Development perspectives of the biobased economy: The need for a systems approach[1]

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Abstract: *This paper provides an outline of the biobased economy, its perspectives for agriculture and for development purposes. Perspectives of biobased products and viable and efficient biorefinery concepts are explored. The paper lists modern bioproducts and presents basic principles of and development options for biorefineries. 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 offering the best perspectives, combining large market volumes with medium to high price levels include products like fine chemicals, lubricants and solvents. The paper further lists impacts of recent crop price increases (2007-8) on malnutrition and agricultural investments as well as biofuel and biobased policies. It describes major types of biorefineries (whole crop, oleochemical, lignocellulosic feedstock and green) and the way these can be utilized to realize development perspectives for smallholders in less-endowed regions while conserving their legal, economic or social positions. Finally, it is discussed how biobased potential studies could benefit from experiences in cropping and farming systems research to develop production systems that take better account of current land use and the position of smallholder farmers and agricultural laborers.*

Introduction

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), which were subsequently formulated, are the halving of hunger and poverty by 2015 in developing countries strongly linked to agriculture. Modest progress towards 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 in this paper is framed by the commitments underpinning the MDGs. This assumes that agricultural production to meet the new demands, emerging 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. Agriculture underpins key livelihoods for most people living in rural areas. In addition to the provision of food, fiber and energy, it contributes to poverty reduction and economic development by providing employment and income. 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 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 food and chemistry is approximately equal. A long term and sustainable market can be envisaged for technologies producing chemicals, materials and pharmaceuticals from plant-based feedstocks (Sanders *et al.*, 2007), which will supplement the demand for bioenergy feedstocks and the growing demand for food and agricultural products. Such a development will need to be supported by processing steps that are energy efficient and cost-effective, as can be provided by biorefineries. 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

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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.

This paper explores possibilities of biomass application for development purposes. 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 describes development opportunities in light of developing a biobased economy that offers opportunities for small scale farmers in less developed areas, and discusses how (cropping and farming) systems oriented research can be used to identify applications that realize technological potentials that also serve the needs of smallholders and/or laborers in less fragile and endowed production regions.

Biobased products

While the principle of biobased production has been known for centuries, current developments favor enhanced, modernized, application of biomass in the production of energy, materials, and chemicals presently made from fossil feedstocks. This section, based on Langeveld et al. (2010), discusses the use of vegetable oils, crop starch, residual proteins (from biofuel production) and cellulose to produce polymers, lubricants, solvents, surfactants and specialty and bulk chemicals.

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). Modern non-medical biomaterials include pharmaceuticals, chemicals, specialty products, industrial oils, biopolymers, and fibers. Production of pharmaceutical feedstocks, providing opportunity to agriculture and household livelihoods, is based on the provision of genetic material and production of feedstocks. It involves specialist markets with small production volumes.

Chemical markets refer to bulk chemicals with high volumes, but low values, and fine chemicals with smaller market size, but higher added value. Biobased chemicals include 1,3-Propanediol (1,3 PDO), a building block for polymers that is mostly made from maize (*Zea maïs*) syrup by modified *Escherichia coli* bacteria, and Succinic acid, another chemical building block generated by fermentation of glucose. Improvement programs for both chemicals involve crops like sugar cane (*Saccharum officinarum*), maize, rice (*Oryza sativa*), barley (*Hordeum vulgare*) and potato (*Solanum tuberosum*).

Specialty chemicals serve as adhesives, solvents and surfactants (an important group of products applied in detergents, cosmetics and manufacturing processes). Surfactants are increasingly made from renewable feedstocks. They provide a large market, involving tropical vegetable oils like coconut (*Cocos nucifera*) and oil palm (*Elaeis guineensis*) while oils from temperate crops (rapeseed - *Brassica spp.*, sunflower - *Helianthus annuus*) are more suited for use in polymers, lubricants, adhesives, solvents and surfactants (Turley, 2008). Solvents, applied in 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 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. 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.

Bioplastics show huge opportunities. Starch plastic application, commercially being produced since the 1970s, 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) (Vaca-Garcia, 2008). PLA is mainly made from glucose syrup originally from maize, cane, potato or wheat (Vaca-Garcia, 2008). It may, in the future, be made from lignocellulosis (Carole et al., 2004). 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*). Composite cellulosic materials are light, safe and offer good acoustic properties (Vaca-Garcia, 2008).

Biofuels and markets

While many adhere to the principle that biofuels should not compete with food security, existing practices suggests that biofuel production can compete for scarce resources (soil, water, nutrients). While increases in agricultural productivity can help to free resources for the production of energy and biobased products, the way biobased production is to be realized alongside production of basic crop elements remains point of debate. Much will depend on the selection of crop feedstocks for biobased production and the way these are processed.

The drive for biofuel production and subsequent demand for stable crops (maize, cane, wheat for bioethanol, palm oil, rape and Jatropha for biodiesel) has attracted a range of investors willing to finance forms of primary agricultural production until recently hardly was in vogue. Major crop price increases in 2007 and 2008 have further drawn attention to potential profits to be made from fuel and traditional food/feed production. The height of the investment wave may have already passed, crop prices showing a decline since their peak in October 2007, but its impact is not to be underestimated. While investments in agriculture have been on the decline since the 1970s, the price peak and its impact on malnutrition have lead to a call for more (public) funding in crop production.

The impact of rising biofuel production on development is not unilateral. While, on the one hand, unbalanced growth in food crop for fuel production can have serious impacts on crop availability, food prices and, hence, malnutrition, it has drawn attention to a sector which long suffered from a lack of incentives. The net effect of these developments are extremely difficult to asses. This has been demonstrated by Langeveld and Sanders (2010), who highlight a chain of interrelated reactions on increased crop demand by farmers, input markets, consumers and policy makers (Figure 1).

Increased demand for biofuel feedstocks reduces availability of food crops, thus raising crop prices. Farmers, maximizing economic returns, respond by increasing the amount of land cultivated as well as the input application level while poor consumers will rationalize their food purchases. The consequences of this development (raising prices of food, land, inputs, and enhanced numbers of malnourished) are likely to provoke counteracting reactions. Increasing production costs (and reduced demand) will force farmers to rationalize production (limiting land and input use) while policy makers may take action to restrict crop use for biofuel production.

Such actions have been observed over the last years in different several parts of the world. China has taken action to prevent some crop’s application in large scale bioethanol production, while European policy for a have called for restrictions in crop for biofuel applications (mostly through formalized standards). The impact of further biobased development will depend on the interaction between growing feedstock demand and the sector’s ability to increase crop production.

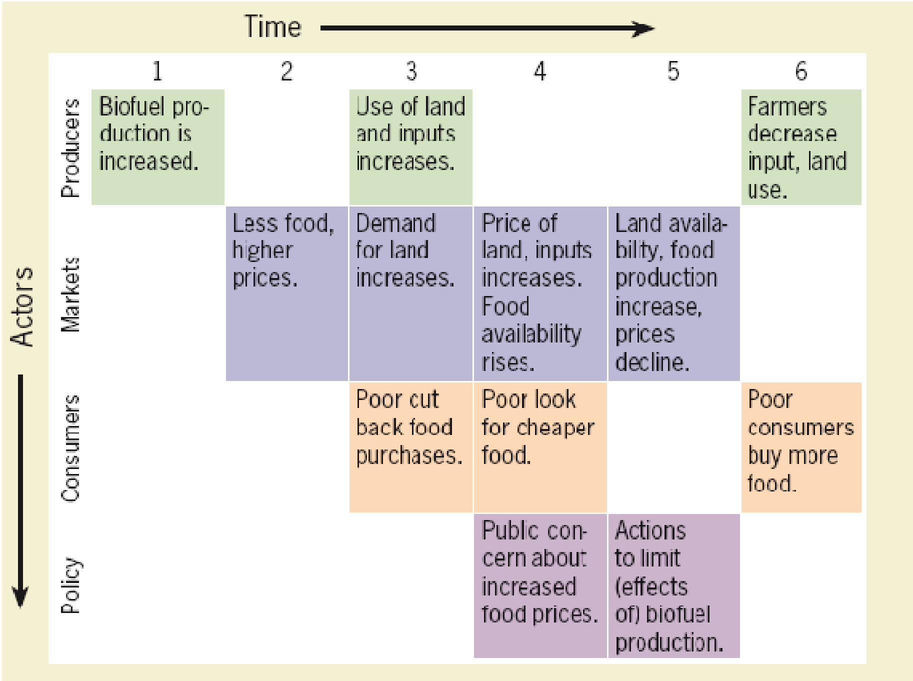

Figure 1. Actions following increases in primary biofuel crop production.
Source: Langeveld and Sanders (2010)

Developments in processing: biorefineries

Related to biobased market development, and realization of the biobased potential, is the way in which crop material is to be processed in the future. While processing of crops, traditionally, was focusing, merely, on a limited number of market applications, over time the number of possible applications has increased. Recent developments in crop processing technologies, in combination with developments in crop demand discussed above, may be expected to cause major shifts in the way crops are processed, utilized and marketed. Biorefineries, aiming to make optimal use of plant components, show an increasing potential to address the demand for advanced food, feed, energy and chemical crop applications.

In this concept, energy production is not a primary, but only one possible application of crop material, using feedstock selection, logistics and biorefining to optimize valorization of available functionalities and biomass utilization. Complex input-output chains can play a crucial role in the realization of economic and social opportunities in industrial, emerging as well as developing countries as they can generate different combinations of both high added value but low volume and high volume but less valuable products (Figure 2).

Based on overviews presented by Kamm *et al*. (2006), Clark and Deswarte (2008), and De Jong *et al*. (2010), we distinguish the following biorefinery types: (1) whole crop, (2) oleochemical, (3) lignocellulosic feedstock and (4) green. Descriptions presented below have been taken from Langeveld *et al*. (2010).

Whole crop biorefineries process grains (mostly wheat, rye or maize) via ‘dry’ or ‘wet’ milling and consequent fermentation and distillation. In wet milling, grains are water-soaken (to soften kernels) before grinding, after which they are separated into starch, cellulose, oil and proteins. Dry milling grinds dry grains, adds water and enzymes to the flour followed by cooking to break-down the starch. Ethanol, formed by fermentation, then is distilled and concentrated. Residues are separated into solid (wet grains) and liquid (syrup) phases, to be used as animal feed (DDGS). Alternative routes for grain refining include production of polymers or bioplastics from starch. Straw can be converted into energy or bioproducts, following principles of the lignocellulosic feedstock biorefinery discussed below (Clark and Deswarte, 2008).

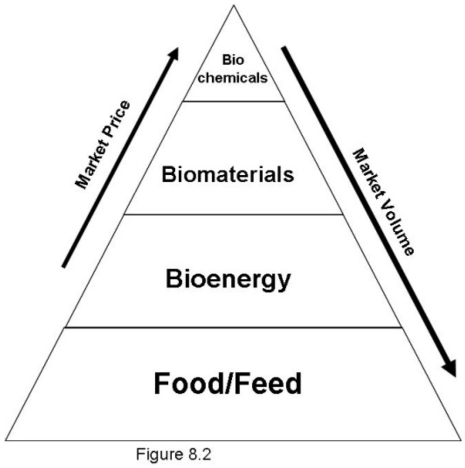

Figure 2. Variations of market prices and market volumes addressed by biorefineries.
Source: De Jong *et al*. (2010)

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

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*., 2010).

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., 2010). 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, finally, feed green plant material to a cascade of processing steps, basically fractioning the biomass into a liquid phase (containing soluble compounds like lactic or amino acids) and a solid phase (fibers) (De Jong *et al*., 2010).

Perspectives for development

The development perspectives of a biobased economy will depend on type and amount of feedstocks processed (on the one hand), and income generated for smallholders and farm laborers (on the other hand). It is difficult to prophesize on the biobased development potential, which basically combines global (market, technology) perspectives with local (land, crops, farming system) resources and conditions. Above, we have discussed what crops may be involved and which technological pathways may be followed for processing marketable products.

Biorefineries offer prospects of enlarged output value and prospects for smallholder incomes, but value added and income effects will depend on product and market differentiation. The relevance of biorefineries for development depends on the way available biomass resources can be linked to economic conversion routes in developing countries, plus the scale and location of the biorefineries.

Major sugar and starch crops can be applied in fermentation processes that provide inputs for 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. In order 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 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.

While there is huge potential for lignocellulosic biomass production in developing countries, 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 locally be a viable alternative.

The size of (potential) biobased markets is showing large variations. Highest market volumes are reported for polymers, solvents and surfactants; highest prices for pharmaceutical ingredients, enzymes and specialties (solvents, surfactants) (Carole *et al*., 2004). Prices for bulk chemicals and biopolymers, although somewhat lower, are also attractive. An evaluation of all opportunities (feedstock added value, employment, import replacement, export) offered by production chains suggests that fine chemicals, lubricants and fibers may offer the best prospects for developing countries (Table 1).

Discussion: calling for a systems approach

A biobased economy that contributes to development purposes requires that production activities integrate into existing cropping and farming systems. In this respect, insights in consequences of biobased production practices on cropping/farming systems in underdeveloped regions in Africa, Asia and Latin America are insufficiently understood. Application of the AEZ-methodology for example, frequently applied in potential biobased production assessment studies (Fischer et al., 2007) is lacking a quantified relationship between current and projected biobased land use systems. This is not limited to AEZ studies; other descriptive biobased production studies (e.g. Mola-Yudego, 2009) also largely ignore existing cropping systems.

Definition of the potential contribution of a given biobased product to the realization of farmer's and policy maker's objectives (or MDGs) requires a clearly defined relationship, thus defining research efforts for both the biobased and the farming systems research communities for the next years. Such research should, ideally, be based in the core of each analytical field, following traditions of multi-disciplinary research to which well defined development targets can be added. Thus, development oriented biobased systems research should identify and select promising cropping practices which fit in a farming systems orientation that can integrate biobased production and market potentials. Only in this way, technological and development potentials can be realized simultaneously.

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 employ-ment	Prospects for develop-ment
Pharma-ceuticals	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: Langeveld et al. (2010)

Examples of such integrated cropping systems have hardly been identified, although some exceptions can be found. It can be expected that they include traditional staple food crops (cereals), industrial (sugar, starch and oil crops) and lignocellulosic crops (tropical grasses, shrubs – Jatropha – and short rotation tree crops). While lignocellulosic crops offer most perspectives for the future, commonly cultivated food, feed and fiber crops may be more easily realized in the short run. As this brings the risk of further undermining the fragile production basis of vulnerable farm households, realization of biobased development perspectives will depend on the ability to integrate legal, social and economic minimum standards in newly developed biobased production systems.

While technical potentials of biobased production systems are well defined, their integration in land use systems must be treated with utmost care especially in regions lacking formal protection of land rights Successful efforts will effectively combine insights in technological production potentials, knowledge of development processes and scientific and development oriented communication skills. Experiences have shown that development initiatives often suffer from an unbalanced set of such capacities. Still, some studies offer practical lessons and useful examples. According to Vellema et al. (2010), emergence of viable local biobased production activities in developing countries can make effective use of (existing or new) links between crop producers on the one hand and agro-industrial clusters on the other hand.

Such a development requires innovation frameworks not focusing on fixed technological development but with a more process oriented setup. Remnants of farming systems research infrastructure can play a role here, as they can link potentials of technological innovations to the needs of development oriented processes. The current analysis suggests that products which combine large market sizes with crop and commodity prices which are sufficiently high to allow effective rewards for smallholder production provide the best perspectives.

References

Carole, T.M., J. Pellegrino and M.D. Paster (2004) Opportunities in the Industrial Biobased Products Industry. Applied Biochemistry and Biotechnology 113–116:872-885.

Clark, J.H. and F.E.I. Deswarte (2008) The biorefinery concept – an integrated approach. p 1-20. *In*: J.H. Clark and F.E.I. Deswarte (eds), Introduction to chemicals from biomass. Wiley series in renewable resources. Wiley, Padstow, UK.

De Jong, E., R. van Ree, J.P.M. Sanders and J.W.A. Langeveld (2010) Biorefinery. *In*: H. Langeveld et al. (eds), The biobased economy: Biofuels, materials and chemicals in the post-oil era, pp. 111-130.. Earthscan, London.

Fischer, G., E. Hizsnyik, S. Prieler and H. van Velthuizen (2007) Assessment of biomass potentials for biofuel feedstock production in Europe: Methodology and results. Laxenburg, (Austria), International Institute for Applied Systems Analysis, pp. 75.

Johansson, D. (2000) Renewable raw materials. A way to reduced greenhouse gas emissions for the EU industry? Brussels, DG Enterprise.

Kamm, B., M. Kamm, P.R. Gruber and S. Kromus (2006) Biorefinery systems, an overview. p. 3-40. *In*: Kamm, B. *et al*., Biorefineries – Industrial processes and products. Status quo and future directions. 2 Volumes. Practical approach book. Wiley, Weinheim.

Langeveld, J.W.A., J. Dixon and J.F. Jaworski (2010) Development perspectives of the biobased economy: a review. *Crop Science* 50: S1-S9.

Langeveld, J.W.A., and J.P.M. Sanders (2010) General introduction. *In*: H. Langeveld et al. (eds), The biobased economy: Biofuels, materials and chemicals in the post-oil era, pp. 3-17. Earthscan, London.

Mola-Yudego, B. (2009) The potential of short rotation willow coppice on agricultural land in Northern Europe based on empirical data. Paper presented at a IEA Bioenergy conference held 23-26 August, 2009 in Vancouver, Canada.

Turley, D. (2008) The chemical value of biomass. p. 21-45. *In*: Clark and Deswarte (eds.), Introduction to chemicals from biomass. Renewable resources. Wiley, Padstow, UK.

Vaca-Garcia, C. (2008) Biomaterials. p. 103-142. *In*: Clark and Deswarte (eds.), Introduction to chemicals from biomass. Wiley series in renewable resources. Wiley, Padstow, UK.

Vellema, S., H.L. Bos and J.E.G. van Dam (2010) Biobased industrialization in developing countries. *In*: H. Langeveld *et al*. (eds.), The biobased economy. Biofuels, materials and chemicals in the post-oil era, pp. 214-228. London, Earthscan.

Wolf, O., M. Crank, M. Patel, F. Marscheider-Weidemann, J. Schleich, B. Hüsing and G. Angerer (2005) Techno-economic Feasibility of Largescale Production of Bio-based Polymers in Europe. EUR 22103 EN. Joint Research Centre. Institute for prospective technological studies.