialty and bulk chemicals traditionally made from fossil feedstocks is receiving more and more attention (Van Haveren et al., 2007). Currently only a tiny proportion of the huge variation of compounds produced by plants is tapped for commercial use. The challenge is to create viable business models for biobased products, and to tailor plants and plant systems to optimize available functionalities. To this purpose, dedicated programs implemented in the United States, European Union (EU), and elsewhere (e.g., Canada, Japan, Malaysia) apply industrial crops and biomass for high-value products in advanced production chains.

Biobased products refer to non-food products derived from biomass (plant, animal, marine, residual), ranging from high-value added (usually low volume) fine chemicals (pharmaceuticals, cosmetics, food additives) to high volume materials (enzymes, biopolymers, biofuels, fibers, etc.) They may include existing products (paper and pulp, detergents, lubricants), or new ones (vaccines made from plants or second generation biofuels).

Biomaterials

Modern non-medical biomaterials include pharmaceuticals, chemicals, specialty products, industrial oils, biopolymers, and fibers (Thoen and Busch, 2006). Production of pharmaceutical feedstocks, providing a major opportunity for agriculture and household livelihoods, is based on the provision of genetic material and production of feedstocks. It involves specialist knowledge markets with small production volumes. The high added value provides a potential avenue for development, but given high research and development costs, it may require long term collaborative relations to link farmers to research, production, and marketing activities.

Chemicals and their feedstocks provide more predictable markets and specifications than pharmaceutical products. Chemical markets refer to bulk chemicals with high volumes, but low values, and fine chemicals with smaller market size, but higher added value. The potential list of biobased chemicals is considerable and includes 1,3-Propanediol (1,3 PDO), a building block for polymers that is mostly made from maize (*Zea mays*) syrup by modified *Escherichia coli* bacteria. The world market has been estimated at 230,000 t in 2020 (Carole et al., 2004). Succinic acid, another chemical building block, is generated by the fermentation of glucose and is applied in food, the chemical industry, and pharmaceutics. The world market currently amounts to 25,000 t (Sijbesma, 2009). Both 1,3 PDO and succinic acid are targets of efforts to improve production efficiency (Carole et al., 2004; Koutinas et al., 2008) involving crops like sugarcane (*Saccharum officinarum*), maize, rice (*Oryza sativa*), barley (*Hordeum vulgare*), and potato (*Solanum tuberosum*) (Thoen and Busch, 2006).

Specialty chemicals serve as adhesives, solvents, and surfactants (an important group of products applied in detergents, cosmetics, and manufacturing processes). Surfactants, still mainly petroleum-derived, are increasingly made from renewable feedstocks. Production exceeds 2 million t. They provide a large market for renewable feedstock, mostly tropical vegetable oils (Turley, 2008). Coconut (*Cocos nucifera*) and oil palm (*Elaeis guineensis*) are preferred feedstocks because of the shorter length of their fatty acids. Longer-chained oils from temperate crops (rapeseed- *Brassica spp.*, sunflower-*Helianthus annuus*) are more suited for use in polymers, lubricants, adhesives, solvents, and surfactants.

Solvents, applied in the manufacturing of pharmaceuticals, paints, and inks, are increasingly produced from biobased products like ethyl lactate, a lactic acid derivative (Carole et al., 2004). Lactate esters are produced from alcohols and fatty acids, with both obtained via fermentation of carbohydrates (cereals, potato, and sugar beets). Rapeseed and sunflower oils are major sources of fatty acids; soybean (*Glycine max*) oil provides the most vegetable resins (Johansson, 2000).

Industrial oil products like high quality lubricants and hydraulic oils offer considerable biobased market potential. Biolubricants constitute an innovative area for agriculture and industry. Biobased hydraulic fluids comply with industrial quality standards, as do soy based color inks, which dominate due to superior performance (Nowicki et al., 2008). Sunflower and safflower (*Carthamus tinctorius*) oils have high oxidation resistance, while oils high in erucic acid (crambe-*Crambe maritima*, carinata– *Brassiaca carinata*) show more lubrication qualities (Lazerri, 2009).

Bioplastics show huge opportunities, given that plastics are extensively used worldwide (Carole et al., 2004). Starch plastic application, beginning already in the 1970s and currently being commercially produced, offers a major end use for cassava (*Manihot esculenta*) (Nigeria, Brazil), maize, and wheat (*Triticum aestivum*). Starch properties depend on the amylose/amylopectin ratio and size of starch granules. Amylose ethers offer biodegradable alternatives for polyethylene and polystyrene (Somerville and Bonetta, 2001).

Commercially interesting polyesters, made from starch or sugar via fermentation, include polylactic acid (PLA) and polyhydroxyalkanoate (PHA) (Turley, 2008; Vaca-Garcia, 2008). The PLA is competing with fossil polymers like PET and links to the large market of packaging and fiber/fiberfill materials. The main feedstock is glucose syrup made from maize, cane, potato, or wheat (Vaca-Garcia, 2008), but may, in the future, be of lignocellulosic origin (Carole et al., 2004; Dornburg et al., 2006). Starch-based bioplastics are applied as packaging materials, kitchenware, car interiors, horticulture devices, and diapers (Johansson, 2000).

Fossil fibers like polyester or nylon offer large opportunities for biobased feedstocks (Carole et al., 2004). Natural fibers can be applied in high value-added composite materials using cellulosic feedstocks from wood and straw, plus classical crops like kenaf (*Hibiscus cannabinus*), sisal (*Agave sisalina*), jute (*Corchorus spp.*), flax (*Linum usitatissimum*), and hemp (*Cannabis sativa*). Additionally, eucalyptus (*Eucalyptus spp.*) may replace synthetics like rayon (Nowicki et al., 2008). Composite materials based on cellulosics offer special qualities (reduced weight, improved safety, and good acoustic properties), and natural fibers are being used to reinforce synthetic materials rather than replace them (Vaca-Garcia, 2008).

Development Perspectives

The size of existing (fossil dominated) markets and potential biobased shares shows large variations. The highest market volumes are reported for polymers, solvents, and surfactants. The best prospects are for pharmaceutical ingredients, enzymes and specialties (solvents, surfactants) (Carole et al., 2004), followed by bulk chemicals and biopolymers (Nowicki et al., 2008). Biobased market developments are supported by ambitious policies in the EU and the United States—the latter targeting a 12% replacement of chemical feedstocks in 2010 and 25% in 2030 (Thoen and Busch, 2006). At current fossil oil prices, however, production is not competitive (Lazerri, 2009).

Impacts of enhanced biomaterial production and application include:

- reduced demand for fossil fuels;
- increased added value generation for biomass producers and traders;
- reduced GHG emissions;
- industrial development;
- development opportunities for rural areas, including employment;
- reduced toxicity and enhanced health implications.

While not all these impacts are options for developing countries, it is difficult to evaluate biobased product groups in terms of their development prospects. They will represent combinations of market size, price plus potential share for biobased feedstocks, and the opportunities this offers for farmers in developing countries or local laborers (Table 1).

Evaluating a combination of opportunities (feedstock added value, employment, import replacement, export) offered by the entire production chain, rather than considering biomass feedstock market values alone, suggests

Table 1. Main development perspective of biobased products.†

Product	Feedstocks	Market size	Market price	Potential biobased share	Potential biobased production size	Potential impact for local producers	Potential local employment	Prospects for development
Pharmaceuticals	Selective crops	Very small	Very high	Very high	Very low	Very low	–	Very poor
Bulk chemicals	Starch, sugar crops, proteins	Very large	Low	Modest	Very low	Very low	–	Poor to modest
Fine chemicals	Oil, starch, sugar crops, straw	Very small	Average to good	Low	Low	Modest	Very limited	Modest to good
Solvents	Oil, starch, sugar crops, straw	Small	Low	Very low	Very low	Very low	Very limited	Very poor
Surfactants	Various	Small	Low	Modest	Low	Low	Very limited	Poor
Lubricants	Oil crops	Very small	Low	Modest to high	Low	Low	Good	Modest to good
Polymers	Mostly starch & sugar crops	Very large	Very low	Low	Modest	Very low	Very limited	Very limited
Fibers	Lignocellulosic crops, residues, grasses	Modest	Rather low	Low	Modest	Low	Good	Modest to good

†Source: composed by the authors using data on market size and price and projections of potential market share and size as well as expected perspectives (employment, income) for local biomass producers and laborers.

that fine chemicals, lubricants, and fibers may offer the best prospects for developing countries.

Research Priorities

Bioproduct research initiatives focus on plant breeding, product development and improvement of production processes. Pharmaceuticals, oil products, and (fine) chemicals often have specific feedstocks. Other product types could be made from larger numbers of crops. In practice, however, production chains often are based on a single crop, such as Dow's PLA, which is made from maize.

Perspectives of breeding are reviewed by Ranalli (2007). Van Beilen et al. (2007) explored the use of sugar beet (*Beta vulgaris*), tobacco (*Nicotiana tabacum*), and *Miscanthus* (*Miscanthus spp.*) for production of chemicals, biopolymers, and fuels. With some exceptions (e.g., tobacco in Zimbabwe, Malawi, China, and Laos), these crops are not generally cultivated by smallholders in developing countries. Restrictions on genetic modification may limit the development of suitable plant varieties.

There is need for a knowledge platform for research on oil-producing plants that are more productive in existing and designer oils, and to identify molecular markers for breeding (Graham, 2007). The EPOBIO, a research consortium in Europe, considers three crops: rapeseed, oat (*Avena spp.*), and crambe (*Crambe abyssinica*) (Carlsson, 2007).

Commercial exploitation of less common fatty acids (e.g., retrieved from *Calenda officanalis*) is hindered by low yield, small seeds, and limited geographical distribution. Further, there is a need to understand the metabolic pathways and molecular interactions linked to a given fatty acid. Many genes have been identified that could be used to alter oilseed fatty acid composition. Transgenic plants created with these genes show low yields, leaving many unanswered questions (Graham, 2007).

ADVANCED BIOFUELS

While many government policies are based on the principle that biofuels should not compete directly with food security, the reality is that biofuel production, whether first or second generation, may compete for scarce natural resources (soil, water, nutrients). Naturally, as agricultural productivity increases, resources can be freed from food production for the production of energy and biobased products. This section explores some options for the sustainable and balanced development of an agriculture providing food and fuel, and the scientific and technological needs for the next generation of biofuels produced in a biobased economy, recognizing that the ultimate limitation on the production of biomass lies with photosynthesis.

Cereals constitute the majority of all crops cultivated, making up 70 to 90% of reported arable annual crops. The potential of cereal biorefinery for biobased production (e.g., biofuels) in developing countries is restricted by public perceptions of cereals as food—although a large and growing proportion of cereal grains is used for animal feed. Social tensions caused by the food versus fuel debate have put serious limits on this development pathway, sometimes leading to the exclusion of specific crops, and defining detailed environmental, economic, and social criteria to be met by producers in other situations.

Sugar and oil crops, two other major sources of first generation fuels, are less common, but may play an important role in specific regions. Research and development have been much less spectacular than those reported for cereals, but still significant efforts for improvement have been made, often in close collaboration with industry.

Availability of lignocellulosic crop residues, a major feedstock of second generation biofuels, is determined by crop area, yield, harvest index, and demand for other purposes, such as livestock fodder. The greatest biomass productivity is expected for sugarcane in Brazil, followed by maize in the U.S. Second generation technology could, however, threaten soil fertility as soil cover is removed, and in a similar fashion soil erosion and soil health, including the depletion of soil nutrients, structure, and organic matter, which underpins agricultural productivity and food security.

While the impact of large-scale cultivation of biomass for first or second generation biofuels is debated, a greater consensus appears to exist about small-scale biomass for biofuel applications in developing countries. Local production of biomass, or local use of residues, may help local communities improve access to renewable energy sources and, hence, reduce workloads and pressure on wood resources, and help gain independence from often expensive fossil fuel sources. This holds promise for less endowed small-scale farmers in isolated inland areas.

Still, developments that take advantage of new technologies are needed to avoid the food vs. fuel controversy, sometimes referred to as 'next generation biofuels'. A specific scientific development is focusing on photosynthesis, production of sugars by plants (and some bacteria), using chlorophyll to harvest solar energy. As photosynthetic efficiency fundamentally limits potential biomass production, it is important to examine ways to increase the current efficiency.

Although higher photosynthetic efficiency may result in a higher production of biomass, energy delivered from this biomass still could not avoid competition with food. In theory, future biofuel systems can be envisaged in which plant fuel cells tap photosynthetic products directly. This bypasses the development of plant structural elements (stems, root, and reproductive elements), potentially realizing productivity and efficiency gains. Innovative applications of biotechnology, nanotechnology, and genomics provide tools to study and understand the fundamental processes of photosynthesis, starting from the molecular building blocks via the thylakoid membrane to the leaf. This knowledge is the key to improving the efficiency of photosynthesis, either by direct energy tapping or by the production of energy-efficient biomass (Fig. 1).

Development Perspectives

The potential contribution of crops or plant systems with enhanced photosynthetic capacity cannot be easily overestimated. Improving existing light use efficiency rates by a tenth of the current values can lead to considerable yield potential increases. The potential for development-related improvement will depend on the application of an enhanced production system. Artificial leaves and biosolar cells are most likely to be implemented in high tech environments and will, for the time being, not be directly linked to vulnerable groups in developing countries.

Algal production may be implemented in a less sophisticated setting, offering potential for resource-poor farmers in the tropics, in ways similar to the complex and integrated crop–fish production systems of Southeast Asia. In the long run, however, these systems may relax biomass constraints, both locally and on an international level. They, further, may be expected to lead to increased input use efficiency (offering more biomass for the same input of water, nitrogen, phosphorus, etc.). Their impact, in combination with other innovative photosynthetic-related research (e.g., on transplanting C4-systems into C3-crops) can be tremendous.

Research Priorities

Current cereal research for advanced biorefining focuses on improving starch and straw for biofuels. Cell wall structure degradability is expected to become an important breeding target, while production of polymers and bioplastics would require breeding for other, specialized, traits.

There are many lignocellulosic crops that are extensively found in developing countries. Choice of a specific crop will depend on agro-ecological and economic conditions. Poplar (*Populus spp*.), a fast growing, vegetative propagated crop native to temperate and subtropical regions, whose genome (40,000 genes) has been sequenced, has been defined as an ideal research crop. Research focuses on insect and disease resistance, herbicide tolerance, and lignin content (Boerjan, 2009).

Miscanthus, a perennial grass, has a high yield potential and can be grown effectively under low input conditions. It is, however, not fully developed for widespread cultivation. There are urgent needs to establish a robust breeding program. Potential improvements of *Miscanthus* include tolerance to drought and low temperatures, stem borers, and fungal diseases (Clifton-Brown et al., 2008).

New concepts for increasing photosynthetic efficiency that are currently being developed include (Arshadi and Sellstedt, 2008):

- Artificial leaves, using light to extract electrons from water to produce hydrogen and synthetic gas. This involves ultra fast light harvesting and micro reactors, a photocatalysis system, and an inorganic nanostructure to generate the fuels;
- BioSolar Cells, which are organisms designed with synthetic biology to produce fuels (butanol, methanol, ethanol, lipids, and hydrogen) without the biomass intermediate, and with a positive contribution to solving the CO_2 problem. Solar energy may be temporarily stored in a carbohydrate biofilm grown on a low-cost biobattery system;
- Plant Microbial Fuel Cells (MFCs) for nondestructive in situ harvesting of bio-energy, which is carbon neutral and free of combustion emissions. Oxidation of organic compounds produced by plant cells and excreted by roots generates electricity as bacteria donate electrons to an anode;

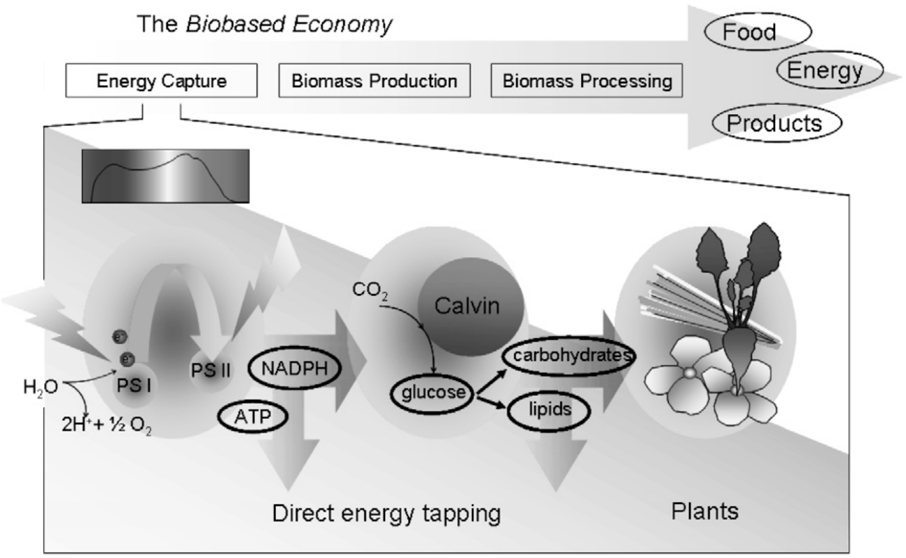

Fig. 1. Options to improve energy capture by plants for enhanced production of food, fuels and products.

- Biofuel and fatty-acid producing algae or cyanobacteria. Algae known to contain very high contents of oil are slow growers. In addition, production of omega-3 fatty acid can be performed by marine algae. Optimizing the photosynthetic capacity of algae will enable commercial production for biofuels and food.

The suggestions discussed above link to innovative and exciting research on more efficient photosynthetic systems, e.g., the introduction of an efficient C4-system with its high CO_2 upload capacity at the surface of the Rubisco enzyme by the transfer of sets of genes to C3-crops such as rice or wheat. This would allow an improvement of the Rubisco system, playing a central role in C3 photosynthesis, which is less efficient at current CO_2 concentrations and will lead to more efficient water use. Another example is the combination of bacteria photosystems absorbing light in the near infrared where plants, algae, and cyanobacteria are not active.

Clearly, it is a long road before advanced systems for direct photosynthetic harvesting can be expected. Major technological challenges lying ahead include improving genetic aspects of photosynthetic systems, increasing insight in biochemical production and composition of photosynthetic products and enzymatic mechanisms, plus development of feasible, affordable, and effective production systems. Other applications, such as the use of algae or cyanobacteria, are close at hand. Successful application will require efficient production systems and organisms adapted to these systems.

PROCESSING FOR THE BIOBASED ECONOMY: BIOREFINERIES

The biorefinery concept aims to make optimal use of plant components. In this concept, energy production is not a primary, but only one optional application of biomass. Feedstock selection, logistics, and biorefining techniques are used to optimize valorization of available functionalities and biomass utilization. Complex input-output chains help to realize optimal economic and social opportunities. This is done by first generating (low volume) high added value products, followed by other, less valuable products (Fig. 2).

The following biorefinery types can be distinguished: (i) whole crop, (ii) oleochemical, (iii) lignocellulosic feedstock, and (iv) green.[1]

A whole crop biorefinery processes grain into a range of products, usually via 'dry' or 'wet' milling and consequent fermentation and distilling of grains (wheat, rye, maize). Wet milling starts with water-soaking to soften grain kernels, followed by grinding. It uses well-known technologies to separate starch, cellulose, oil, and proteins. Dry milling grinds whole grains before mixing the flour with water, adding enzymes and cooking the mash to break down the starch. This hydrolysis step can be eliminated by the simultaneous use of enzymes and yeast. After fermentation, ethanol is distilled, concentrated, purified, and dehydrated. The residue (stillage) is separated into a solid (wet grains) and liquid (syrup) phase, which can be combined and dried to produce distillers dried grains with solubles (DDGS), an animal feed. Alternatively, grains may be processed into starch, and further to polymers or bioplastics. In a simultaneous process, straw can be converted into energy or products, following the principles of the lignocellulosic feedstock biorefinery discussed below (Clark and Deswarte, 2008).

An oleochemical biorefinery combines production of biodiesel with that of high added-value vegetable-oil

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[1] Description of biorefineries is based on Kamm et al. (2006), Clark and Deswarte (2008), and De Jong et al. (2009).

based products. It uses oil-crop fatty acids, fatty esters, and glycerol to produce (basic) chemicals, functional monomers, lubricants, and surfactants. In the long run, oleochemical biorefining may produce feedstocks for fossil-based refineries. Success of the biorefinery will depend on its integration with existing fossil chains, its building blocks providing a neat interface (De Jong et al., 2009).

Lignocellulosic feedstock biorefinery encompasses transformation of lignocellulosic biomass into intermediate outputs (cellulose, hemicellulose, lignin) to be processed into a spectrum of products and bioenergy. Three processing routes may be chosen. Following the bio-chemical route, a Sugar Platform Biorefinery treats lignocellulosic biomass to release cellulose, hemicellulose, and lignin. Cellulose then is converted using enzymatic hydrolysis into glucose, mannose, and xylose. The sugars are converted into biofuels (ethanol, butanol, hydrogen) and/or added-value chemicals. Lignin is applied in combined heat and power combustion, but may in the future be transformed into added-value chemicals (De Jong et al., 2009).

Thermo-chemical refining applied in the Syngas Platform Biorefinery consists of high-temperature-cum-pressure gasification of lignocellulosic biomass into syngas. The gas is cleaned and used to produce biofuels [Fischer-Tropsch diesel, dimethylether (DME), or alcohol] and/or a variety of base chemicals (ethylene, propylene, butadiene, etc.) using catalytic synthesis processes (De Jong et al., 2009). A mixed approach, the so-called Two Platform Concept Biorefinery (or Integrated Bio/Thermo-chemical Biorefinery), integrates sugar and syngas refineries to generate bioenergy and/or biobased products. For this purpose, sugars are treated and biochemically processed, whereas lignin is thermochemically treated. Sugar refining (fermentation and distillation) and syngas residues are applied in combined heat and power production units to cover (part of) the energy requirements.

Green biorefineries, feeding grass to a cascade of processing stages, offer an innovative alternative processing route for grass feedstocks. Essential is the mechanical grass ("green biomass") fractionation into a liquid phase containing soluble compounds (lactic acid, amino acids) and a solid phase mainly consisting of fibers. Overall economic efficiency of the biorefinery is mainly determined by the economic return of the fibers (De Jong et al., 2009). Major characteristics of these dominant biorefinery processes are presented in Table 2.

Development Perspectives

Biorefineries offer prospects of enlarged sector output value and prospects for growth of smallholder farmers' incomes, but value added and income effects will depend on product and market differentiation. The relevance of biorefineries for development depends on a link to available biomass resources, options for economic conversion routes in developing countries, and the scale and location of the biorefineries.

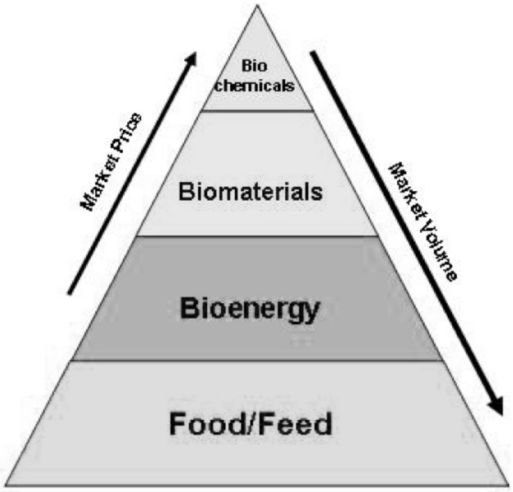

Fig. 2. Market prices versus market volumes biobased "products." Source: De Jong et al. (2009).

Major sugar and starch crops can be applied in fermentation processes that provide inputs for the production of chemicals, specialty products, and fuels. Vegetable oils can be applied as plasticizers, lubricants, dyes, and resins. While most small-scale farmers produce some of these crops, they will not necessarily profit from future biobased developments. Well endowed large-scale farmers are the first to fill the need for extra biomass feedstocks. To realize development potentials, biorefineries should fit in the needs and possibilities of small scale farmers and their families.

Further, their role in production chains should safeguard perspectives for a profitable feedstock provision and/or integration in labor patterns and local employment, while increased demand for local resources (land, water) should not limit their access to such critical resources. It is likely that the best prospects are for systems with limited capital requirements or systems providing a guarantee for a long collaboration. Refineries offering cheap and local sources of energy, and activities that reduce water contents of (intermediate) feedstocks (limiting transportation costs and risks of decay) offer the best development options.

The potential of lignocellulosic biomass production in developing countries is huge, but current use or ecosystem service (fuel production, biodiversity, water capture) places limits on its application. Marginal lands may provide only low to moderate yield levels. The potential for the production of chemicals, lubricants, and other biobased products has to be evaluated but second generation bioethanol production may be a viable alternative locally.

Sugar beet has been identified as model crop for research on chemical building blocks, but its relevance for developing countries currently is limited. Cassava, a local low-cost source of starch, has interesting prospects as a source of bioethanol. EMBRAPA has bred cassava

Table 2. Main characteristics of major biorefinery types.†

Biorefinery	Feedstock & conversion	Impacts	Remarks
Whole crop biorefinery	Cereal crops, dry or wet milling	Link to monomer and polymer production, but large scale production leads to competition with food production. Straw applicable to lignocellulosic biorefinery.	Mainly from maize, wheat. Moderately capital intensive.
Oleochemical feedstock biorefinery	Oil crops (rape seed, soybean, oil palm)	Links to production of chemicals, functional monomers, lubricants, and surfactants. Direct competition with food.	Close to full commer-cialization. Capital intensity is moderate.
Lignocellu losic biorefinery	Lignocellulosic crops, residues of food & feed crops	Reduced competition with food, feed production, high water use efficiency, high potential for GHG emission reduction.	Not yet on commercial scale. Capital intensive.
Green Biorefinery	Mainly grass	Links to production of proteins, sugars and fibers. No direct competition with food.	R&D phase.

†Source: Kamm et al. (2006), Wolf et al. (2005), De Jong et al. (2009).

cultivars with high sugar content specifically designed for bioethanol production.

Research Priorities

Prospects for biorefinery research are mainly found in determining its potential for development applications. What refinery systems offer opportunities to poor farmers in isolated areas? How are existing systems for food and the systems for feed production and processing linked? Routes need to be identified to develop cheap and robust, but efficient, systems that do not threaten the position of vulnerable groups.

Priorities for research should be linked to those formulated for crop applications (biobased products, biofuels). As was discussed above, a combination of market size, price, and perspectives for competitive feedstock production must be considered against the needs and possibilities of rural poor plus farmers. Extra attention here is needed to link existing crop production with biorefinery systems and to define systems that are best fit to serve local needs, while preserving fragile social and ecological systems.

DISCUSSION

From a value chain and systems perspective, the biobased economy opens a range of research and development issues, which can be grouped into four principal emphases along a “U impact pathway/value chain” framework (Dixon et al., 2007). These are (i) consumer preferences, (ii) process engineering, (iii) socioeconomics, and (iv) production.

First, market research needs to be done on consumer preferences for biobased products. While of less importance when such products are used in intermediate steps, consumer acceptance of innovative biobased end products will need to be assured. In many cases consumers may prefer biobased products to petroleum products provided quality is not compromised. While there has been consumer resistance to GM products in many countries, this may be different for non-food applications.

Related to this, and moving down the produce value chain, a strong growth in process engineering research may be expected, especially related to process efficiency, food safety, and risk assessments. In this connection, good agricultural practices (GAP) promoted in agriculture and processing by FAO are of significance. Public-private partnerships could coalesce around improved crop cultivars and production practices for smallholder farmers. Research could also refer to ex ante impact assessment with a particular focus on equity outcomes of biobased economy.

Third, in relation to sustainable development, research on production and processing scale is important. In the early stages of the development of a biobased economy, downsizing processing technologies and plant sizes to the local level will contribute to three economic drivers. A larger share of the farm population will have the opportunity to grow feedstocks, including those in poor marginal environments. Local employment opportunities will be created in regions lacking in development opportunities, while short feedstock value chains may raise farm gate feedstock prices.

Related to this is the organization of processing facilities. Economies of scale may be expected to apply to biobased production as they do to food production chains. Feedstock production may in many instances be expected to cluster biorefineries, which may often be located in higher production areas (e.g., irrigated areas), thus indirectly leading to negative equity outcomes. Application of remote and local pre-treatment units linked to central processing facilities may provide an interesting alternative for this problem (Clark and Deswarte, 2008).

On the other hand, by-products can stimulate the development of enhanced secondary income generating opportunities, e.g., distiller’s grains as concentrate feed for animal fattening activities. Therefore, livestock extension and improvement may well be an ideal complement to biorefinery development.

A fourth major research area will be sustainable feedstock production practices. Increasing demand for agricultural products may cause food prices to increase, increasing income and land values for large farmers and reducing net income/increasing food insecurity for the majority of small farmers who are net purchasers of food. The tendency for expansion of production onto marginal land will threaten soil health, thus requiring two major research thrusts: first, conservation agriculture systems that maintain soil cover, increase water use efficiency and reduce soil erosion; second, the substitution of perennials for annual feedstocks for similar reasons. The latter may lead to increases in agroforestry or mixed food-feedstock-livestock plantation systems, which can provide low cost and reliable biomass and avoid annual cultivation and management costs while stabilizing standing biomass in times of drought, plus self-evident advantages in relation to habitat and biodiversity.

The increased demand for biomass may lead to increased harvest of crop residues, including straw and stover, as feedstock, whether for biofuels, biobased products, or biorefineries. The removal of a high fraction of crop residues could lead to a shortage of fodder for ruminants, and reduce practices of mulching systems, which protect the soil surface, reduce erosion, reduce weed pressure, and improve water productivity. In this respect, the proportion of crop residues required to maintain soil health should be determined (Sayre and Dixon, 2006). There is sufficient potential to redirect nutrients contained in byproducts from bioenergy and biorefinery systems to farmers' fields. Anex et al. (2007) report a potential return rate of 78% of applied N in maize or switchgrass (*Panicum virgatum*) production.

CONCLUDING REMARKS

There is a huge potential for agriculture as we move toward a biobased economy. To capitalize on this, systems and participatory approaches are needed to develop agriculture practices, institutions (including markets), and processing systems. As the anticipated growth of the biobased economy will strengthen the demand for biomass, ecosystem function in biomass scarce regions such as South Asia may be threatened. Resource planning, including water, energy and byproducts, and associated transportation, storage, and processing infrastructure can ensure optimal supply of agricultural produce to a variety of markets.

While the food versus fuel debate has been overheated, we conclude that food security should not be threatened by the plethora of new options. Focus should be on optimizing economic and energetic efficiency, while protecting the position of vulnerable groups in developing countries. The reality is that most poor rural households are net food consumers. In this context, one pathway to household food security and poverty reduction comprises household entitlements (income) associated with high value added products from biomass, through small-scale local biorefineries producing bioenergy or other biobased products in poor marginal and remote areas. Incentives for such decentralized investment in biorefineries would require pro-poor institutional and policy environments.

Balanced rural development will be essential to position the growth of the biobased technologies and economy in sustainable development space. Mankind requires a wide range of products from agriculture, including food, feed, and ecosystem services, alongside newer products described in this article. Experience from the green revolution suggests that agricultural intensification should be dispersed rather than concentrated in high potential zones; it should also be "pro-poor, pro-women, and pro-environment," embodying sustainability and equity principles.

A focus on rural development does not imply that there is no need for technological research. The challenge is to foster an innovative biobased economy that is technically feasible, profitable, and socially desirable. With respect to research, there is need to understand how to capture more value from existing crops.

There is a need to aim for ecological efficiency, but residue recovery and biomass harvest demand more of water and soil resources that are already heavily stressed. Consequently, it is important that processing must be integrated with biomass production to yield ecological improvements. Demand for biomass as a feedstock may allow a redesigning of agriculture, in terms of crops, cropping systems, and nutrient management.

Biorefineries will be a key component of a resilient and sustainable bioeconomy, preferably with viable small-scale options to foster local economic development in marginal and remote areas. The various components of healthy agricultural and industrial ecosystems need to be integrated. Biorefineries will need to be optimized so that a wider range of the ecological functions that agricultural and natural lands currently provide, such as nutrient cycling, carbon sequestration and the protection of water and soil resources, will be delivered. However, it should be noted that this is unlikely to happen unless appropriate economic incentives are created (Anex et al., 2007).

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