Biorefineries:

adding value to the sustainable utilisation of biomass

IEA Bioenergy

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IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international co-operation and information exchange between national bioenergy RD&D programmes. IEA Bioenergy aims to accelerate the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide increased security of supply and a substantial contribution to future energy demands.

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C5/C6 sugar and lignin platform biorefinery for ethanol, animal feed, power and heat from lignocellulosic residues. Courtesy Inbicon IBUS, Denmark; and Task 42.

Biorefineries: adding value to the sustainable utilisation of biomass

This feature article provides an overview of the work of Task 42: Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass. It was prepared by the Task Leaders, Mr Ed de Jong, Avantium Technologies BV, and Mr René van Ree, Wageningen University and Research Centre, the Netherlands.

Introduction

The energy and material needs of human society will reach a crisis point in the near future. This will be due mainly to the rising cost of, and demands for, fossil resources upon which we have become dependant for energy, fuels, chemicals and materials. The world's population continues to grow and development is taking place at rates unprecedented in our recent history, especially in areas that have traditionally had very low per capita demand on our fossil resources.

Commensurate with these increasing demands it has become apparent that the continued emissions of greenhouse gases (GHGs) and loss of carbon sinks are influencing the world climate. The main strategy proposed to ameliorate the effects of climate change is to reduce global demand for fossil fuel resources. Biomass can provide a more positive solution – a renewable source of energy services, including heat, electrical energy, and transportation fuels which can reduce CO_2 emissions, sulphur and heavy metals in the atmosphere while potentially improving rural income and energy security through the substitution of coal, oil and natural gas. The use of domestic bioenergy resources and biomass imports would generally contribute to the diversification of the energy mix. The international bioenergy market is expected to have a wide range of suppliers from several world regions and the importation of bioenergy is therefore not affected by the same geopolitical concerns as are oil and natural gas. However, the contribution of bioenergy to improving energy security largely depends on decoupling the bioenergy system from oil and gas inputs.

In many countries, stronger climate change and environmental directives have become an impetus for the accelerated development of renewable energy supply to meet both stationary and transportation fuel demands. Similarly, in some areas of the world new directives for the development of alternative and sustainable chemical sources e.g., Registration, Evaluation, Authorisation and Restriction of Chemical substances (REACH EC 1907/2006), will lead countries to re-evaluate the feasibility of using biomass feedstocks and biotechnologies for chemical production. Although this is a European example, such directives are believed to influence manufacturers and distributors worldwide.

Pyrolytic liquid platform biorefinery for polymers, synthetic fuels, food, power and heat from lignocellulosic residues. Courtesy Ensyn, Canada; and Task 42.

It is recognised by many countries that energy security, environmental concerns and the development of alternative, cleaner sources of chemicals and materials for manufacturing and user industries is becoming a driving imperative.

These are just some of the drivers for the development of sustainable energy and chemicals. The recent expansion of the bioenergy industries – power, CHP, gaseous energy carriers, and biofuels for transport – together with a strong increase in many commodity prices has raised concerns over the land use choices between energy needs and food and feed. This conflict may not be as obvious as the popular press has reported. The development of what we term 'first generation' biofuels may be seen as a necessary step in the advancement of technology to a more sustainable and environmentally benign system.

The cost of environmental damage due to production and use of fossil fuel energy and certain chemicals and materials leads us to the inevitable conclusion that new systems of production must be developed. These should focus on reduction of pollution or hazardous materials, producing safe and environmentally benign products in a green and sustainable supply chain. For this to occur, a constant and renewable supply that has a low carbon cost is required. Globally, the only source of such renewable feedstock is biomass.

This overview sets out to illustrate the developments in sustainable production for commercial, and close to commercialisation, energy carriers and co-products developed from biomass using biorefineries. Technology is developing rapidly in these areas. With the understanding that biomass contains all the elements found in fossil resources, albeit in different combinations, we can begin to understand that present and developing technologies can lead to a future based on renewable, sustainable and low carbon economies.

It should also be highlighted that changes in the world economy challenge us to develop the industries of the future now, so that as we emerge from this changed world we are ready, on a global scale, to advance the material wealth of human society in terms of energy supply and materials for a new sustainable industrial development. Advanced biorefineries may address many of the issues raised above. We set out here to paint a broad picture of present and future developments.

The Role of Task 42

The Executive Committee recognised the importance of co-production of chemicals and materials along with bioenergy, and therefore established a separate biorefineries Task in 2007. As shown in the schematic, Task 42 links many of the other IEA Bioenergy Tasks. It seeks to create synergies between work on sustainable biomass feedstock production and on efficient technologies for processing biomass, while also paying attention to socio-economic and environmental drivers, including GHG mitigation. Figure 1 illustrates the relationship with other IEA Bioenergy Tasks. economists, and social scientists.

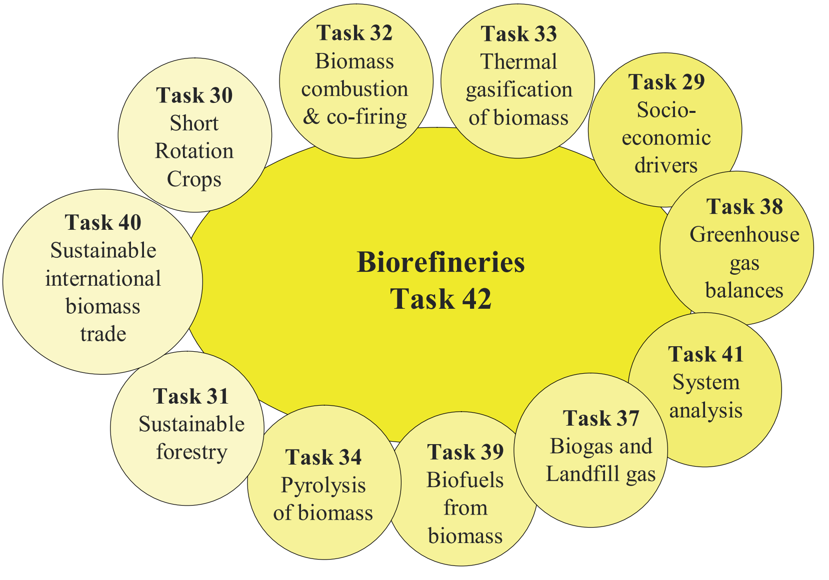

Figure 1: Schematic representation of the relationship of Task 42 to other IEA Bioenergy Tasks.

There is also strong co-operation between Task 42 and national, international stakeholders and RD&D programmes, and the EU Technology Platforms.

The participants in Task 42 act as National Team Leaders for biorefinery technology knowledge transfer and reporting. The Task addresses issues such as:

- Biorefinery definition and biorefinery classification system.
- Country reports describing and mapping current processing potential of existing biorefineries in the participating countries, and assessment of biorefinery-related RD&D programmes to assist national governments in defining their national biorefinery policy goals and related programmes.
- Bringing together key stakeholders (industry, policy, NGOs, research) normally operating in different market sectors (e.g., transportation fuels, chemicals, energy, etc.) in multi-disciplinary partnerships to discuss common biorefinery-related topics, to foster necessary RD&D trajectories, and to accelerate the deployment of developed technologies.

Why Biorefineries?

C5/C6 sugar and lignin platform biorefinery for ethanol, animal feed, power and heat from lignocellulosic residues. Courtesy Inbicon IBUS, Denmark; and Task 42.

The conventional refinery takes crude oil and refines it into products that may be used as fuel for transport, electricity and high value chemicals (approximately 5% by volume). The advantage of this technology is that it is highly predictable and is not subject to seasonality of supply. Petroleum refineries are also highly optimised and are considered to make use of 'mature technologies'. However, disadvantages that have become evident in recent years are volatility in price, security of supply, competition from emerging markets for a limited resource and the production of atmospheric pollution and greenhouse gases. We contend that the world needs feedstocks that are widely available, relatively low cost in terms of economics and carbon, renewable and that can be grown and processed in a sustainable manner. It is indisputable that biomass can fulfil these requirements. The conversion of biomass to energy carriers and a range of useful products, including food and feed, can be carried out in multi-product biorefineries.

Although the biofuel and associated co-products market are not fully developed, first generation operations that focus on single products (such as ethanol and biodiesel) are regarded as a starting point in the development of sustainable biorefineries. The most profitable of these is based on sucrose (sugar cane). Some of these 'first generation' plants are also subject to changes in market conditions such as strongly fluctuating commodity prices, as has recently been seen with the price of wheat and corn. With the increasing pressures for alternative sources of energy carriers, platform chemicals and bio-based materials, 'first generation' production based on starch to ethanol and Dried Distillers Grain and Solubles (DDGS) may have a limited lifespan. It may be argued that advanced biorefineries have a distinct advantage over conventional refineries (mineral oil) and first generation 'single product focus' operations e.g., recovered vegetable oil (RVO), or rapeseed oil to biodiesel plants, in that a variety of raw materials may be utilised to produce a range of added-value products. We will deal with the varying technologies later.

Advanced or second generation biorefineries are developing on the basis of more sustainably-derived biomass feedstocks, and cleaner thermochemical and biological conversion technologies to efficiently produce a range of different energy carriers and marketable co-products. To avoid the criticism attributed to first generation biorefineries, these new designs should aim to reduce the impacts and maximise the benefits of social, economic, and environmental factors on a lifecycle basis. These emerging advanced biorefineries promise to provide complex materials for supplying our chemical and manufacturing industries in the near future, as well as contributing partially to energy needs in a more sustainable way.

What is a Biorefinery?

It is necessary to define what is meant by biorefineries. Task 42 members, aware that biorefineries exist in a wide variety of configurations and generate many different end products, required a succinct definition that encompassed these many facets and decided upon *'the sustainable processing of biomass into a spectrum of marketable products and energy'*. See Figure 2.

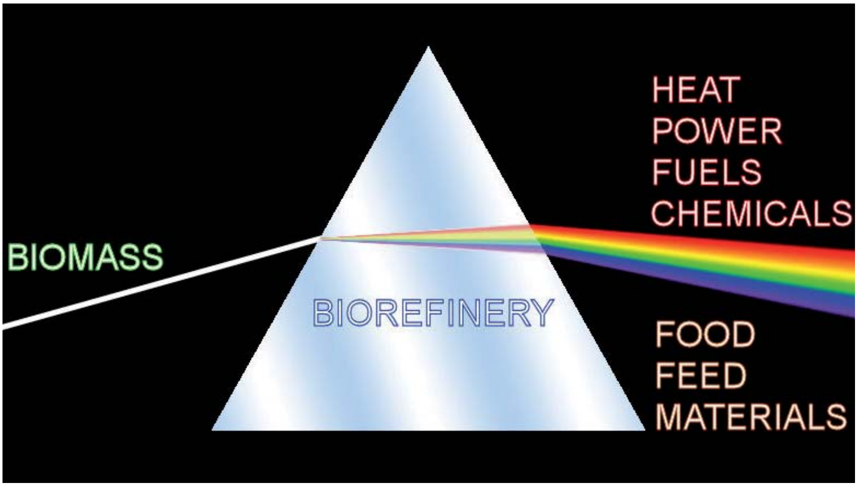

Figure 2: Biorefinery: the sustainable processing of biomass into a spectrum of marketable products and energy

This biorefinery definition includes systems that may exist as a concept, a facility, a process, a plant, or even a cluster of facilities. In this overview we present the different kinds of biorefineries. More examples can be found in the forthcoming Task 42 brochure. The brochure indicates the scale (i.e., commercial, demonstration or pilot) at which these biorefineries are currently operational. As an example, the port of Rotterdam has a cluster of facilities that act together and can be considered a 'biorefinery'.

A main driver for the establishment of biorefineries is sustainability. All biorefineries should be assessed through the entire value chain for environmental, economic, and social sustainability. This assessment should also take into account the possible consequences due to competition for food and biomass resources, the impact on water use and quality, changes in land-use, soil carbon and fertility, the net balance of greenhouse gases, the impact on biodiversity, potential toxicological risks, and energy efficiency. Impacts on international and regional dynamics, end-users and consumer needs, and investment feasibility are also important aspects for consideration.

A biorefinery is the integrated upstream, midstream and downstream processing of biomass into a range of products. In the classification system we have differentiated between mechanical pre-treatments (extraction, fractionation, and separation), thermochemical conversions, chemical conversions, enzymatic conversions, and microbial fermentation (both aerobic, anaerobic) conversions.

A biorefinery can use all kinds of biomass including dedicated wood and agricultural crops, organic residues (both plant and animal derived, and industrial and municipal wastes) and aquatic biomass (e.g., algae, sea weed, chitin, etc.). Biorefining is not a completely new concept. Many of the traditional biomass converting technologies such as the sugar, starch and the pulp and paper industries, utilise technologies in a similar manner to biorefineries. However, several economic and environmental drivers such as global warming, energy conservation, security of supply and agricultural policies have also directed these industries to further improve their operations. This should result in improved integration and optimisation of all the biorefinery sub-systems.

A biorefinery should produce a spectrum of marketable products and energy. The products can be both intermediates and final products, and include food, feed, materials, chemicals, and energy (defined as fuels, power and/or heat). Task 42 considers a true biorefinery has multiple energy and non-energy products.

The volume and prices of present and forecasted products should be market competitive. The biorefinery systems which will come into operation within the next years are expected to focus on the production of transportation biofuels. Some of the most interesting biofuels might be ones that can be mixed with gasoline, diesel and natural gas, reflecting the main advantage of using the already existing infrastructure in the transportation sector.

What are the Advantages of Biorefineries?

The saying 'if you have energy you have everything' is not strictly true. If we have energy we can produce solutions for the other needs of humans from sustainable biomass feedstock production. Biorefineries address these needs and will also address the environmental, social and economic needs of our society. They will be instrumental in providing rural development and employment, with relatively low carbon costs and decreasing production costs with economies of scale and the development of emerging technologies.

The production of energy carriers and co-products that also make these systems more economic, are the strengths of biorefineries. It is the variety of feedstocks that can be regionally based, producing a variety of marketable products that identify this concept as the strongest contender in future sustainable developments. Biorefineries address issues of sustainability from all aspects – economic, social and environmental. The approach is dependent upon the collaboration of the agro-engineering, chemistry, science, and marketing disciplines requiring a new paradigm in sustainable development.

How can Biorefineries be Classified?

At present, biorefineries are classified based on, technological (implementation) status, type of raw materials used or main type of conversion processes applied. A search of the literature revealed a variety of terms describing biorefineries – see below.

Conventional Biorefineries	1st, 2nd, and 3rd Generation Biorefineries
Whole Crop Biorefineries	Thermochemical Biorefineries
Advanced Biorefineries	Lignocellulosic Feedstock Biorefineries
Marine Biorefineries	Two Platform Concept Biorefineries
Green Biorefineries	

Task 42 has developed a more appropriate biorefinery classification system. This classification system is based on a schematic representation of full 'biomass to end product' chains. Roughly we can divide biorefineries in two categories:

- The **Energy-driven Biorefinery** (Main target: the production of biofuels/energy. The biorefinery aspect adds value to co-products).
- The **Product-driven Biorefinery** (Main target: production of food/feed/chemicals/ materials, in general by biorefinery processes. Often side-products are used for the production of secondary energy carriers [power/heat] both for in-house applications as well as for distribution into the market).

Task 42 has further classified the different biorefineries. The proposed classification system is based on the current main driver in biorefinery development, that is efficient and cost-effective production of transportation biofuels, to increase the biofuel share in the transportation sector. The classification approach consists of four main features that identify, classify and describe the different biorefinery systems: platforms, energy/products, feedstocks, and conversion processes (if necessary).

- The platforms (e.g., C5/C6 sugars, syngas, and biogas) are intermediates connecting different biorefinery systems and their processes. The number of involved platforms is an indication of the system complexity.
- The two biorefinery product groups are energy (e.g., bioethanol, biodiesel, and synthetic biofuels) and products (e.g., chemicals, materials, food and feed).
- The two main feedstock groups are 'energy crops' from agriculture (e.g., starch crops, short rotation forestry) and 'biomass residues' from agriculture, forestry, trade and industry (e.g., straw, bark, wood chips from forest residues, used cooking oils, waste streams from biomass processing).
- The four main conversion processes are biochemical (e.g., fermentation, enzymatic conversion) [orange squares], thermo-chemical (e.g., gasification, pyrolysis) [blue squares], chemical (e.g., acid hydrolysis, synthesis, esterification) [blue squares] and mechanical processes (e.g., fractionation, pressing, size reduction) [white squares].

The biorefinery systems are classified by quoting the involved platforms, products, feedstocks and, if necessary, the processes.

Lignin platform biorefinery for materials, power and heat from lignocellulosic crops or residues. Courtesy Zellstoff Stendal, Germany; and Task 42.

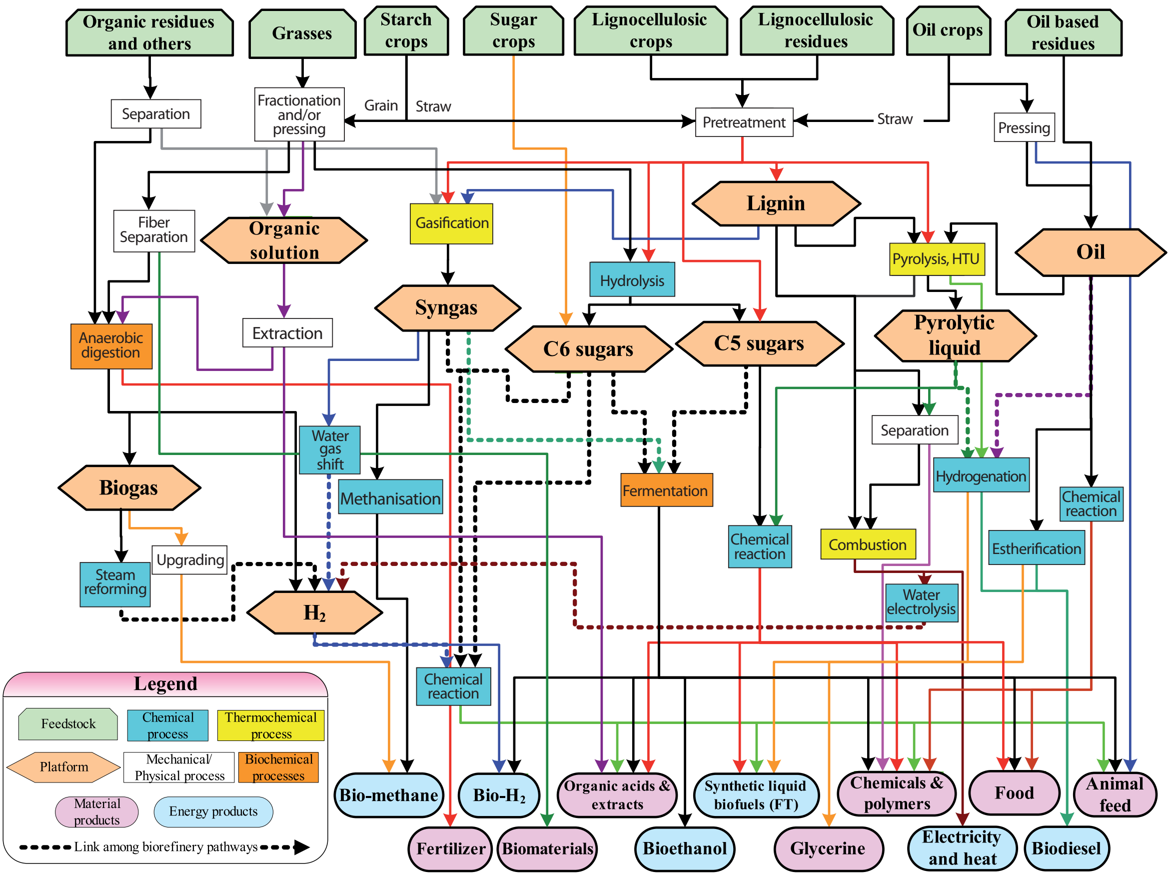

Figure 3: Network on which the biorefinery classification system is based.

Some examples of classifications are:

- C6 sugar platform biorefinery for bioethanol and animal feed from starch crops.
- Syngas platform biorefinery for FT-diesel and phenols from straw.
- C6 and C5 sugar and syngas platform biorefinery for bioethanol, FT-diesel and furfural from saw mill residues.

A full overview of the platforms, products, feedstocks and conversion processes is given in Figure 3.

This biorefinery classification is based upon feedstocks, platforms, products, and conversion processes. It presents a clear framework for defining the various feedstocks utilised and conversions within any given system.

What is the Current Status of Biorefineries?

Table 1 provides an overview of existing commercial biorefinery initiatives. An overview of all the biorefinery demonstration plants, pilot plants, and R&D initiatives within the Task 42 Participating Countries has been published in the country reports which can be found on the Task website *(www.iea-bioenergy.task42-biorefineries.com)*.

Table 1: Existing Commercial Facilities

Country	Feedstock	Products	Description
Austria			
Lenzing AG	Fibre and pulp	Furfural, acetic acid, sodium sulphate, potassium-lignin-sulphate	Separation of chemicals as a co-product of fibre and pulp processes. CHP from lignin
Danisco	Wastewater of pulp and paper industry	Xylose	Separation of xylose out of wastewater
Canada			
Ensyn	Agricultural and wood residues	Bio-oil, charcoal, food flavours, adhesive resins, green gasoline, diesel and jet fuels.	Rapid pyrolysis produces bio-oil that can be used for power generation, renewable transportation fuels and a range of chemicals.
Tembec	Pulp mill biomass	Ethanol, acetic acid, phenol-formaldehyde resins and lignosulfonates	Conversion of cellulose wastes to ethanol and fine chemicals
Dynamotive	Waste sawdust / recycled lumber	Bio-oil, char	Rapid pyrolysis to produce Bio-oil and char
Nexterra/Tolko	Wood residue	Heat energy	Gasification to syngas
Denmark			
Agroferm	Green juices	Lysin for animal feed	Production of lysin for animal feed by fermentation of green juices from green pellet production
Dangront	Grasses	Green pellets and green juices	Production of green pellets and juices from grasses
Daka Biodiesel	Fat from slaughterhouses	Biodiesel, glycerol and potassium sulphate	Operational for one year with a capacity of 55 million litres per year.
France			
Novance	Vegetable oil	Oleochemistry for non-food markets	Production of solvents, lubricants, biodiesel, resins
DRT	Terpenes, resins	Chemicals from paper and pulp industry by-products	Resin, gum rosin, resin, fine chemicals, tall oil derivatives, surfactants
Roquette	Wheat, potato, maize, pea straw	Starch, food, feed, bulk and fine chemicals, succinic acid, ethanol ...	Physical, chemical and fermentation processes
ARD, Cristal Union, Chamtor	Wheat, sugar beet,	Food, feed, ethanol, succinic acid, cosmetics, electricity	Physical, chemical and fermentation processes
Tembec, Smurfit.	Wood	Cellulose, paper, tall oil, lignosulfonates, electricity, steam	Production of products and energy

Country	Feedstock	Products	Description
Germany			
Südzucker	Sugar, grain	Sugar, palatinose, food additives, feed, ethanol biogas, electricity	Logistics, sugar/starch-refinery, palatinose plant, CropEnergies for ethanol and by-products
Zellstoff Stendal	Wood	Cellulose, paper, tall oil, methanol, turpentine, electricity, steam	Production of products and energy from wood by cooking, bleaching, drying, power plant waste water treatment
Emsland-Stärke GmbH, Wietzendorf	Whole crop biorefinery (potato starch and biogas) demonstration and commercial	Potato starch and biogas	Integrated unit for bioproducts and bioenergy
Biowert	Grass	Biogas, insulation material, biocomposites	Production of fibres and juice from grasses
CropEnergies	Sugar, grain	Ethanol, DGGS, electricity	See Südzucker
Netherlands			
Bio MCN	Glycerin	Methanol	Upgrading of the biodiesel by-product glycerin to biomethanol for transport
Vierhouten Vet	Waste oils/fats	Biodiesel	Waste plant oils and animal fats used in the food industry are upgraded to biodiesel
Ecoson/Vion	Waste meat industry	Biogas, CHP, Biodiesel	Integrated production of biogas, fats and biodiesel from meat waste
BioValue	Waste oils/fats	Biodiesel, fuel additives	Integrated production of biodiesel, and fuel additives from glycerin fraction
Ten Kate Vetten	Raw animal fats	Consumable fats, aromas and flavours, gelatine, CHP	Integrated production of food and CHP
Food industry	Various	Various	Various

Some of the initiatives mentioned are not real biorefineries within the scope of the present definition. However, these initiatives are mentioned because they represent facilities that could easily be upgraded to biorefineries, for example by adding value to the process residues or by potential alternative applications of the main intermediates produced (pyrolysis oil, syngas, biogas, etc).

A SWOT Analysis of Biorefineries

The continued development of these biorefineries will lead to a greater variety of feedstocks, technologies and co-products. Opportunities will inevitably arise in all areas of our present economies. Research and development will feed into agricultural and rural development, new industrial areas and openings in existing and newly created markets.

Table 2: SWOT analysis of Biorefineries

Strengths	Weaknesses
• Adds value to the sustainable use of biomass • Maximises biomass conversion efficiency – minimising raw material requirements • Produces a spectrum of bio-based products (food, feed, materials, chemicals) and bioenergy (fuels, power and/or heat) feeding the full bio-based economy • Strong knowledge of infrastructure available to tackle any non-technical and technical issues potentially hindering the deployment trajectory • Is not new, and in some market sectors (food, paper, etc.) it is common practice	• Broad undefined and unclassified area • Needs involvement of stakeholders from different market sectors (agro, energy, chemical, ...) over the full biomass value chain • Most promising biorefinery processes/concepts not clear • Most promising biomass value chains, including current/future market volumes/prices, not clear • Still at a stage of studying and concept development instead of real market implementation • Variability of quality and energy density of biomass
Opportunities	**Threats**
• Make a significant contribution to sustainable development • Challenging national, European and global policy goals – international focus on sustainable use of biomass for the production of bioenergy • Biomass availability is limited so the raw material should be used as efficiently as possible – i.e., development of multi-purpose biorefineries in a framework of scarce raw materials and energy • International development of a portfolio of biorefinery concepts, including designing technical processes • Strengthening of the economic position of various market sectors (e.g., agriculture, forestry, chemical and energy)	• Biorefinery is seen as hype that still has to prove its benefits in the real market • Economic change and drop in fossil fuel prices • Fast implementation of other renewable energy technologies filling market needs • No level playing field concerning bio-based products and bioenergy (assessed to a higher standard) • Global, national and regional availability and contractibility of raw materials (e.g., climate change, policies, logistics) • High investment capital for pilot and demonstration initiatives difficult to find, and existing industrial infrastructure is not depreciated yet • Fluctuating (long-term) governmental policies • Questioning of food/feed/fuels (land use competition) and sustainability of biomass production • Goals of end users often focused upon single product

The current perceived conflict between energy and food production can be allayed by developing technologies that are not fully based on starch, such as lignocellulosic materials. Biorefining is a concept that is dependent upon continued innovation presenting opportunities to all sectors. The building of a bio-based economy has the capacity to not only address present difficulties but also result in an environmentally benign industry.

In Table 2 we analyse the strengths, weaknesses, opportunities and threats of biorefineries and indicate the role Task 42 can play to support the development of biorefineries.

Final Comments

We can conclude that biorefineries can make a significant contribution to sustainable development by adding value to the sustainable use of biomass. They can produce a spectrum of bio-based products (food, feed, materials, chemicals) and bioenergy (fuels, power and/or heat) feeding the full bio-based economy. This should be realised by maximising biomass conversion efficiency – minimising raw material requirements while at the same time strengthening the economic position of market sectors such as agriculture, forestry, chemical, and energy. There is general international agreement that biomass availability is limited so raw materials should be used as efficiently as possible, hence the development of multi-purpose biorefineries in a framework of scarce raw materials and energy.

One of the critical success factors for biorefineries is bringing together key stakeholders normally operating in different market sectors (e.g., agriculture and forestry, transportation fuels, chemicals, energy, etc.) into multi-disciplinary partnerships to discuss common biorefinery-related topics, to foster necessary RD&D direction, and to accelerate the deployment of developed technologies (platform function).

In 2009, the number of participants in the Task have increased to 10 with the addition of Italy and Australia. Our target for the next triennium is the addition of at least two more countries – with more participants more progress can be achieved. Task 42 can contribute to the growth of biorefineries by identifying the most promising bio-based products, i.e., food, feed, added-value materials and chemicals (functionalised chemicals and platform chemicals or building blocks) to be co-produced with bioenergy, to optimise overall process economics, and minimise the overall environmental impact. Major initiatives in the immediate future include the preparation of a review and guidance document on approaches for sustainability assessment of biorefineries, and a strategic position paper 'Biorefineries: Adding Value to the Sustainable Utilisation of Biomass on a Global Scale'.

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