European Biorefinery Joint Strategic Research Roadmap

Star-COLIBRI

STRATEGIC TARGETS FOR 2020 – COLLABORATION INITIATIVE ON BIOREFINERIES



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Contents

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Executive Summary

By 2030, the Biobased Economy is expected to have grown significantly in Europe. A pillar of this, both now and in the future, is biorefining, the sustainable processing of biomass into a spectrum of marketable products and energy. The European sector of 2030 will evolve from established biorefinery operations for products like food, biofuels, paper and board, to a broader, more mature sector. In 2030, biorefineries will use a wider range of feedstocks and will produce a greater variety of end-products than today.

Achieving the European Biorefinery 2030 vision[1] will require future biorefineries to be better integrated, more flexible and operating more sustainably. This will only be possible if crucial bottlenecks along the entire value-chain can be removed. To address these challenges, several strategic research areas must be developed by 2020. The objective of this document is to identify these key research areas and their specific requirements.

Four important topics can be identified: biomass production and supply (including logistics), processing (both pre-treatment and conversion), programme integration (cross-sector, value-chain optimisation, process integration and overall sustainability assessments) and market development (from research to markets). The **main challenges and key R&D needs** for these areas are presented in all chapters from 'Biomass' to 'From research to markets'. Finally, the final chapter highlights 25 recommendations for Strategic Research and 9 recommendations for Innovation and Support Actions.

These **Strategic Research recommendations for 2020** are summarised below:

Biomass

Higher yields, more efficient use of nutrients and water and greater pest and disease resistance should be achieved through plant breeding and improved agronomy to provide a range of solutions suitable for the range of soil types, climate (current and future) and socioeconomic conditions across Europe.

Better basic knowledge of plant metabolism and structure (focusing on lignocellulosic crops or feedstocks) should be developed in order to provide an adequate, sustainable supply of good quality biomass to meet future industrial requirements.

Because of the low energy density of biomass, it is recommended that the logistics from harvest to the factory gate should be optimised to enable demand to be met from the smallest possible area.

To improve the appreciation of biomass as a raw material for non-food products, it is recommended that the sustainability of supply (including environmental, economic and social aspects) be optimised and techniques developed to produce sufficient feedstock from the existing agricultural land area.

1. Star-COLIBRI European Biorefinery 2030 Vision

Pre-treatment

New, flexible biomass pre-treatment processes should be developed and tailored to suit improved biomass feedstocks in order to obtain fully functional fractions (e.g. lignin and carbohydrates from lignocellulose).

Current research on lignocellulose breakdown must be accelerated, by improving existing technologies to develop efficient and cost-effective enzyme cocktails.

Production processes

For thermo-chemical processes, research should focus on scaling-up and integrating them into existing production units, together with end-product quality improvement (e.g. syngas purification for catalytic conversion and pyrolysis oil upgrading and fractionation).

For chemical catalysis, the main R&D need is for the development of new catalysts tailored for biomass feedstock components and able to work in aqueous media. Use of high throughput screening technology would give a considerable advantage.

The key issue for biochemical processes is to develop new biocatalysts (microorganisms and enzymes) based on a better understanding of microbiology in an industrial context and on the use of industrial performance criteria in the early stages of the selection process.

It is also recommended that research should be focused on downstream processes (separation and purification) and optimisation of water management.

As water will be the usual reaction media for catalytic processes in future biorefineries, it is recommended that a new area of science combining both chemical and biochemical catalysis should be developed.

To strengthen the biomass conversion toolkit, today mainly focused on carbohydrates, it is recommended that improved conversion technologies for lignin, fatty acids and other natural polymers should be developed.

Finally, systems and synthetic biology-based research into advanced fermentation techniques for the production of "drop-in" biofuels should be promoted.

Integration

The key conversion processes should not be developed in isolation. Future solutions will need process integration modelling, taking into account recycling and waste management. These models have to be validated (at pilot and demonstration scales) within flexible integrated biorefineries (i.e. multi-product, multi-process, for multiple feedstocks).

It is recommended that foresight studies are used to help understand the "system" into which integrated biorefinery value-chains would be fitted. This would include studying market trends, biomass-related policy issues, the impact of bioenergy targets, customer expectations, etc.

It is also recommended that an integrated, rational and transparent evaluation framework for sustainability assessments, such as Life Cycle Sustainability Assessment (LCSA) be developed, based on a common methodology.

Rural biorefineries are an integral part of their supply area, and help to optimise resource flows (mass, energy, water, nutrients, waste, etc.) within a closed loop system. Research is needed to understand the impact of the integration of biomass cropping systems and biorefineries in specific regions on biodiversity, water and soil quality, landscape, etc.

Given the complexity of the network of stakeholders involved in biomass supply, social science research is required to develop innovative strategies to facilitate cooperation in a sustainable way.

From research to markets

As demand for innovative bio-based products will be driven by the extent to which they can address societal challenges and needs, tools to assess appreciation of bio-based products should be developed, in order to better evaluate potential market penetration and growth.

Introduction

This document covers the strategic research that needs to be done in Europe by 2020 to make the European Biorefinery 2030 Vision, developed within the Star-COLIBRI project, a reality.

The Star-COLIBRI Vision Document lays out a view of the biorefinery industry in 2030 (and the developments needed to achieve this), within the broader context of the evolution of the Knowledge-Based BioEconomy. The main issues are summarised below.

The European Biorefinery Vision 2030

The European Biorefinery 2030 Vision is the product of the collaborative effort of the Star-COLIBRI team, involving five European Technology Platforms and five major European research organisations. Achieving this vision is a vital part of the overall evolution of the Biobased Economy. The Star-COLIBRI Vision document provides the information and tools to enable policy makers to build a framework for the development of a sustainable European Knowledge-Based Bioeconomy, with a network of biorefineries playing an essential role.

We can assume that **biomass in Europe will be produced roughly in line with the current patterns of land use**. However, we expect an increase in the cultivation of perennial crops (including forestry) which can have a number of positive impacts, such as increasing soil-water retention capacity and reducing erosion.

In the short-term, the main sources of biomass will continue to be traditional agricultural crops (cereals, potatoes, sugar beet and rapeseed) together with wood and dedicated energy crops, with forestry and agricultural waste also playing a role. After 2020, there will be an increasing use of dedicated lignocellulosic crops (both from farms and short rotation plantations on woodland) and of algae, assuming that technical and economic hurdles have been overcome by then. With the exception of Northern European forests, biomass production areas will continue to be fragmented. Under these circumstances, harvesting and transport costs become significant factors in the overall value-chain.

However, available research suggests that future development of the European biomass sector will be subject to a high degree of uncertainty, mainly depending on crop yields and land availability. Although the extent of yield improvement is not certain, the technical and scientific knowledge that will enable progress is already well established. **Consequently, a key issue for biomass production in Europe is land availability**.

The uneven geographical development of agricultural production and demand for both food and feed will influence patterns of global trade in general and the demand for European agricultural exports in particular. In turn this will determine the availability of land to grow biomass as an industrial feedstock. But as food demand puts further pressure on land, availability can be increased by yield improvements, optimisation of biomass production and reduction of losses in the agricultural supply chain. One of the key challenges for Europe is therefore to manage the short- and mid-term constraints on biomass availability without jeopardising long-term sustainability of supply.

The European Biorefinery Vision 2030 has been developed by analyzing the various factors that will shape development of the sector, as well as the different biorefinery models themselves. But this must be seen in the context of the overall Biobased Economy, which will see both the development and increasing integration of the relevant industrial sectors.

The overarching vision for 2030 is of a world-leading and competitive Biobased European Economy. The European bioindustry sector in 2030 is innovative and competitive, with cooperation between research institutes and the industrial, forestry and agriculture sectors and enjoying the support of civil society.

All links in the value-chain profit from this flourishing Biobased Economy. The success of European bioindustry comes from being a world leader in the efficient and flexible utilisation of biomass while having a strong focus on value-added products. By 2030, a significant proportion of the overall European demand for food, chemicals, energy, materials and fibres is fulfilled using biomass as a feedstock for biorefining technologies:

- ✓ 30% of overall chemicals production is biobased. For high added-value chemicals and polymers (specialities and fine chemicals) the proportion is more than 50%, but less than 10% of bulk commodity chemicals are derived from renewable feedstocks.
- ✓ 25% of Europe's transport energy needs are supplied by biofuels, with advanced fuels — especially biobased jet fuels — taking an increasing share.
- ✓ The European market for biobased fibre and polymers such as viscose, carbon fibres, nano-cellulose derivatives and bioplastics will continue to grow rapidly. Traditional fibre products such as paper remain 100% bio-based.
- ✓ A new generation of biobased materials and composites produced in biorefineries allows the production of lightweight, better performing components for industries including automotive and construction.
- ✓ 30% of Europe's heat and power generation is from biomass.

The European Biorefinery Vision 2030

Biorefineries produce a wide spectrum of biobased products which are fully competitive with their conventional equivalents

In 2030, Europe is a Biobased Economy in which biorefineries play an important role. Full-scale, highly efficient, integrated biorefineries allow competitive manufacturing of high value biobased products.

There is a range of biorefinery types utilising many different types of biomass feedstock and various technology options.

Versatile biomass supply chains

A diverse and flexible biomass production sector supplies biorefineries with a wide variety of agricultural crops, residues (agri-food or urban waste, forestry and agricultural by-products) and dedicated lignocellulosic crops (including forest biomass) together with an increasing volume of algal and aquatic biomass.

Europe's capacity for sustainable production of biomass has increased due to the introduction of new and improved crops, investment in Central and Eastern European agriculture, and new policy, training and cooperation initiatives. In addition, Europe's many millions of small-scale, family owners of woodland harvest their wood more efficiently and profitably, making a greater contribution to European biomass supply.

The demand from biorefineries continues to drive efficiency improvements in the production of food and feed crops.

Europe's versatile biomass feedstocks are an asset to a flexible and resilient biorefinery sector.

A revitalised, competitive and knowledge-intensive rural economy based on biorefineries

European industries have developed an extensive network of regional/rural biorefineries producing food, biofuels and numerous biobased products from local biomass in a sustainable way. This has led to significant economic growth and created millions of jobs in rural areas.

Innovative high-tech companies are prospering around larger regional biorefinery units. They specialise in producing a range of high-value products from biomass fractions and side-streams coming from the main biorefinery process, and create skilled jobs in rural areas. Decentralised, small-scale biorefineries are also part of this development.

Growing integration of biobased industrial sectors

Integration of supply and manufacturing chains and increased collaboration between innovative players from traditional industries such as the chemical, energy, agriculture and forestry sectors combines the key strengths of each sector, creating the critical mass to attract investors, policymakers and young talent. This has become the basis for maximising the value added to biomass streams.

An open and collaborative approach creates synergies in education, research, development, and innovation throughout the biorefinery value-chain.

Most biorefineries are closely integrated with traditional biomass processing industries. However, some have been established to exploit new value-chains, such as aquatic/marine biomass.

A focus on sustainable bioproducts gives Europe a competitive edge

A long-term focus on sustainability and "green" products has given European companies a competitive edge in the global market by 2030.

A combination of progressive standardisation, an environmentally aware consumer base and widespread eco-labelling ensures that European biobased products are developed to be as sustainable as possible throughout the full product life-cycle. They are designed to be recyclable, biodegradable, or used to generate bioenergy at the end of life. They are manufactured using non-polluting biorefinery production processes.

Biorefineries are highly energy-efficient and make use of mostly zero-waste production processes. They allow European industries to manufacture environmentally friendly products with small carbon and water footprints.

Versatile biorefinery development routes

Particular biorefinery technologies will have been used as necessary to provide optimal processing solutions for specific feedstocks and end products. The development of biorefineries will of course always remain an enabling technology concept and not a goal in itself.

Flexibility is the key. This means processing technologies that can deal with multiple biomass feedstock streams either via a single process or through a combination of several integrated ones. This will enable a broad spectrum of valuable, marketable products to be manufactured.

Economic constraints dictate that biorefineries need to be operated efficiently and at low cost. Sustainability criteria also still drive their continued development.

Making the Vision a reality

The European Biorefinery Vision 2030 can only be achieved if various bottlenecks along the value-chain have been removed. This requires the development of several strategic research areas by 2020. Ultimately, progress must be made in all these if the biorefinery concept is to achieve its full potential. This roadmap identifies the main challenges and the key research area requirements.

A core issue addressed by this roadmap is integration of the overall programme. To identify and fully understand the key challenges and the corresponding research needs, a **multi-disciplinary integration approach** is needed, taking account of needs along the entire value-chain. This approach must address:

- ✓ Biomass cultivation (selection of feedstocks, rotations, sustainability, waste recovery)
- ✓ Logistics (harvesting, collection, storage, transport)
- ✓ Conversion processes (chemical catalysis, bio-catalysis, thermochemistry and their use in combination)
- ✓ Separation techniques (biomass fractionation, oil extraction, separation of reaction products etc.)
- ✓ Process optimisation (new individual processes and new combinations)
- ✓ Ethical considerations (competition with food/feed supply, invasive species, transgenic crop varieties etc.)
- ✓ Socio-economic studies, including Life Cycle Analysis
- ✓ Specification setting and new products

This document is divided into seven chapters, as shown in Figure 1. The chapter on biomass addresses the main issues for feedstock production, logistics and pre-treatment (before delivery to the biorefinery). The following chapters cover pre-treatment processes within the biorefinery, biorefinery processing, the key issue of integration, as well as innovation and research on markets. Finally, the final chapter puts forward recommendations for Strategic Research programmes and Support Actions.

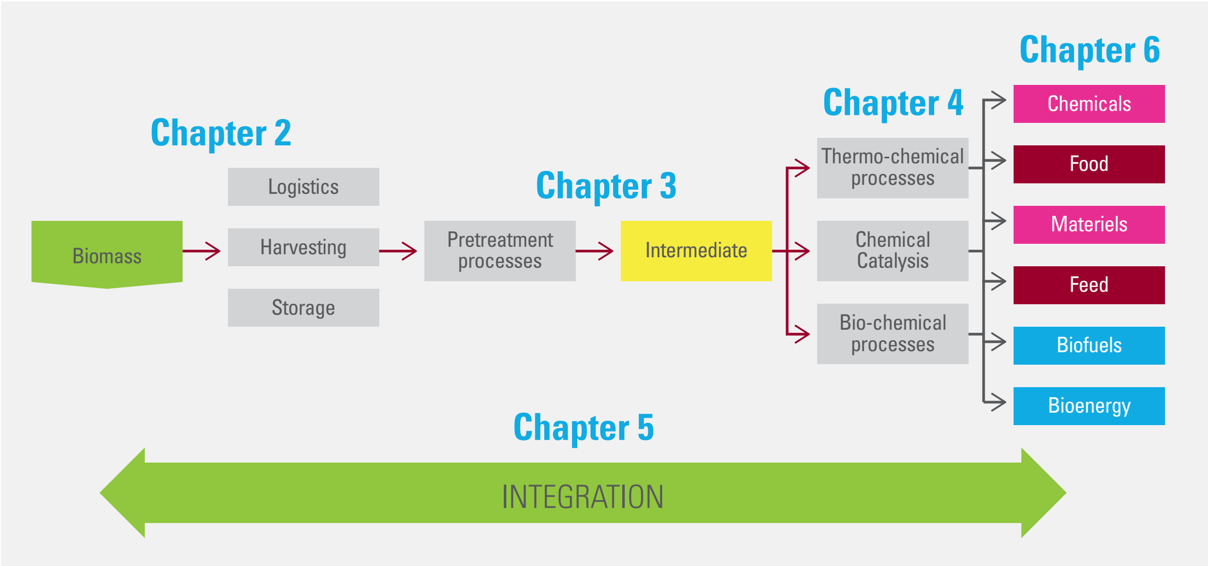


Figure 1: Schematic representation of the biorefinery value-chain and chapter coverage

Biomass

Introduction

Deliverable 2.1 of the Star-COLIBRI project "Background information and biorefinery status, potential and sustainability" provides a comprehensive classification of biomass resources that could be relevant to the concept of biorefineries. In brief, these consist of existing arable crops (e.g. cereals, oilseeds), dedicated biomass crops (e.g. perennial lignocellulosic crops), residues from agriculture (e.g. straw), woody biomass from forestry thinning, logging residues and side products from the wood processing industry, as well as algal-based biomass production systems.

Feedstock represents a large fraction of the costs of running a biorefinery facility. As such, it has a crucial role in determining the viability of the biorefinery concept, and investment in facilities will only be achieved when sustainable provision of affordable feedstock can be assured.

Main challenges

As the starting point of all downstream processes, feedstock availability is crucial for the feasibility and economic viability of every biomass processing activity, irrespective of whether or not this is carried out in an integrated biorefinery. Because of this, this roadmap includes generic research areas for the improvement of biomass supply as well as specific biorefinery-relevant feedstock research needs. It is important to note that the opportunities and constraints vary with the feedstock type. Below is a list of goals relating to biomass production and supply (both biorefinery-specific and generic), which provides the basis for the identification of areas warranting focussed research:

Improve yield, nutrient efficiency (water, N, P, K) and sustainability of biomass production. Not only must biomass yield per unit area be increased but this must be achieved in a way that minimises negative environmental impacts and maximises socio-economic benefits, using sustainable agronomic practices. This is particularly important in the case of biomass crops that have not yet been subject to intensive crop improvement, and for which there is a high potential for rapid gains to be made.

Improve feedstock raw material quality for biorefinery applications. Research, primarily on model species, has already identified potentially successful strategies to improve lignocellulose digestibility, and novel strategies will emerge from continuing basic research on cell wall structure and biosynthesis. It is important that these traits are transferred into commercially relevant species, with trial plantings that would demonstrate their potential to produce biomass in sufficient quantities for pilot scale processing. This will require close cooperation between plant scientists, breeders and the processing industry. From a broader perspective, the content of valuable components such as organic acids, proteins and lipids should be optimised to maximise the economic value of a particular crop.

Use the largest possible percentage of the feedstock, while leaving unharvested what is required to maintain soil structure and fertility. Efficient biorefineries aim to maximise the value from the feedstock being processed. This requires a thorough understanding of its composition (e.g. lignocellulose structure and biosynthesis), efficient harvesting, storage and supply systems, as well as a wide range of end product and processing options.

Provide a continuous supply of feedstock to biorefineries. To maximise the return on investment, biorefineries should operate all year round, so the seasonality of biomass cropping poses a particular challenge. Enough biomass should be available, but diversified and integrated logistics systems are needed to supply different types of biomass out of season at both a local and regional scale.

Make biomass a useful source of income for regional development. Appropriate management of local land, selection of suitable biomass crops and analysis of the market demand for biorefinery products can together ensure that benefits from this new industry are appropriately distributed. Robust and efficient logistic systems are also required to deliver locally produced biomass to biorefineries as needed.

Ensure biomass suitability for downstream processing. The supply chain up to the factory gate has to ensure that the feedstock is suitable for the subsequent biorefinery processes, so that the final products meet relevant specifications.

- Improving the yield and sustainability of biomass production
- Improving feedstock quality for biorefinery applications
- Utilising the largest possible fraction of the feedstock
- Providing a continuous supply of feedstock to biorefineries
- Ensuring biomass cultivation and use helps drive regional development
- Enhancing biomass suitability for downstream processing

Box 1 Main biomass challenges

R&D needs

Achievement of these goals requires research along the entire biomass production and supply value-chain. These research needs can be classified into two main themes (Figure 2):

- ✓ Research on the feedstock side, with a focus on plant science, cultivation methods, biomass availability and the sustainability of production
- ✓ Research on logistics systems and pre-treatment options before delivery to the biorefinery gate

Research on biomass spans various areas and not every research need can be clearly allocated to a single area; for that reason this classification should be seen as indicative only. The different areas are interdependent and the development of one of them also influences the others (e.g. increased use of a formerly underutilised biomass resource may lead to development of new logistic operations).

Research on the feedstock side

The focus of this theme is both on the development of high yielding, high quality arable or perennial crop varieties as well as on the sustainability of agricultural and forestry practices used in their production. The main goals of research are to provide feedstock that is tailored for biorefinery applications and to increase the efficiency of biomass production systems under sustainable conditions, optimising land use and reducing the costs of production and transport.

IMPROVING YIELD AND PROPERTIES

Understanding the metabolism, biochemistry and structure of the plant is crucial for the development and cultivation of new varieties, not only to increase the yield of useful components but also to develop varieties that exhibit improved processing characteristics.

Post-genomic approaches to feedstock improvement have advanced greatly in recent years, allowing rapid advances to be made even in recently domesticated varieties; together with the use of modern biotechnology, genetic modification and precision breeding, this has opened up a number of new

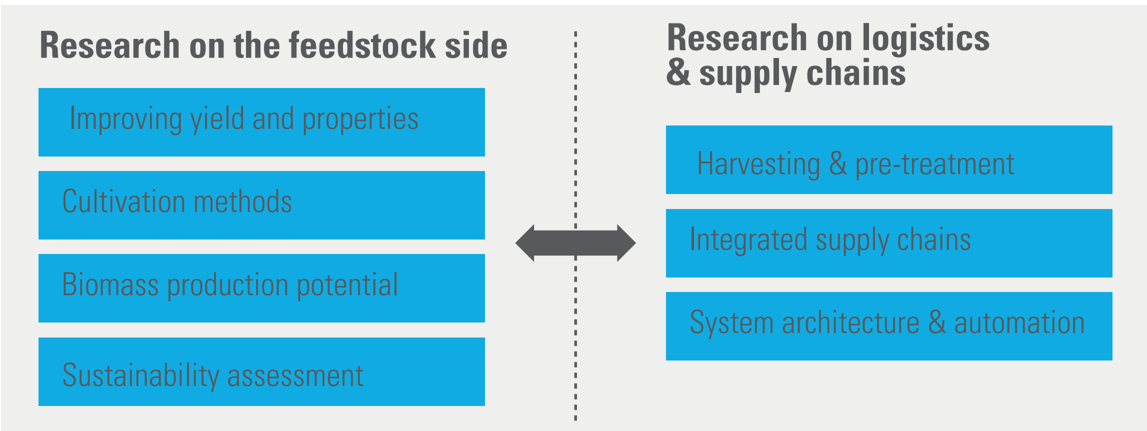


Figure 2 Research needs for biomass development

opportunities. Understanding plant growth and development is critical if the tools of modern breeding technologies are to be used effectively in breeding programmes aimed at increasing biomass yield, controlling plant development and producing varieties adapted to particular environmental conditions.

Particularly for the lignocellulosic crops and agricultural and forestry wastes that are of special interest for biorefineries, understanding the structure and interactions of the components (i.e., cellulose, hemicellulose and lignin), will allow the development of better fractionation processes, in order to extract the largest possible amount of usable material. For example, a modified lignocellulose structure can have a significant impact on processing costs by, for example, reducing the energy needed for pre-treatment and the enzyme requirements for downstream processing.

Screening of plant species and plant breeding is of critical importance in increasing the efficiency of biomass production. The wide range of feedstock and the maturity of each type have a big influence on the need for research. For example, arable crops like cereals and oilseeds have a long history of breeding for yield improvement, whereas the potential gains from breeding programmes for dedicated biomass crops are still largely unexploited. Breeding will identify robust traits (e.g. disease resistance, drought tolerance and improved nutrient use efficiency) and help to reduce overall crop production input requirements. Breeding should, of course, always be based on high yielding genotypes and aim to produce feedstock with appropriate downstream pre-treatment and processing properties, as this can improve the efficiency of the entire supply chain.

Plant biotechnologies (including genomics, marker-assisted selection, genetic modification and precision breeding) will make it possible to produce feedstock with improved properties, including high yield and greater value for industrial processing (e.g. higher oil or starch content, reduced water content, more digestible lignocellulose, in-plant-produced microbial cell wall hydrolytic enzymes or higher lipid contents of algae) but also targeted properties, which will allow the production of speciality biorefinery products with specific quality requirements. Targeted properties will also allow cultivation under unfavourable climatic and soil conditions, which is especially important for the exploitation of marginal land to supply biorefinery feedstock.

Two of the main obstacles to the transfer of scientific knowledge from the lab to the field are public appreciation and regulatory issues. Many of the concerns about genetically modified plants should be obviated by the long record of safety obtained from field experiments. Unnecessary regulatory bottlenecks need to be identified and (ideally) the system modified, for example when it concerns down-regulation of endogenous genes.

Analytical tools to determine the composition and important physical and chemical properties of different biomass types (including residues and waste) and their structural components should be further developed and standardised. Databases drawing together such important information should be well documented and easily accessible. Knowledge of the composition and properties of biomass is vital for the subsequent design of the handling and transportation stages that will, in turn, impact the entire biomass supply chain. Such databases are also important to ensure compliance with any quality requirements for downstream processing, particularly so for the biorefinery concept, where a wide range of products can be produced.

Main research areas would be:

- Improving the overall annual yield of biomass on a given land area. For some feedstocks also increasing the yield of specific components (e.g. lipids, sugars, and proteins).
- Understanding the biosynthesis and structure of lignocellulosic cell walls and studying options for engineering improved yields of polymers, oligomers and monomers.
- Understanding metabolic pathways and engineering them in order to identify potential ways to improve products (e.g. platform chemicals, pharmaceutical compounds) produced in biorefinery processes.
- Further developing breeding programmes that exploit the full range of technologies for feedstock improvement (see details below).
- Standardising techniques for the determination of biomass structure and composition and creating and managing the associated databases.

Box 2 Main research areas for biomass yield and properties improvement

Specifically, for breeding programmes, targets should include:

- ✓ Improving crops for a wider range of climatic and soil conditions
- ✓ Improving disease management (e.g. developing a portfolio of varieties with complementary disease resistance)
- ✓ Controlling reproduction to facilitate breeding and multiplication of biomass crops (e.g. somatic embryogenesis, rooting, auto-incompatibility, seed versus rhizome multiplication, doubled haploid production and apomixis)
- ✓ Improving biomass characteristics for subsequent logistic chains (e.g. increasing the dry matter content of plants to reduce drying, handling and transport costs)
- ✓ Transferring relevant knowledge (such as improved digestibility) from model plant species into key biomass crops and assessing the impact on field performance in demonstration plots. Demonstrating the impact of these improved feedstocks on appropriate biorefinery processes will also be important.
- ✓ Accelerating crop domestication (e.g. poplar domestication for better carbon allocation between storage and structural components, less extensive root system and larger stem diameter, or domestication of orphan crops, like dandelion for latex production)
- ✓ Ensuring the preservation of genetic resources by maintaining a seed bank of multiple varieties, land races and closely related wild relatives of domesticated species, or potential biomass crops, for selection of novel traits
- ✓ Investigating the link between environmental factors and plant genotype (e.g. high throughput phenotyping to discover stress tolerance traits)
- ✓ Studying and trying to improve public appreciation of genetic modification applied to biorefinery feedstock, possibly allowing the relaxation of unnecessary regulatory hurdles.

CULTIVATION METHODS

Efficient cultivation systems which increase yield, reduce feedstock costs and allow sustainable production are a major goal for biomass production in general (for both land-based and aquatic systems). Some of the issues that are already being studied and need constant monitoring are: appropriate cultivation systems (e.g. plantation forestry, improved establishment of perennial grasses, arable crop rotation, mixed cropping), efficient use of land, possible use of marginal or abandoned land, types of biomass suitable for cultivation, efficient use of fertilisers and other inputs and maintenance of soil fertility, minimisation of soil erosion, efficient water use, and control of invasiveness.

These issues are particularly important for biomass production systems that are expected to play a significant future role but are not yet widely used (e.g. those based on short rotation coppice, miscanthus, switchgrass or eucalyptus). An integrated approach to land use management is needed for sustainable, efficient production. One focus will be on the identification of suitable areas for agroforestry systems, based on economic (e.g. land tenure, productivity), ecological (e.g. nutrient cycling, water balance) and social (e.g. diversification of systems) factors.

The goal, as far as is possible, is to introduce new crops (e.g. perennial lignocellulosic crops, fast clonal forestry) into existing agricultural and forestry-based systems and thus create dedicated multipurpose cropping systems to support the development of biorefineries. Use of multi-use feedstock requires careful resource planning and systems which avoid any unwanted impacts from competition with other uses. Another aspect is the management of the supply chain between the producers and users of biomass (e.g. contractual guarantees between producers and biorefinery operators).

For agricultural residues such as straw, research should focus on monitoring the development of grain-to-residue ratios. Also, the need for straw and other agricultural residues (including residues from biogas production) for humus production has to be considered and managed regionally in order to maintain soil structure and fertility. In the case of forestry systems providing sustainable wood for energy production, research activities should focus on the environmental and economic impacts of the increased use of logging residues as biorefinery feedstock.

Research on cultivation systems for potential energy cropping (e.g. switchgrass) should focus on optimising sustainable land use efficiency and crop yield performance. The main research areas should include:

- **Identifying the most appropriate energy crop cultivation systems** taking into account nutrient balance, water use efficiency, soil tillage practices and management needs
- **Improving** crop propagation and establishment
- **Establishing appropriate site-specific field trials** to evaluate performance under simulated climate change scenarios and to identify stress tolerant genotypes
- **Examining ways to optimise environmental performance, particularly carbon sequestration**, and the role of root structure in reducing erosion and fostering biodiversity
- **Focusing on soil science** and other limiting factors for crop production (see details below)
- **Establishing recommended lists of new biomass genotypes** (e.g., poplar, willow, miscanthus, reed canary grass) to be grown for biorefining purposes, based on independent tests in multi-site demonstration trials (similar to existing lists for food crops). Ensuring that the introduction of exotic germplasm does not result in the establishment of naturalised or invasive populations.
- **Monitoring the implications of competition between different uses of a crop** and social concerns about multipurpose biorefinery feedstock as part of the food-fuel-fibre mix
- **Optimising large-scale algal biomass production systems** for economic feasibility (e.g., open ponds, photo bioreactors), and a more detailed consideration of how the products could be used most efficiently (e.g., as high-quality/low volume products such as fine chemicals or high-volume commodity products like biofuels)
- **Analysing the impacts of increased logging residue removal** on the ecological and economic performance of forestry systems

Box 3 Main research areas for agronomic issues

Specifically for soil science, research targets should include:

✓ How to maintain soil fertility

✓ Improvement and stabilisation of yield on marginal or abandoned sites (e.g. through the use of soil 'additives' like mycorrhiza, biochar or hydrogel)

✓ Assessment of the performance of crops on polluted soils and their impact on the fate of pollutants (e.g. accumulation in foliage and stems, extent of mobilisation of pollutants from the soil into the water table)

✓ Investigation of interactions between crops, endophytes and soil microorganisms (e.g. for improved nitrogen use efficiency, better phosphorus uptake or reduced greenhouse gas emissions)

✓ Research on the effect of agricultural residues (e.g., straw) on the maintenance of soil organic matter

BIOMASS PRODUCTION POTENTIAL

The economic viability of biorefineries will depend largely on the availability of a reliable supply of appropriate quality biomass at fair prices. An important research area is therefore the detailed estimation of current European biomass production potential. For this, qualitative (i.e. types of biomass) and quantitative (i.e. amounts, yields) statistical databases of cultivated biomass (including agricultural, forestry and industrial residues) at both regional and local scales should be compiled and updated regularly. Further development of mapping systems will provide a more complete picture of the spatial distribution of potential biomass production. Such data will allow industry to assess the potential of different areas to deliver biomass in the appropriate volumes and quality for biorefinery applications.

Research on improved approaches for projecting future biomass production potential is vital for the development of policies to facilitate biorefinery development. Such projections are influenced by a range of factors on a European and global scale (e.g. land availability, population growth, food consumption patterns, trade balances, agricultural productivity, land allocation between biomass types, market incentives, etc.). These estimates will therefore always be based on scenario approaches and will retain a high level of uncertainty. With research on modelling, good management of biomass databases and close monitoring of influencing factors, the uncertainty margin could be reduced somewhat.

There also has to be a clear separation between estimates of potential biomass production and the quantity of biomass actually used by biorefineries. Research is needed on the factors that influence the amount actually used for biorefining purposes. This has to take into account regional circumstances, competition for land (limited biomass amounts and various potential uses and markets), the interest of industrial sectors in exploiting various biomass fractions, and the market demand for biorefinery products. Research on approaches such as Multi Criteria Analysis (MCA) could determine which biomass types would best fit biorefinery use under specific regional conditions. This would be based on the development of cost-supply curves for different feedstock types, for different regions and for different uses, in order to identify first, second and third preferred options.

The main research topics in this area should include:

- **Improvement of techniques for yield estimation** (e.g. remote sensing and the differentiation of biomass types), supported by validation of modelling approaches by actual field data
- **Further development of mapping systems**, both at regional and local scale, for a more complete picture of the spatial distribution of biomass
- **Convergence of modelling approaches for estimating future biomass production potential and consistent use of terminology** (e.g., theoretical, technical, economic or realisable potential)
- **Monitoring of constraints that hinder the use of the available potential for biorefining purposes** (e.g., market interest, competition from other users)

Box 4 Main research areas for biomass production potential

ASSESSMENT OF PRODUCTION SUSTAINABILITY

The sustainability of production is a topic that concerns the entire value-chain. It is mentioned only briefly here, because of the importance of the biomass production stage and the fact that a large part of the total impact on the entire supply chain is generated at the beginning of the chain.

The focus so far has been on Life Cycle Assessment (LCA), a standardised approach which provides an overall assessment of the environmental impact of biomass production (e.g. greenhouse gas emissions and consumption of primary energy) for the entire chain. However, there are issues that are so far unresolved and require further research, like the development of approaches for the evaluation of emissions due to direct or indirect land use change (LUC and iLUC) or quantification of the impacts of biomass production on regional biodiversity. The assessment of biomass production practices should also include approaches like risk management or certification schemes for good and sustainable agricultural practices, such as Eco-Management and Audit Schemes (EMAS). But sustainability is broader than simply an environmental impact assessment, and research should also be focused on the development of integrated methodologies that include all three aspects: environmental, economic and social (see also chapter on sustainability assessments). This approach could be described as Life Cycle Sustainability assessment (LCSA).

Alternative sustainability criteria for biomass production, together with certification schemes for compliance with existing standards have emerged recently (e.g. EU Directive 2009/28/EC for the Promotion of the Use of Energy from Renewable Sources, the Roundtable for Sustainable Biofuels, and International Sustainability and Carbon Certification). Taking into account the various scheme objectives and regional circumstances, effort should be dedicated to harmonising different approaches and developing uniform terminology, in order to facilitate sustainable production, trade and use of biomass resources. More broadly, there is a need for a common sustainability framework for all biomass uses.

Research on logistics and supply chains

Because of the costs inherent in transporting low density biomass over long distances, logistics systems have a significant influence on the efficiency and competitiveness of the entire biorefinery value-chain. Costs depend largely on the type of biomass and how it is produced and prepared, but in this section, pre-treatment options (i.e., prior to delivery to the biorefinery) are also considered. In the following section, research areas are separated into segments along the logistics chain.

HARVESTING AND PRE-TREATMENT

Improvement of existing machinery and development of new harvesting systems for emerging biomass sources such as short rotation coppice (SRC), perennial grasses (e.g. miscanthus) and annual crops (such as sweet sorghum) are some of the challenges facing the agricultural sector. In the forestry sector, the challenges relate to efficient approaches to biomass harvesting from low-bearing stands, stands on steep slopes or those that are difficult to reach and expensive to harvest. Also, whole tree harvesting and fractionation of thinning wood material should be developed. Efficient technology for small volume and small diameter stems should be developed, because these incur the highest harvesting costs. Finally, integrated harvesting approaches should be. developed for wood both for energy and pulping.

Agricultural residues are expected to play a major role in future biomass provision within the biorefinery concept, but their availability from current farming practices is regionally and seasonally limited. Their advantage is that most of the cultivation costs are usually attributed to the main crop component (e.g. grain). The supply chain for cereal straw is well developed and established; continued research is focused on process automation (e.g. radio-frequency identification [RFID] tracking of bales, automatic collection in the field and loading onto lorries). Research is, however, also needed to broaden and increase the range of biorefining feedstock to include residues from other crops (e.g. sunflower). This may also require improvements to harvesting technology and practices for collecting these materials.

Forestry residues such as tops, branches, stumps and roots require specific equipment for harvesting, collection, transport and subsequent shredding or chipping. Major outstanding issues include reducing soil and stone contaminants and the associated effort and investment required, size reduction of the material (during wood chipping at harvest, at the roadside or at the wood fuel terminal/hub/plant) and reduction of ash content, which affects processing equipment. As well as agriculture and forestry residues, other underutilised residual fractions (e.g. industrial waste oils, sawdust) or recycled fractions may find use in the multi-feedstock biorefinery and the waste-reducing integrated logistics concept.

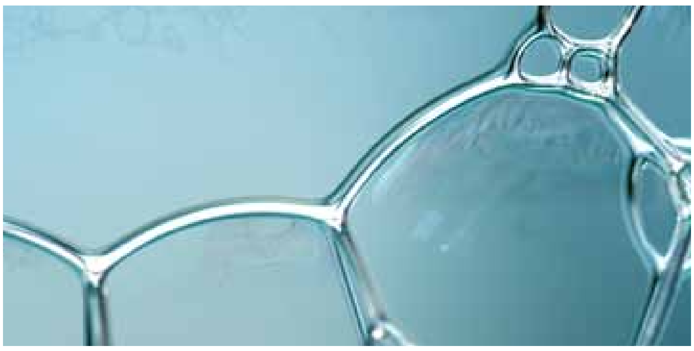
In the case of **micro-algae,** optimising harvesting costs and devising efficient large-scale production are the biggest challenges. The main challenges for macro-algae (seaweed) are the available infrastructure for collection and harvesting and whether to use natural (e.g., open-sea or coastal) or novel 'artificial' production systems.

Transport of bulky biomass and agricultural residues with relatively high moisture content is generally costly and inefficient over long distances. A typical chain between harvesting and the biorefinery includes in-field transport (loading/unloading), shredding/cutting, drying, conditioning, pelletising, storage and packaging (or baling). Depending on the specific requirements, the sequence may differ and some of those processes may take place at the biorefinery.

A major challenge in the logistics chain is quality management of perishable, wet material. The ability to store feedstock reduces the seasonality of biomass availability and bridges the gap between harvest and processing. To avoid problems associated with biomass breakdown due to factors such as microbiological activity, high temperatures, combustion, fungal spore release or emission of terpenes, storage conditions should be well designed for the particular material. In-field storage methods like wet conservation (ensiling) could also be evaluated for different types of feedstock and processes.

Drying is one possible solution to improving storability. Another is compaction, to produce a homogenous material with favourable physical and mechanical properties. The advantages of conditioning and pre-treatment include higher material densities and thus logistical advantages, favourable flow and dosing characteristics, low water content and so better storage stability, reduced dustiness during handling and standardisation of quality. However, this has to be set against higher processing costs. Compaction methods include briquetting (by an extrusion press, press chamber or cylinder press), pelletising and centrifugal methods for materials with high water retention capacity or a slimy nature. Torrefaction (moderate heat treatment in an inert atmostphere) of biomass can also improve the quality and stability of the raw material.

Conditioning and production of pellets from biomass is an efficient process, and the economics depends strongly on the volume and cost of the biomass raw material. To improve profitability, the pre-treatment chain should be flexible enough to handle different raw materials. In terms of the standardisation of activities, it is important to note that the feedstock quality may vary with the cultivation system and the site of production and this should also be monitored and considered in the design of the pre-treatment chain.



The main research objectives in this area include:

- To **develop, test and improve harvesting technologies for straw** (e.g. from rapeseed, sunflower, cereal or legume crops)
- To **optimise infield processing machinery** (e.g. biobaler concept with simultaneous harvesting and compaction; separation processes in a combine harvester)
- To **prevent losses** during harvesting, handling and storage
- To **develop and optimise precision equipment for harvesting** and collection of forest residues and reduce the costs of thinning and wood harvesting
- To **develop technologies to improve biomass storage properties** and to improve feedstock quality (e.g. separation of problematic fractions or use of additives)
- To **improve the efficiency of compaction technologies** (e.g. pellets, briquettes or bales) for different types of biomass at different operating scales (centralised/ decentralised) in order to reduce energy demand and costs
- To **develop small scale (pre-)processing** to obtain storable intermediate products and close the nutrient cycle in the field
- To **monitor the effect of cultivation systems on feedstock quality** and on the requirements of the pre-treatment chain

Box 5 Main research areas for harvesting and pre-treatment

INTEGRATED SUPPLY CHAINS

To create efficient logistics chains, different supply systems need to be brought together to form integrated networks. Very large processing plants need large amounts of feedstock and this requires transport over long distances via integrated transport chains (including shipping and rail). Smaller, more localised biorefineries will have smaller catchment areas and different requirements both for feedstock delivery and end-product distribution. Careful planning is therefore needed when siting a biorefinery, together with a good knowledge of biomass availability and the delivery infrastructure. Different biomass supply systems also imply differences in the quality of the feedstock delivered, a fact which should be taken into account in the design of logistics operations for multi-feedstock biorefineries. Market analysis of biomass demand (e.g. for energy and materials) is required to develop integrated logistics systems, which combine information on quality parameters, delivery quantities, times and frequency. The development of appropriate web tools and databases would be very helpful.

One solution for improving the efficiency of biomass transport (especially wood) is the creation of regional hubs or terminals in which the raw material can be fractionated and treated for different transport methods and downstream processes. Such terminals can act as a buffer against annual changes in the availability of wood and non-wood biomass and thus contribute to the security of supply.

Main research objectives include:

- To **plan and manage integrated logistics chains** at local and regional scale to achieve the maximum supply potential (also combining different transport types, like road, railways and waterways)
- **To** develop logistics concepts and appropriate machinery especially for **handling large amounts of biomass in a short time**
- To develop **mapping tools that combine information on biomass inventories and local infrastructure provision**
- To **establish regional hubs** for collection and fractionation of the material for different users and transport methods, taking account of projected product demand
- To **facilitate cooperation among stakeholders in the value-chain** in order to minimise the inefficient dispersal of biomass-related operations
- To monitor **shipments of imported** biomass in order to prevent transfer of pathogens (e.g. chemical testing prior to shipment or fumigation during shipment to make use of the "dead" time)

Box 6 Main research areas for integrated supply chains

SYSTEM ARCHITECTURE FOR SMART AND SUSTAINABLE PRODUCTION

Further development and optimisation of logistics systems will require modernisation and implementation of integrated networks based on high level model software to allow management, automation and traceability of agricultural and forestry production. This would contribute to sustainability, product quality and the overall efficiency of the value-chain.

The term system architecture refers to the hardware components of an automation system and the communication between them. Integrated hardware and software systems should be developed and demonstrated (including training activities) to enable the use of state models and optimised machinery systems control. State models allow processes to be virtualised for study and enable the development of software which forms the basis for the automation of the operation. Additionally, automated, highly efficient, pollution- and maintenance-free drive trains for mobile machinery are needed, which can be linked to the software in order to establish model-based control of the total production system. At the same time, complex machine systems will require effective Human Machine Interfaces (HMI) to guarantee easy and safe usage and to avoid potentially dangerous situations.

Recommendations

The key R&D priorities are:

- ✓ **Research to identify factors that influence yield stability and improvement** for sustainable biomass production (e.g. genetic and environmental factors)
- ✓ **Research on the structure of lignocellulosic feedstock**, in order to improve fractionation processes, utilise as much of the feedstock as possible and support plant breeding
- ✓ **Understanding variation in metabolic pathways** and engineering them in order to identify routes to improved products (e.g. platform chemicals, pharmaceutical compounds)
- ✓ **Research and use of advanced plant breeding technologies** (e.g., marker-assisted selection, association genetics, genetic modification, precision breeding and synthetic biology) to develop dedicated biomass crops tailored for biorefining applications and adapted to grow in a range of soil types and climatic conditions, and with increased tolerance to pests and diseases
- ✓ Establishment of **demonstration plots** providing biomass for biorefinery process evaluation
- ✓ **Investigate the production potential and specific requirements of aquatic biomass** to provide biorefinery feedstock on an industrial scale
- ✓ **Research on resource use efficiency, soil science and stress and disease tolerance** to improve biomass output, particularly under specific climatic conditions and on marginal land
- ✓ **Identification of sustainable multiplication and cultivation practices** having improved nutrient and water balances and allowing the incorporation of biorefinery-relevant crops into existing agricultural systems
- ✓ **Establish integrated cultivation systems for the food-fuel-fibre concept** and monitor the potential impacts of competition across various end uses. **Scale up to supply at area level as part of an integrated strategy**, taking into account projected demand.
- ✓ Further development of approaches and techniques for **determination of current and future biomass production potentials** (e.g. mapping systems, remote sensing)
- ✓ **Examination of the need for a common framework for sustainability criteria** and certification schemes for different types of biomass use (e.g., energy or materials)
- ✓ **Optimisation of harvesting equipment** (e.g. precision equipment for forest residues, combined in-field harvesting and processing for agricultural crops)
- ✓ Optimisation of pre-treatment chains and **adaptation to specific raw materials** to improve quality and standardisation of feedstock
- ✓ **Establishment of integrated logistics networks** to maximise local and regional feedstock supply potential

Pre-treatment processes

Main challenges

The manufacture of various bulk and speciality chemicals, biofuels, materials and other biomass-derived products in different biorefinery processes depends heavily on the availability of efficient fractionation, separation and purification processes. This chapter discusses the processes required after harvesting the biomass and before it enters the production process. Pre-treatment processes include collection, physical separation (e.g. of bark from wood) and other processes that yield biomass or biomass fractions with the appropriate size or shape for further processing. Production processes themselves need to be improved, as the optimal physical form for current reactors or other processing equipment may not be best suited to improved systems (e.g. intensified processing, alternative reactor designs, microwave processing etc.).

Also included in this pre-treatment chapter are processes where fractions of biomass are extracted with solvents, which avoids chemical changes to the substrate. Some minor changes to the biomass chemical composition may however occur during other extraction processes. In cases of significant chemical change to one of the biomass components (e.g. depolymerisation of a polysaccharide to improve solubility, extractability or further processing) the characteristics of the other components in the mixture should not be affected. Processes involving significant change to a biomass component or components will be discussed in the chapter on conversion processes.

Currently, various biomass extraction and fractionation processes are used industrially in volumes ranging from hundreds of kilograms to hundreds of millions of tonnes. Several novel fractionation technologies are still under development and are likely to reach commercial scale in the near future.

Typically, extraction and other fractionation processes are used to i) pre-treat raw materials before further processing, ii) fractionate raw materials into their main constituents for further use or processing, or iii) recover the fractions or chemicals for final purification and use. During fractionation, only one of the major components (or depolymerised fractions of the component) is usually recovered for further use, while the others are degraded with inevitable reduction in their utility and value (e.g. cellulose and hemicelluloses in the Kraft papermaking process are recovered but the lignin component is heavily degraded and therefore has limited processing options, despite being potentially valuable).

A key feature of the majority of lignocellulosic biomass fractionation processes is that they are almost exclusively aimed at producing only one product, while sacrificing significant proportions of the remaining material. The majority of recent research has focussed on the efficient depolymerisation of cellulose to fermentable sugars. However, despite this being an important objective, research into value-added uses of the other biomass components is also important. The separation of biomass into its component polymers (or their constituent monomers), without their degradation, therefore represents a worthwhile challenge. A separate challenge is to develop techniques which can maximise the value of individual components within the total biomass, that is, without pre-fractionation and without compromising the utility and value of the other components, leaving them available for further processing.

- Development of processes (chemical and mechanical) which can cope with variable feedstock quality
- Development of technologies that can separate each of the components without reducing the value of any as a raw material
- Development of chemical or biological techniques which allow individual components to be processed within intact biomass without degradation of the other components
- Development of mechanical processing methods which have lower energy requirements
- Development of processing technologies with a significantly reduced water demand
- Improvement in the separation of extracted materials to simplify their conversion to high value-added products
- Integration of process intensification into the these challenges to improve efficiency and allow for the implementation of smaller-scale, more readily distributed, processing technology
- To find value-added uses for the inorganic components of biomass, where these can be readily isolated

Box 7 Main challenges for biomass pre-treatment

There are several approaches to the pre-treatment of biomass according to the maximum value criteria set out above. These include mechanical processing, drying, torrefaction, extraction, and processes involving pressure change such as steam explosion and extrusion/ pelletisation. These approaches will now be discussed after a brief discussion of the main types of biomasses for processing.

Specific challenges

Fractionation technologies by biomass type

SUGAR AND STARCH CROPS

Examples of mature processes using large volumes raw material include sugar extraction from beet and cane, the fractionation of cereals and other starch-rich crops to provide starch for further processing (as well as functional proteins), and chemical pulping of wood and other lignocellulosic materials. These processes have been used for a very long time and have been well optimised. Though evolutionary improvements are regularly introduced, no critical disruptive innovation has been identified for these processes.

OILSEEDS

Organic solvents (most commonly hexane), are used to extract oil from seeds such as soy or rape. The challenge is to develop alternative extraction methods, moving away from petroleum-derived solvents. Microwave technology and bio-derived, supercritical fluid solvents (e.g. supercritical CO_2) can be used to separate residual oil from the press cake. This can improve yields of oil, as well as simplifying further processing steps.

PROTEINS

These can be grouped into two main categories: grain proteins (gluten, pea protein, rapeseed/sunflower press cake) and leaf proteins

Grain proteins are valuable for food and feed after separation. For oilseeds, proteins in the press cake are used as feed after oil has been extracted. These processes have been used for very long time and are well optimised. There is no major bottleneck with the exception of those linked to oil extraction, as described in the previous section.

In the case of leaf proteins, concentrates are obtained by drying (mainly for alfalfa). The techniques currently in use are not particularly effective and they involve high energy costs; an innovative approach is needed. There are opportunities for green biorefineries for optimised novel, advanced extraction processes. Microwave drying is a well-established technique used on a large scale for e.g. coal drying as well as food preservation. Because microwaves heat water selectively, microwave drying could also be a solution for leaf protein drying. The biomass density should be increased to increase process efficiency and to avoid the use of high energy density microwave radiation which might damage biomass components.

LIGNOCELLULOSIC BIOMASS

Conventional chemical pulping processes, globally handling over 300 million tonnes of wood and over 30 million tonnes of non-wood raw materials, are based on two main methods: i) the dominant Kraft process, working under alkaline conditions, and ii) the less commonly used acidic sulphite processes. In both of these processes, cellulose fibres (for papermaking or chemical cellulose applications) are recovered by reactive extraction of lignin, hemicelluloses, and certain minor constituents from the feedstock. Under normal process conditions, the extracted materials typically also undergo various degradation reactions. Substantial efforts are needed to develop methods which can create maximum the value derived from each of the three major components of lignocellulosic biomass, and this topic thus forms the bulk of this chapter.

Types of pre-treatment processes

MECHANICAL PROCESSING

Mechanical processing is widely used to prepare biomass for specific processing technologies. An alternative or additional objective is to optimise the supply chain and minimise factory gate raw material costs. In most cases, the physical and mechanical properties of the biomass will be changed (density, size or size distribution). Mechanical processing covers a range of different methods, including comminution (size reduction), sieving or sorting, separation and compaction.

The processing of biomass typically uses technologies to remove unwanted components, to tailor the size of the particles (and thereby make them more uniform and easier to handle) by comminution and fractionation steps, and to modify particles – if necessary – by simple and cost-effective chemical or enzymatic means, to improve the efficiency of downstream processing.

Both wet and dry technologies can be used to produce particles of different materials for various applications. After shredding and chopping, intensive dry milling technologies can be applied combined with air classification, to obtain a fraction with controlled particle size distribution. Modern technologies include dry milling (such as long gap milling and air jet milling), performed either at room temperature or under cryogenic conditions, or wet milling (e.g. agitated pearl milling in water or in organic solvent). For cost-effective production of biobased materials, the powders or pulps produced have to be classified either in air or in solution. Challenges here are to develop technologies and processes which minimise the energy requirements for mechanical pre-treatment (which are often large) and/or reduce the need for such treatments by being able to handle larger or less uniform particles.

Comminution

The comminution of woody biomass and agricultural produce is necessary when a particular material structure is required for further processing steps. Depending on how materials are loaded and recycled, either crushed raw material or distinct pieces may be needed. Combining chemical pretreatments with mechanical processing can produce micro- or nano-scale particles. Also, reactive downsizing can produce the necessary size range or particular types of desired particles. The main methods of comminution are shredding, chopping (drum chipper, disk chipper or rotary debarker), milling (hammer mill, edge mill or disk mill), ultrafine dry or wet milling (air turbulence milling, agitated ball/pearl milling) and bale breaking.

Here, a significant challenge is to reduce the energy involved in these processes either by energy recovery, or by more effective drying technologies. Where individual components are separated, processes have to be developed which leave the other components suitable as feedstocks for further processing.

Sorting and Sieving

Free flowing biomass that does not have the required particle size distribution needs an additional pre-treatment step. If the particles are, for example, too long, the danger of material blockage or bridging exists. If foreign materials are present in the mixture, they need to be removed. Also the separation of fine components can be useful to avoid handling problems. A range of different sieves may be used — disk and star screens, drum screens or flat screens (horizontal) — as well as air classification of dry fine material.

Pelletisation is a technique whereby biomass can be extruded to form cylinders, with typical diameters ranging from a few millimetres to a few centimetres. Often this causes densification of the biomass, which is useful for transport and also has a beneficial effect on, for example, microwave processing. The majority of biomass types appear to be pelletisable, which makes handling of significant quantities much easier.

DRYING PROCESSES

Material may be dried either before or after mechanical processing, or potentially before further processing without any mechanical treatment. Uniform and reproducible drying must be achieved at a low energy cost and without excessive temperature gradients which could damage parts of the material before drying is complete. Preservation of physical form is also vital, and clumping must be avoided.

Torrefaction is a thermal process which operates at temperatures between 200 and 300°C. It dries and partly decomposes biomass to give a grindable hydrophobic solid of high energy value. It has promise for increasing the density and storage stability of biomass for fuel, and torrefied grains also have a minor role in brewing. However, the temperature is sufficient to cause some breakdown of the three major components, and therefore it is questionable whether it can find use for chemical production (except by pyrolytic processes, leading to high selectivity for individual processes).

Separation of biomass components

PULPING

Currently, the chemical pulping industry produces about three million tonnes of different chemicals, isolated or produced as pulping by-products. They range from million tonne levels of lignin products and tall oil (containing fatty acids, resin acids, and phytosterols) to minor amounts of products like ethanol, acetic acid, vanillin, and torula yeast. Although the technology is generally well established industrially, there is still a need to develop the current pulping processes further as part of more advanced and flexible biorefinery concepts. This requires, for example, new efforts to develop selective methods for the isolation of additional valuable chemicals from the pulping spent liquors and other process streams.

Some novel pulping processes and pulping-related fractionation processes are also under development; some are close to commercialisation. In these modified or novel processes, one of the essential challenges is to preserve the natural structure of the cellulose, hemicelluloses and lignin during their selective isolation. For this purpose, different organosolv processes (pulping methods using organic solvents), ionic liquid-aided fractionations, and hot water treatments (even under supercritical water conditions) have been tested. Of these, some organosolv processes have been demonstrated in the past (even at a mill scale), while some others are currently reaching commercial-scale production. However, it is very unlikely that any of these processes can genuinely separate the three major components intact.

HYDROLYTIC PROCESSES

Other widely studied commercial processes for lignocellulosic raw materials include enzymatically catalysed hydrolysis processes (usually following a suitable pre-treatment). In pre-treatment/hydrolysis processes, a large number of different lignin-derived phenols and other types of components are formed, as well as the desired monosaccharides. Many of the impurities can act as inhibitors during fermentation of sugars to ethanol or other chemicals, and so a key challenge is to develop methods for the selective removal of these after hydrolysis. Alternatively, more selective pre-treatment methods are needed, to give sugar mixtures that are more suitable for fermentation.

Acid and alkaline hydrolyses are common, but suffer from the drawback of needing additional neutralisation steps. However, they are effective in hydrolysing polysaccharides. Phosphoric acid systems appear to have promise, as the acid is relatively mild and is able to disrupt the cellulose structure without drastic degradation of other components. Recovery of the acid via precipitation as calcium phosphate and then regeneration with sulphuric acid is also possible.

In contrast to most of these processes, hot water hydrolyses have mainly been aimed at the formation and isolation of soluble polymeric hemicelluloses. One of the key challenges is to constantly remove the dissolved polymers before further degradation takes place. Therefore, it is likely that the process intensification could have an important role to play in the rapid formation, dissolution and removal of such polymers. Indeed, in many of the pre-treatment and subsequent steps, process intensification could have significant benefits over more traditional processing concepts.

STEAM AND AMMONIA EXPLOSION TECHNOLOGY

Steam and ammonia explosion both involve the high temperature pressurisation of biomass with water or ammonia (AFEX — ammonia fibre expansion) respectively, followed by a very rapid depressurisation of the system.

Steam explosion rapidly breaks down hemicelluloses to oligosaccharides, and partly depolymerises lignin, leaving crystalline cellulose behind. Depending on the treatment conditions, the depolymerised hemicelluloses can decompose further to monosaccharides and furans, both of which are potentially valuable classes of compound. Commercial steam explosion facilities currently exist.

The AFEX process operates on a similar principle to break down lignocellulosics to soluble sugars, leaving behind lignin and some low grade cellulose. It is less well developed than steam explosion.

These processes are on the borderline of pre-treatment and chemical conversion, but as the sugars are themselves likely to be further processed, the techniques are included in this chapter. It should also be noted that the lignin that remains has been redistributed within the material, and has a lower softening point, so there is some structural change (degree of depolymerisation) during these processes. This means that there is significant chemical change occurring; however it appears that the lignin produced might have useful mechanical properties, including improved pelletisation, which will have implications for densification and storage. There are also implications for further chemical processing of the modified lignin. Challenges include the characterisation of modified lignin and how it influences further processing for chemicals or materials. Currently, the lignin that is produced during these processes is highly branched and cross linked due to degradation and re-polymerisation, making further processing and value extraction extremely challenging.

SOLVENT EXTRACTION

Organic solvents can be used to extract a range of molecules from biomass feedstocks, often without breaking chemical bonds or causing any chemical changes. However, there may be some changes to certain molecules (e.g. an ethanol extraction may deliver ethyl esters, rather than the acid — or glyceride — itself). It is clear that such processes can often produce valuable products without substantial degradation of other components, which are then available for subsequent processing.

Solvent extraction can be used to remove waxes, oils and other non-polar compounds such as terpenoids. While conventional organic solvents can be used for this purpose, there are problems with cost, safety and the removal of residues from the products. Also, being mostly petrochemical-derived, there are questions about their sustainability. Supercritical fluids (such as CO_2, possibly with additives such as ethanol) are particularly effective. Benefits over conventional solvents include lack of flammability, cost, and lack of solvent residues in the products.

Variation of the temperature and pressure of supercritical fluids can also be used to control the solubilising effect, with higher densities generally being better solvents. Stepwise depressurisation can also be used to fractionate the dissolved substrates. Overall, changing the conditions of extraction and decompression can significantly alter the extractive profile. During this process, the biomass is also dried, which can be beneficial for further processing. Supercritical fluids are generally of very low polarity, which can lead to very selective extraction, but can also have the drawback of not dissolving some valuable compounds. Addition of more polar adjuncts (e.g. ethanol) can increase the range of molecules extractable in these systems.

High temperature (near- but sub-critical) water can also be used to extract fractions from biomass. While this may be a more reactive medium, it can extract a different series of products than CO_2. Typically, such extractions give mixtures of products corresponding to 1–2% of the biomass. Supercritical fluids are already well established in the decaffeination of coffee and the extraction of flavour components from hops for the brewing industry.

Currently, some extracted components can have a significant value in small quantities for markets such as flavours and fragrances, but the potential quantities of extractives that could be obtained is much larger. Given the economics of supercritical plant operation, large-scale units have a significant advantage. Key challenges include developing the technology to extract different biomass types on an appropriate scale, including efficient separation, determination of the influence of extraction on further processing of residual biomass, and the development of the downstream chemistry of the extractives to build a broader portfolio of products to balance the scale of the extractive production with the market opportunities.

Microwave steam distillation, in which wet biomass is rapidly heated by microwaves and volatile compounds are steam-distilled, is an alternative method for extraction of small molecules. Residual oils (from pressed seedcake) can also be recovered. Further research is needed to assess this technique and define the fractions which are obtainable, together with any concomitant changes in the residual biomass. Separation and downstream processing are also challenges for the products obtained from this technology, as is the need to develop efficient large-scale processes in collaboration with microwave manufacturers.

Ionic liquids

Ionic liquids[2, 3, 4] can be employed in biorefineries to solubilise lignin and cellulose and also as an extraction and reaction medium. Recent extensive studies with numerous ionic liquids have revealed their significant future potential for the fractionation of lignocellulosic materials, although further studies are needed, as there are issues concerning cost, sustainability and toxicity. The development of low cost, sustainable formulations and the development of processes for solvent recovery, purification and reuse are also aspects of great importance for the development of this potentially very useful technique.

Organosolv processes

Organosolv processing is a form of pulping using aqueous organic solvents (such as methanol, ethanol, acetic acid and a few others) with the lignocellulosic biomass being heated to temperatures typically between 140 and 200°C. This causes breakdown and solubilisation of the lignins and hemicelluloses but leaves most of the cellulose intact. While this process avoids or minimises the inorganic additives and sulphurous odours associated with traditions pulping, it has the drawback of relatively higher cost dues to the organic solvents used, which also have to be recovered. It also breaks down the lignin into reactive fragments which then recombine to give a relatively intractable product. Here, the challenge is to reduce costs and also to separate the lignin and hemicellulose components in a form which allows purification and further value-added processing, plus ideally development of new solvents and/or processing techniques that minimise lignin degradation, hence reducing the formation of intractable products.

R&D needs

It is clear from the above that the route chosen to extract maximum value from the major components of biomass is critical. With the exception of extractives such as oils, waxes, terpenes, steroidal compounds etc., the major components are interlinked, complex polymers. While there are some processes capable of isolating one or more of these components (typically by depolymerisation of one or more of the others) there is no effective way at the moment to separate all the components without some loss of potential value of one or more of them.

Polysaccharide breakdown can give high yields of mono- and oligo-saccharide, but at the expense of the lignin components, which may depolymerise to very reactive species which then re-polymerise to give an intractable product. Developing routes where value can be extracted from all three major components of lignocellulosic biomass is a key R&D need.

For this, cheaper and more effective pulping methods could hold the key, with the focus shifted from the production of just one product to the provision of several, while remaining an economic, sustainable and environmentally acceptable operation. The acidic sulphite process is today the most efficient industrial process for separation of woody biomass into its components. However, the process could be further optimised, with improved organosolv systems and ionic liquids showing promise for the separation of key components.

2. Annegret Stark, Energy Environ. Sci., 2010, Ionic liquids in the biorefinery: a critical assessment of their potential.
3. P. Maki-Arvelaa, I. Anugwoma, P. Virtanena, R. Sjoholma, J.P. Mikkola, Industrial Crops and Products 32, 2010, 175–201.
4. Hua-Jiang Huang, Shri Ramaswamy, U.W. Tschirner, B.V. Ramarao, Separation and Purification Technology 62, 2008, 1–21.

The ability to selectively extract value from one component of biomass without compromising subsequent processing of the remainder is also an important target for a complementary strand of research to fractionate biomass followed by processing of separate streams.

The development of efficient extraction and separation methods for the commercial exploitation of non-polymeric extractives is also a key area of interest, where energy efficient techniques such as microwave extraction and supercritical fluids can play a significant role.

Process intensification can bring significant benefits to most of these areas. This approach to chemical processing enhances heat and mass transport, often by orders of magnitude, and can improve both the efficiency and flexibility of positioning of processing plant, by reducing its size and making decentralised processing more feasible.

As an example, the implementation of reactive extrusion, using modified twin screw extruders (made from chemically resistant alloys) could challenge chemical modification of viscous biomass (e.g. starch, cellulose and other hydrocolloids). The extruders operate with a very low water content, in a continuous process with, of course, high energy input but also requiring less energy for final drying of the end product. Lots of developments are under way: the thermo-mechanical energy of the extruder contributes to the pre-treatment of the biomass while the chemical part of the process allows good control of the hydrolysis.

- Developing routes where value can be extracted from all three major components of lignocellulosic biomass
  - ✓ Improved acidic sulphite (pulping) process
  - ✓ Improved organosolv process
  - ✓ Ionic liquid extraction
- Development of efficient extraction and separation methods for the commercial exploitation of non-polymeric extractives
- Process intensification

Box 8 Main general research areas for pre-treatment processes for biorefineries

Recommendations for innovation

- ✓ Develop high-value applications for the key lignocellulosic biomass components (cellulose fibre, lignin and hemicelluloses).
- ✓ Develop new extraction processes which are technically, economically and environmentally feasible, efficient, and produce new materials and chemicals suitable for further upgrading. An overriding goal should be highly consistent processes, which in turn would maximise the concentration of interesting materials and chemicals in the fractions.
- ✓ Develop the commercial exploitation of extractives beyond the low volume/high value applications currently available, such that market size matches available extractive volumes.
- ✓ Develop new purification and separation processes to support the implementation of the new biorefinery concept. Supercritical and organosolv processes along with improved pulping systems, allowing the value of all biomass components to be maximised, are important targets. Continuous extrusion-extraction is a good example of a technique whose development should be taken to a commercial scale. One of the big advantages of this technique is that it is continuous and enables counter-flow extraction. The disadvantage is that it is energy intensive, although overall energy consumption can be reduced if other processes are mild. Up-scaling of existing continuous extrusion-extraction processes is the next step.
- ✓ Improve energy efficient pre-treatment technologies to minimise the energy cost of biomass pre-treatment. Microwave drying is a promising technology, already proven in other contexts (coal, food preservation) and should be considered for biomass pre-treatment too. Likewise, process intensification is an important area which should be developed to provide better efficiency and flexibility.
- ✓ Develop new technologies and processes, which are capable of processing significant quantities of biomass without the need for large quantities of water either for cooling (highly energy inefficient) or as diluents for liquid waste streams.
- ✓ Develop strategies for the recovery of inorganic components of biomass and routes for their commercial exploitation.

Biorefinery conversion processes

Biorefinery conversion processes are presented in a standard classification: thermo-chemical, chemical catalysis and biochemical processes. Separation and purification issues are addressed in the respective conversion process sections.

However, it is clear that these key conversion processes should not be developed separately. Future process solutions will be combinations of the best technologies available, working together seamlessly. This issue is addressed in the chapter on integration.

Thermo-chemical processes

Introduction

Thermo-chemical conversion processes are sub-processes in a biorefinery, which aim to convert raw materials to a uniform intermediate product which can be further processed into a final value-added product using biochemical, catalytic or thermal methods. Thermo-chemical biomass conversion processes can be broadly classified as torrefaction, pyrolysis, gasification, combustion and hydrothermal liquefaction. Combustion processes are applied for power, heat or combined heat and power (CHP) production.

TORREFACTION

Torrefied bioenergy carriers have been under development since the beginning of this century, building on earlier work in France which focused on the production of reducing agents for the metallurgical industry.

Torrefaction is a thermal process which operates at temperatures between 200 and 300°C (lower than in pyrolysis) in the absence of oxygen. The list of equipment used includes, but is not limited to, rotary drum reactors, belt reactors, screw conveyers, and fixed and moving beds. In general, torrefaction is combined with pelletisation, giving torrefied pellets (TOP) as the end product. Biomass is dried and partly decomposed to give a grindable, hydrophobic solid with high energy value. Torrefaction technology is not yet fully commercially available for this application.

PYROLYSIS

Pyrolysis is treatment of a raw material at higher temperatures (around 500°C) in the absence of oxygen, to cause partial depolymerisation. The process produces pyrolysis oil (or bio-oil), non-condensable gases and char.

Use of various wood feedstocks has been demonstrated at a pilot scale. Many lignocellulosic biomass types (including agricultural wastes like straw, food processing residues etc.) may also be used as feedstocks, but some of them are more challenging to use than wood.

A number of fast pyrolysis technologies are all currently at various stages of development. Most processes employ fluidised-bed reactors, although other systems have also been designed. The largest existing commercial-scale units are used to produce chemicals for the food flavouring industry. However, these units would only be considered pilot-scale for fuel production.

Pyrolysis technologies may be applied in different ways as part of a biorefinery. Pyrolysis oil may be upgraded to conventional refinery feedstock, converted to fuel additives, or it may be converted to chemical intermediates and final products.

- ✓ Pyrolysis is being developed as a decentralised pretreatment method to provide higher energy density feedstocks for large centralised synthesis gas (syngas) plants.
- ✓ Bio-oil may also be upgraded to feed existing oil refineries. In the simplest case bio-oil can be used to replace fuel oils in heat and power production. This alternative may be applied technically in the very near future. Once this route is demonstrated, higher value uses for bio-oil may become possible.
- ✓ Bio-oil has also been upgraded to transport fuel components on a small scale. However, because of the high oxygen and water content of bio-oils (which make them incompatible with conventional fuels), upgrading to complete liquid transport fuels is much more challenging, especially for demanding applications like jet fuels.

In this context, an interesting approach is catalytic pyrolysis, which is a process where a part or all of the sand in a pyrolyzer is replaced with a catalyst in order to change the product distribution in a particular direction. One important goal of catalytic pyrolysis process development is to produce drop-in hydrocarbon fuels from various biomass resources. Scaling-up of these technologies remains to be done.

GASIFICATION

Gasification is a high temperature (>700°C) conversion of solid, carbonaceous fuels into combustible product gas which is used commercially in heat, power and CHP production. The gas made in this process is cleaned and processed to form a so-called syngas, the composition of which can be controlled.

Depending on the final goal, gasification processes can be used either for the production of heat and/or power, hydrogen, or chemicals (mainly short-chain alcohols) and biofuels (such as Fischer-Tropsch diesel) by chemical synthesis after purification (discussed in the section on chemical catalysis). Alternative microbial production systems based on synthesis gas are under development (discussed in the section on biochemical processes).

Alternative gasification technologies have been used for different biomass feedstocks and different applications. High-pressure, oxygen-blown **entrained-flow** gasifiers originally developed for coal and oil gasification are also being developed for biomass-based syngas production. Major industrial developments are ongoing e.g. in Germany using solid wood fuels and in Sweden using black liquor from the pulping industry. Raw pyrolysis oil can also be used as the feedstock.

The other main gasification alternative is **fluidised-bed** technology, which can be either oxygen-blown direct gasification or indirectly-heated steam gasification. These gasifiers usually require less feedstock pre-treatment than entrained flow gasifiers but produce more tars and light hydrocarbon gases, which need more complicated gas purification systems. These technologies are presently being developed, for example by two industrial groups in Finland.

Hydrothermal Liquefaction (HTL)

Hydrothermal Liquefaction (HTL)[5], previously called high-pressure liquefaction, is an alternative process for the conversion of biomass into liquid products. It is typically performed at about 350°C and 200 atmospheres pressure so that the water carrier for the biomass slurry is maintained in a liquid phase, (i.e. below super-critical conditions).

Difficulties with high-pressure pumping of biomass slurry have been a major limitation in the development of this process. Process research in this field faded away in the 1990s except for the HydroThermal Upgrading (HTU) effort at a demonstration plant in the Netherlands.

The HTU process converts biomass in liquid water at a temperature of 300-350°C and at 120-180 bars pressure to crude bio-oil called "biocrude". Other products are gases (predominantly CO_2), water and dissolved organics. All types of biomass as well as domestic, agricultural and industrial residues are suitable as feedstock. Biocrude may be utilised in co-combustion in coal- and oil-fired power stations or it may be upgraded by catalytic hydro-de-oxygenation (HDO) processing, for example into premium diesel fuel, kerosene and feedstock for chemical manufacturing.

Main challenges

GENERAL CHALLENGES

The most important challenge in the development of thermo-chemical conversion processes for commercial applications is the **lack of large scale demonstration of these technologies,** including, scale-up from the pilot scale. This challenge of full-scale demonstrations includes economic, technical as well as social aspects. As biomass-based processes are often resource constrained, another general challenge is the economic downscaling of the processes, in order to enable smaller units to be developed and operated profitably.

Product quality is a general challenge with all processes using variable raw materials. Uniform, classifiable and quality controlled end and intermediate products are prerequisites for good market penetration and stable and reliable use in various applications. On the other hand, the **raw material flexibility of processes is also a challenge**, and needs to be improved.

Because of the low energy density and high oxygen content of most biomass feedstocks the overall energy and carbon efficiency tends to be low. This emphasises the need for integrated production concepts.

5. Doug Elliot. Hydrothermal Liquefaction of biomass. IEA Bioenergy Agreement Task 34 Newsletter — Pyne 28. December 2010.

TORREFACTION

In torrefaction processes, the challenges are related to the raw material flexibility of the process. Raw material properties have an effect on process behaviour and, in some cases, on end product quality. Achieving consistent and controlled end product quality is the main challenge to be overcome to ensure market penetration and reliable operation of facilities relying on torrefied pellets as a raw material.

PYROLYSIS

The most significant challenges in the pyrolysis process are related to **quality of bio-oil and its utilisation.** This includes bio-oil quality control, stability improvement, and also challenges in upgrading bio-oil to higher value products. Currently their only commercial use is in the food flavouring industry. For the production of biochemicals from bio-oil or its fractions, the challenge is to assess and develop the most feasible isolation and purification methods.

GASIFICATION

The challenges in gasification are different for different types of gasifier. In entrained flow gasification the challenges relate to the fuel feed to the gasifier, whereas this is not a challenge in fluidised bed gasification.

Syngas cleaning and conditioning is the biggest challenge in fluidised-bed gasification due to the high content of particulates, tar and other impurities. The process economics depend strongly on the integration of the gasifier and the initial gas clean-up steps and the methods that are chosen: the gas can be filtered followed by reforming or scrubbing steps or vice versa. The sizing and operation (i.e. cost) of the purification steps which follow depend on the efficiency of the initial clean-up process chosen.

Syngas produced by gasification offers a platform for processes based on C1-chemistry, with the possibility of producing a wide variety of important industrial chemicals like methanol, Fischer-Tropsch-derived transport fuels, hydrogen, Synthetic Natural Gas, etc. The main challenge in all C1-synthesis processes is the requirement for ultra-clean syngas, with contaminant levels at a parts per billion level. Readily available commercial technology for gas clean-up can be uneconomic in the relatively small plant size range that is possible for biomass feeds (50—300 MW). There is therefore a strong need for optimisation and development of integrated gas clean-up equipment which can combine different unit processes, for example particulate removal and gas reforming steps, in a single catalytic filter unit.

One of the main possibilities and challenges in future biomass-based gasification processes is poly-generation, that is, the option to produce multiple product streams. This sets targets for future R&D work: how to economically integrate different C1-synthesis, gas separation and purification or power production steps in a single plant.

R&D needs

Currently, R&D is focused on developing production technologies for so-called second-generation biofuels and added-value chemicals. **The main goal for ongoing research is to develop more cost-effective and resource-efficient production methods.** An underlying driver is the carbon footprint of the end products.

GENERAL R&D NEEDS

A general need is to **validate the existing concepts by scale-up to the commercial scale** and to demonstrate the technologies and process chains. This is made possible by the development of industrialised, reliable design of unit processes and components. For current commercial value-chains and technology the R&D focus is on the improvement of economic and environmental performance (water, energy balance, material balance, waste) and GHG emissions reduction.

End product quality improvement is essential for market penetration. The final goal should be an improved performance compared to conventional products, e.g. biofuels that perform better than fossil fuels. Also, a greater variety of end products and flexibility of production processes will help improve the economic viability of concepts. The **increase of raw material** flexibility is essential to enable secure raw material supply for viable scale production and the adaptability of processes worldwide.

Integration of concepts can be developed by internal process integration and especially **by integrating concepts and processes in existing industrial facilities** and platforms (see integration chapter). Significant integration opportunities are available, for example in forest-based industries (pulp and paper production, timber supply), CHP production, other industries and agricultural production complexes.

- Validate existing concepts by scale-up and development of industrialised, reliable design and components
- Improve economic and environmental performance (water, energy balance, material balance, impurities) and reduce GHG emissions
- Improve quality of end products (e.g. biofuels that perform better than fossil fuels)
- Increase the variety of end products and flexibility of production processes to enable varying production
- Increase raw material flexibility
- Process integration

Box 9 Main general research areas for thermo-chemical processes for biorefineries

TORREFACTION

R&D in relation to torrefaction is focused on adaptation and further development of more cost- and environmentally-efficient processes. Broadening of the feedstock range combined with systematic, large-scale testing and quality control of torrefied end product properties is essential for commercialisation of the process. A key target is the development of optimised bioenergy carrier formulations based on systematic, large-scale testing.

- Adapt and develop cost- and environmentally-efficient torrefaction processes
- Broaden the feedstock range
- Systematic, large-scale testing and quality control of torrefied end product properties
- Development of dedicated analysis and testing methods for product standardisation
- Development of optimised bioenergy carrier formulations based on systematic, large-scale testing

Box 10 Main research areas for torrefaction processes for biorefineries

PYROLYSIS

Pyrolysis processes are still at the development stage. The next step towards commercial applications is scale-up and industrial demonstration of bio-oil production technologies with different biomass feedstocks and mixtures. Demonstration activities should primarily aim at the development of two pyrolysis concepts: first, development and demonstration of the use of bio-oil as replacement for fuel oil (heavy and light) in boilers and second, the development and demonstration of the use of bio-oil as a co-feedstock for oil refineries. The use of bio-oil as a feedstock for entrained-flow gasifiers should also be demonstrated. Bio-oil storage, transport, and utilisation properties should be improved. R&D is needed for catalytic pyrolysis, or upgrading of bio-oil to a refinery co-feed for transport and aviation fuels. This includes the development of catalysts.

- Scaling-up and industrial demonstration of bio-oil production technologies with different biomass feedstocks
- Improving bio-oil storage, transport, and utilisation properties
- Catalytic pyrolysis or upgrading of bio-oil to a refinery co-feed for transport and aviation fuels, including development of catalysts
- Development and demonstration of the use of bio-oil as a co-feedstock in oil refineries
- Industrial demonstration of the use of bio-oil as the feedstock for entrained-flow gasifiers, and development of novel process chains using bio-oil as a feedstock for novel gasification technologies
- Upgrading bio-oil to enable production of biochemicals

Box 11 Main research areas for pyrolysis processes for biorefineries

GASIFICATION

Currently, the primary R&D need for the commercialisation of gasification processes in biorefineries is to enable industrial demonstration of both fluidised-bed and entrained-flow gasification systems, with each followed by conversion to transport fuels. The main challenge is to optimise cleaning and conditioning of the raw gas from fluidised-bed gasifiers and improve feedstock pre-treatment and feeding for entrained flow gasifiers. Further R&D is needed on synthesis processes and their catalysts to improve cost competiveness, particularly at smaller scales than are typical in oil refining or the chemical industry.

- **Industrial demonstration of fluidised-bed and entrained-flow gasification systems** followed by chemical synthesis to transport fuels
- R&D on optimised **cleaning and conditioning of the raw gas from fluidised-bed gasifiers**
- R&D on feedstock **pre-treatment and feeding for entrained flow gasifiers**
- R&D on **chemical catalysis synthesis processes** (and their catalysts) in order to improve cost competiveness

Box 12 Main research areas for gasification processes for biorefineries

HYDROTHERMAL LIQUEFACTION (HTL)

The HTU process in the Netherlands is at the pre-commercial stage and there are major moves towards demonstration and commercial-scale process development. The most essential research and development targets are pressurizing feedstocks and continuous integrated operation of pilot plants. Other important topics are oil/water separation, product properties and applications as well as effluent treatment. For HTL processes, the results and means to address the barriers will likely be different for each biomass feedstock type, so identifying the biomass feedstock is a critical first step.

- Pressurizing and heating feedstock
- Oil/water separation
- Product properties and applications
- Effluent treatment
- Phase equilibria

Box 13 Main research areas for HTL processes for biorefineries

Recommendations for innovation

As the current major need to enable biorefineries to develop as commercial production facilities is for large scale demonstration of processes, the general recommendation (as for thermo-chemical conversion processes) is **to focus the current activities on industrial demonstration of selected, viable processes**. For advanced biofuels, this also means that activities on process optimisation and integration should focus on specific value-chains, with on-going pilot, demonstration and reference projects.

Production processes for **advanced biofuels for transport deserve to be given priority**, because of the increasing demand of biofuels.

Priority should also be given to value-chains able to exploit synergies with existing facilities, building a better economic and industrial base for the development of commercial processes.

Chemical Catalysis[6]

Introduction

Catalysis represents a key technology as 95% (by volume) of all the products of the chemical industry are made using at least one catalyst. More than 70 % of all industrial chemical processes involve catalysts, which can be heterogeneous (80 % of the total), homogeneous (15 %), or enzymatic (5 %). More than 80 % of chemical industry added value is generated by catalysis[7]. Catalysis is a very widespread technology in chemistry, which is of great importance for many of society's priorities, such as the environment, health and energy.

When considering large-scale industrial applications, **catalysts need to be highly robust, readily available, low cost and reusable**. Generally, these properties are typical of heterogeneous solid catalysts. Consequently, major efforts have been devoted to the research for heterogeneous catalysts presenting controlled physical and morphological properties, such as micellar silicates, active carbon, Al_2O_3, ZrO_2, zeolites and clays[8,9], with the main aim of improving the active surface and thus the catalytic activity.

6. The whole section 4.2 has been written in close collaboration with UCCS, France. (Prof. Franck Dumeignil, Prof. Sébastien Paul, Dr. Benjamin Katryniok)
7. Industrial Catalysis : a practical approach , J. Hagen, 2nd ed., 2006, Wiley-VCH.
8. Corma, A.; Garcia, H.Chem.Rev.2003, 103, 4307-4365.
9. Comerford, J.; Clark, J.H.; Macquarrie, D.J. & Breeden, S. Chemical Communications, 2009, 18, 2562—2564.

Another trend is for the selection of appropriate reaction media. Generally speaking, catalysis in the gaseous phase is obviously preferable for ease of processing, but due to the high molecular weight of the organic compounds derived from biomass, the use of liquid phase processes is increasing. Non-organic solvents, ideally water (e.g., KF-Alumina catalysis and carbonized polysaccharides STARBONS®[10,11]) are preferable, for a green chemistry approach. Alternative thermo-chemical processes, like microwave heating, are also widely used.

Main challenges

GENERAL CHALLENGES

As chemical catalysts are industrially synthesized and are not limited to what nature can provide, they can be designed with tailor-made chemical and physical properties for a wide variety of feedstocks and products. However, the **traditional methods for synthesizing and testing catalysts are time-consuming**, as theoretical prediction of the optimal catalyst composition, structure and conditions of preparation is not yet possible. Therefore, a preliminary "trial and error" approach has to be followed, which begins with a first "rough" design step, followed by a preparation and characterization stage. The loop is closed by a final testing step. Then, many iterations of this loop are needed to progressively improve performance and focus on the most efficient catalysts. Of course, there are a large number of parameters to be explored, and developing a new catalyst using this conventional methodology is time- and money-consuming, but unavoidable. The average development time of a new catalyst following this route is several years. Hence, in a highly competitive environment, as for biomass processing, **methodologies that could accelerate the rate of development and innovation in catalysis would be a great advantage**.

SPECIFIC CHALLENGES FOR BIOMASS-DERIVED MOLECULES

Currently, over 90% of petrochemicals are produced via catalytic processes. The petrochemical industry is based on only a few hydrocarbons (ethylene, propylene, C4-olefins, benzene, toluene and xylenes), from which all other chemicals and materials are derived. Specific chemical functionality (often derived from functional groups including heteroatoms — elements other than carbon or hydrogen — such as oxygen) is added in subsequent catalytic processes. In contrast, **biomass-derived molecules already contain large numbers of oxygen-containing functional groups and are in effect 'over-functionalised'**.

Because of this basic difference in chemistry, one of the biggest challenges over the next few years will be to retrofit existing chemical technology to start with more oxidized carbon and go to less oxidized carbon, whereas the current chemical industry takes things in the opposite direction. The challenge will be to adapt hydrocarbon-based "petrochemical thinking" to oxygen-rich, biomass-derived feedstocks[12].

A specific challenge in processing these highly functionalised, biomass-derived molecules (with several different types of functional groups) is the **selectivity issue** (the need to selectively hydrogenate different groups).

Another challenge is the design of robust catalysts, which is made difficult for two main reasons, both specific to biomass. Firstly, **biomass-derived molecules** are highly functionalised and therefore **very reactive**. A drawback of this high reactivity is the **rapid deactivation** of catalysts by accumulation of carbonaceous compounds on their surface.

The second reason is the **large percentage of water in the reaction media**, either mixed with the substrate or generated by the reaction. Therefore, **catalysts must be resistant to water** (with no leaching, no destruction of the active phase and/or support), but **the main issue is the surface properties of the catalyst in an aqueous environment**. Understanding the detailed structure of the active sites is a challenge due to the presence of water, which considerably modifies the way catalysts behave under real conditions. Acidity or alkalinity, for example, are extremely difficult to control during processing, because conditions are modified by the presence of water, while catalysts are usually characterised under laboratory conditions. The conventional view of catalysis – structure controls morphology, which determines function – has to be totally rethought because of this discrepancy between laboratory work and operating conditions.

10. Budarin, V.L.; Clark, J.H.; Luque, R. & White, R. 2009, Material Matters, 4, 1, 21—24.
11. Clark, J.H.; Luque, R.; Yoshida, K.; Gai, P. 2009, Chem. Communications, 21, 35, 5305—5307.
12. LeGrande M. Slaughter "Harnessing Catalysis for Sustainable Production of Chemicals from Bio-mass" presented at the DAAD/Alexander von Humboldt Foundation Joint Alumni Meeting, October 28-30, 2010, New York, USA.

General challenges

- Traditional methods for synthesizing and testing catalysts are time-consuming. The challenge is to accelerate the rate of development and innovation in catalysis

Specific challenges linked to biomass-derived molecules

- Molecules are oxygen-rich (compared to petroleum-derived ones) and, in most cases, new catalysts must be developed. The challenge will be to adapt hydrocarbon-centred "petrochemical thinking" to oxygen-rich biomass-derived feedstocks (using reduction instead of oxidation chemistry).
- Highly functionalised molecules lead to selectivity issues
- The high reactivity of the substrates quickly leads to catalyst coking
- The presence of water in reaction media modifies the surface properties of catalysts
- Tolerance issues to impurities and to compositional variations inherent to biomass

Box 14 Main challenges for chemical catalysis processes for biorefineries

R&D needs

HIGH-THROUGHPUT TECHNOLOGIES (HTT)

High-Throughput Technologies (HTT), similar to the tools used for new drugs discovery, provide a way to reduce the time required for catalyst development[13,14,15,16,17]. HT approaches that enable large quantities of data to be generated in a short period of time, combined with statistical experimental design to minimise the number of experiments, is an outstandingly efficient strategy[18,19].

The use of combinatorial chemistry and high-speed screening has been in common use for catalyst development for less than 20 years[20]. However, the interest from both academic and industrial sectors has steadily increased, as reflected by the number of publications on this subject (see Figure 3a). In recent years, considerable effort has been devoted to the development of a set of technologies to enable sustainable processing of the various platform molecules derived from biomass (see Figure 3b)[21].

Technological breakthroughs will undoubtedly come from the development of new catalytic formulations for biomass processing, which is a new and extremely wide field offering many possibilities. The main objectives are to develop efficient catalysts more rapidly, while making them more stable and cost-effective. In this extremely competitive field, the HTT strategy will be a major advantage, with more intensive research leading to a much higher rate of catalyst innovation, as shown in Figure 3.

CATALYTIC CONVERSION OF BIOMASS STREAMS TO PLATFORM AND FINE CHEMICALS

Once biomass has been separated into its primary constituents, generally cellulose, hemicellulose, lignin, proteins and fatty acids, the typical reactions that are needed to convert these streams to chemical intermediates and end products are decarbonylation, decarboxylation, dehydration, hydrolysis and hydrogenolysis. These reactions break down biopolymers and partially remove the oxygenated functional groups. There is therefore a need to perform research in order to **develop novel catalysts that are able to perform** these **reduction reactions**, in contrast to the oxidation reactions typical of the conventional chemical industry.

Processing these highly functionalised, biomass-derived molecules leads to **selectivity issues** (with selective hydrogenation being needed to modify some groups but not others). The catalytic processes need to remove this functionality selectively, often to generate "bi-functional" molecules that can be used as building blocks for bulk chemicals and bulk bio-based polymers. **R&D is needed to develop bi- or even multi-functional catalysts.**

Developing low temperature catalysis used to polymerize monomers to bio-based polymers is essential, as many bio-based monomers are temperature-sensitive (although their polymers are generally more stable).

13. W. F. Maier, K. Stöwe, S. Sieg, Angew. Chem. Int. Ed., 46, 2007, 6016-6067.
14. P. P. Pescarmona, J. C. van der Waal, I. E. Maxwell, T. Maschmeyer, Catal. Lett., 63, 1999, 1-11.
15. R. J. Hendershot, C. M. Snively, J. Lauterbach, Chem. Eur. J., 11, 2005, 806-814.
16. I. E. Maxwell, P. van den Brink, R. S. Downing, A. H. Sijpkes, S. Gomez, Th. Maschmeyer, Top. Catal., 24(1-4), 2003, 125-135.
17. S.I. Woo, K.W. Kim, H.Y. Cho, K.S. Oh, M. K. Jeon, N. H. Tarte, T. S. Kim, A. Mahmood, QSAR Comb. Sci., 24, 2005, 138-154.
18. S. Senkan, Angew. Chem. Int. Ed., 40, 2001, 312-329.
19. J. M. Caruthers, J.A. Lauterbach, K. T. Thomson, V. Venkatasubramanaian, C. M. Snively, A. Bhan, S. Katare, G. Oskarsdottir, J. Catal., 216, 2003, 98-109.
20. High-Throughput Screening in ChemicalCatalysis, A. Hagemeyer, P. Strasser, A. F. Volpe, Jr., 2004, Wiley-VCH.
21. E.-J. Ras, S. Maisuls, P. Haesakkers, G.-J. Gruter, G. Rothenberg, Adv. Synth. Catal., 351, 2009, 3175-3185.

Further research needs to be focused on the development of catalysts that are capable of selectively transforming biomass-derived monomers (sugars, fatty acids, etc.) to platform molecules, or catalysing the reaction from these intermediates to final products. At the same time, the work should also focus on the possible modification of catalyst surface properties to improve their functionality in the presence of water. **R&D is needed to understand catalyst functionality and to revise the structure/ morphology/ function approach to catalyst development** using new tools (such as process spectroscopy, etc.).

The high reactivity of biomass-derived molecules leads to **catalyst coking issues** (rapid deactivation of catalysts by accumulation of carbonaceous compounds on their surface). Solutions to these issues can be found via the **development of more robust catalytic formulations** and also **in process design**, by designing new reactors (see below) and introducing small doses of oxygen in the reaction medium, optionally with the addition of an oxygen-splitting function on the catalyst surface to facilitate the process.

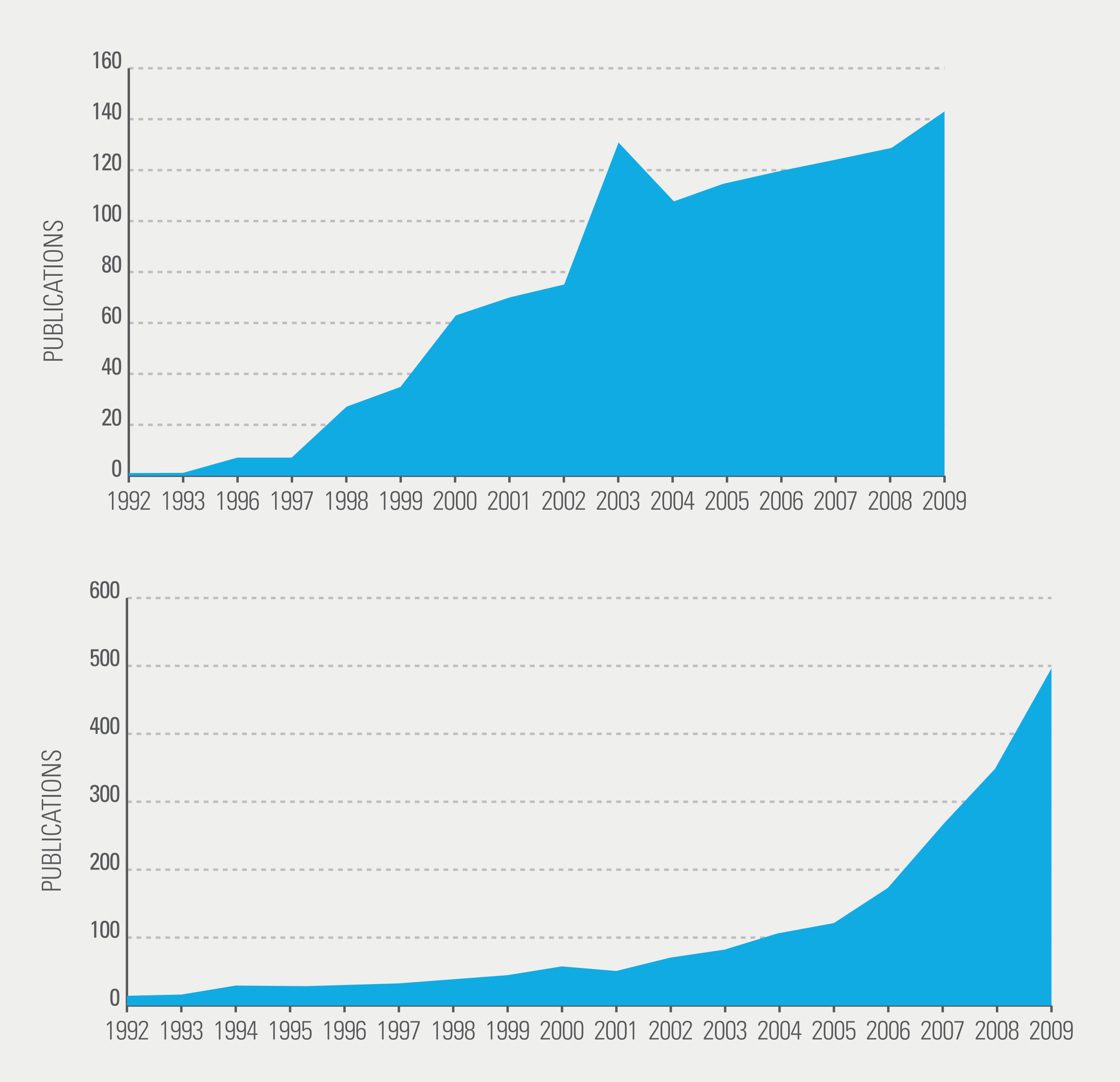


Figure 3: Statistics on the literature published on:
a) the use of HT technologies for new catalysts development[22]
b) new catalysts development in the biomass field.[23]

22. ISI Web of Knowledge – Thoman Reuters. Keywords: « catalyst and high-throughput » or « catalyst and combinatorial ».
23. ISI Webof Knowledge – Thoman Reuters. Keywords: « biomass and catalysis ».

NEW REACTOR TECHNOLOGIES AND KINETIC STUDIES

The most common reactor technology used for hydrocarbon-based heterogeneous catalytic processes (i.e., fixed-bed reactors) is not always well suited to biomass-based reactions. The increased formation of unwanted carbon deposits results in the uncontrolled production of oligomers, resulting in the rapid deactivation of the catalyst. An effort has therefore to be made to develop adapted reactor technologies to deal with these unavoidable deactivation processes. Studies on "unusual" operating conditions need to be performed (for instance, under dynamic operating conditions) in parallel to the development of more robust catalytic formulations. A good knowledge of the kinetics of biomass-based reactions and of the process of catalyst deactivation is also very important for the design of future biomass-fed industrial reactors.

CATALYTIC UPGRADING OF VALUABLE PRODUCTS FROM SYNGAS

Syngas made by biomass gasification can be used to produce hydrogen (via the catalytic water-gas shift reaction to H_2 and CO_2), biofuels (e.g. synthetic diesel by Fischer-Tropsch synthesis) or chemicals (mainly short-chain alcohols)[24]. The main problems arise from contamination of the syngas by impurities that "poison" or inactivate the catalyst (see section on thermochemical processes). Future catalysts for syngas conversion have to be developed which have a greater resistance to poisoning, allowing syngas purification costs to be reduced.

- To develop High-Throughput Technologies (HTT) for catalyst screening
- To develop novel catalysts specific for molecules from biomass
  - ✓ able to perform reduction reactions (such as decarbonylation, decarboxylation, dehydration, hydrolysis and hydrogenolysis)
  - ✓ bi- or even multi-functional catalysts
  - ✓ more robust catalytic formulations to limit poisoning
- To understand and rethink the structure/morphology/function approach when developing catalysts for aqueous media
- To develop a novel approach by combining biotech and catalysis (see below).

Box 15 Main R&D needs for chemical catalysis

BIOTECH AND CATALYSIS

The combination of bio- and chemical catalysis offers a new route to improve performance. In fact, the selectivity of enzyme-catalysed reactions is generally outstanding compared to chemical catalysis, due to the high specificity of enzyme structures, which ideally match only one substrate (the key-lock principle). In addition — even though the opposite is often thought to be the case — the activity of biocatalysts is quite high, especially when taking into account the low temperature needed for reactions. However, this low-temperature activity can also be a major drawback for enzymatic reactions, as the activity can only be increased within narrow limits, because of the temperature sensitivity of the protein complex. Enzymes can also be liable to poisoning from impurities in the substrate and can easily be denatured if reaction conditions are wrong (e.g. pH value, the presence of solvent, etc.).

On the other hand, chemical catalysis enables much higher productivity — particularly because of higher reaction temperatures — and is overall less sensitive to variations in reaction conditions. The ideal catalyst should therefore combine the advantages of both enzymes and chemical catalysts.

One example of such a combination is the addition of chemical catalysts to the fermentation of cellulose or lignocellulose biomass to ethanol. The microorganisms used for this reaction are generally not resistant to fermentation by-products such as furfural or methyl-furfural, which are inevitably produced. One way to decrease the formation of these inhibiting molecules is — of course — by pre-treatment of the substrate. But this process increases costs and only prolongs the lifetime of the microorganism to a certain extent. This makes a second approach more promising: addition of chemical catalysts selectively decarbonylates furfural to furan which can be easily removed from the reaction mixture due to its low boiling point (32°C)[25]. Another advantage is that the furan is a valuable raw material for the synthesis of tetrahydrofuran (THF), a widely used solvent, which is currently made from acetylene in a non—sustainable way.

24. Chen et al., Fuel Processing Technology, 92 (2010) 456-461.
25. W. Zhang, Q. Zhu, S. Niu, Y. Lie, J. Mol. Catal. A: Chem. 335 (2011) 71-81.

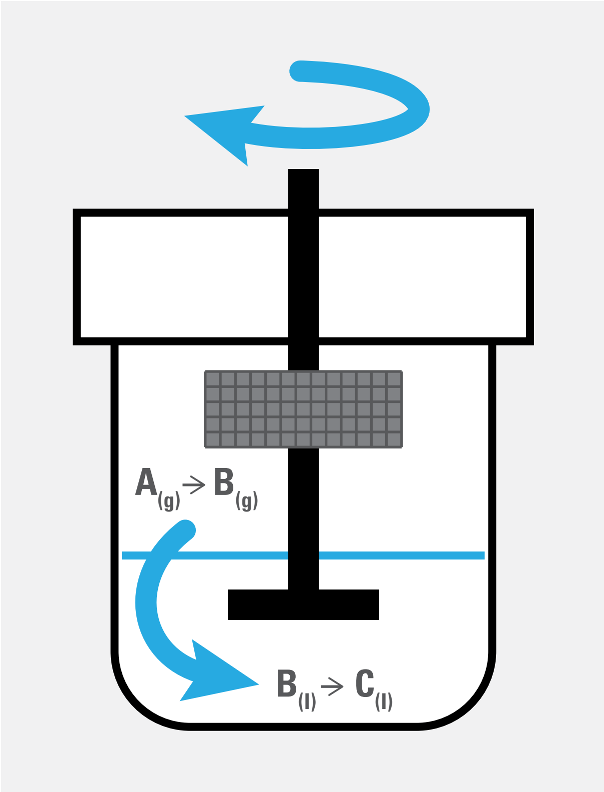


Figure 4: modified Robinson-Mahoney reactor

While this example uses chemical catalysis only to avoid the accumulation of inhibiting by-products, another concept combines enzymatic and chemical catalysis in a **one-pot cascade reaction** in order to obtain the final product. One example of such a cascade reaction is the synthesis of D-mannitol from D-glucose. In the first step, D-glucose is selectively isomerised to D-fructose using isomerase enzymes. The resulting D-fructose is then hydrogenated yielding D-mannitol using conventional cobalt-nickel or ruthenium catalysts[26].

Although these examples are liquid phase reactions, the combination of bio- and chemical-catalysis is not limited to this reaction medium. Of course, enzymatic catalysed reactions need to be performed in water, but a combination of liquid-phase bio-catalysis and gas-phase heterogeneous catalysis is possible, in a multiphase reactor (e.g. figure 4). Indeed, heterogeneous catalysis in the gaseous phase can easily be applied to the one-pot cascade reaction, with the reaction from A to B taking place in the gas phase, and the product dissolving in the liquid by diffusion. The enzymes then catalyse the reaction from B to C in the liquid phase.

Enzymes need not always be used in homogeneous catalysis. There is great potential for the simultaneous fixation of both the bio-catalyst and chemical catalyst on a support, making downstream separation of product easier. For example, the use of supported ionic liquid phase technology (SILP) has been demonstrated to be an efficient tool for the immobilisation of enzymes and homogeneous chemical catalysts[27]. This technique offers the possibility of combining biotech and chemical catalysis in the same reaction medium, with the advantage of easy product separation.

- Development of **selectivity driven strategies**:
  - ✓ In situ inhibitor destruction during fermentation and bioconversion processes
  - ✓ One pot cascade reactions combining enzymatic catalysis with homogeneous/heterogeneous catalysis
- Development of **new strategies for 'active phase' combination**
- Development of **new reactors based on enzymatic/catalytic engineering**

Box 16 Main R&D needs for combination of bio- and chemical catalysis

26. A.W. Heinen, J.A. Peters, H. van Bekkum, Carboh. Res. 328, 2000, 449-457.
27. P. Lozano, GreenChem 12 (2010), 555-569.

Recommendations for innovation

- ✓ High throughput discovery should become a more widely employed technique to develop novel catalysts for the conversion of biomass to chemicals. Greater use of this technique should help to compensate for the decreasing competitiveness of European research in catalysis in comparison to the expanding research activities in emerging countries.
- ✓ Upgrading of sugars and amino acids to platform molecules and to final products must be re-focused to achieve rapid commercialisation.
- ✓ Research on bio-catalysts should be also intensified, particularly as EU flavours and fragrances legislation will exclude all inorganic catalysts for the production of products labelled as natural.
- ✓ Last but not least, the combination of biotechnology and chemical catalysis needs to be further developed to ensure that bio-derived materials can be converted effectively into useful products using the most efficient and greenest methods.

Biochemical processes

Introduction

Biochemical processes are based on the catalytic function of specific proteins called enzymes. All living cells, including human cells, rely on enzymes to function, and their activity is also exploited industrially. Fermentation processes using living microorganisms (bacteria, yeast, etc.) are the most common form of biochemical processing. The process typically takes place in a contained reactor (a bioreactor or fermenter). The term "cell factory" is also often used, with a cell being regarded as a minuscule industrial unit.

Enzymes can also be isolated from cells, and used either in processes such as the conversion of starch to iso-glucose (the main sweetener used in soft drinks) or in end products like washing detergents. The use of enzymes in manufacturing is called "biocatalysis" (or biotransformation). In this discussion, a biocatalyst means either an isolated enzyme or a microorganism used in fermentation processes.

Today, biochemical processes are used in many parts of existing biorefineries. Biochemical processing is used to make, for example, bioethanol and chemicals like lactic and citric acids. One of the main advantages is that processing is carried out typically under very mild conditions (low temperature, low pressure and moderate pH values). Biochemical processes are also usually water-based. Although this is generally a positive attribute, it can, in some cases, result in problems of integration with other biorefinery processes.

In the context of this roadmap, it is important to note that biotechnology (the technology of biochemical processing) has been one of the fastest developing sciences over the past 30 years, and the pace shows no signs of slackening in the future. With the cost of sequencing whole genomes (all the genes of an organism) constantly falling, more and more genetic data is becoming available. The current challenge, both scientifically and industrially, is to learn how to use this enormous pool of information for the benefit of humans and the environment.

Thus, biotechnology, if developed efficiently and wisely, should become one of the key enabling technologies of future biorefineries. Biotechnology is well suited to refine and process renewable raw materials (sugars, proteins, organic acids, fatty acids, lignocellulose, etc.).

Main challenges

GENERAL BOTTLENECKS AND CHALLENGES

A general bottleneck for biochemical processes is the fact that product concentrations are typically relatively low. Also, it is common for several by-products to be produced during fermentation processes. These two factors make downstream processing (isolation and purification) of products comparatively expensive and energy-intensive.

The general challenges for biochemical processes are therefore:

- ✓ To increase yield and overall productivity: In future integrated biorefineries, it will be very important to limit material loss during the different processes to maximise their sustainability and economic viability.
- ✓ To develop processes working at high concentrations of both raw material and end-product: Biochemical processes generally work at relatively low concentrations (typical for fermentation processes). This is considered to be one of the big differences between biotechnology and conventional 'organic' chemistry.

- ✓ To develop cheaper and more efficient processes for downstream processing (DSP) after biochemical processes: DSP has a big impact on the economics of the system, in most cases being the critical factor. Challenges for DSP in biochemical processes are similar to those mentioned in the catalysis section dealing with chemistry in aqueous media.

SPECIFIC CHALLENGES FOR BIOREFINERIES

One particular point of the Biorefinery Vision document is that lignocellulosic raw materials will be used more and more (as such or mixed with other classical feedstocks) in commercial biorefineries by 2030. This implies that the primary technical and economic bottlenecks (e.g. biomass breeding, cultivating, harvesting, logistics issues and lignocellulose breakdown) should be solved by 2020.

The main bottlenecks in using lignocellulosic raw materials as a fermentation substrate are:

- ✓ Efficient and cheap breakdown of lignocellulosic raw material to fermentable sugars or oligosaccharides: enzymes can be used to facilitate this process, especially accelerating the hydrolysis of carbohydrate polymers. This, however, typically require a mixture of different enzymes ("enzyme cocktail").
- ✓ Sensitivity of biochemical reactions to impurities: Impurities are generated in the processes needed for digestion (including pre-treatments, see corresponding chapter), which can inhibit the activity of microorganisms (this is less of a problem for yeasts), as well as enzymes. Thus, more sophisticated and milder pre-treatment methods need to be developed.

Related specific challenges are:

- ✓ Utilisation of pentose (C5) sugars: Lignocellulosic biomass is partly formed from a variety of sugar monomers. The second most abundant sugar, xylose, is a pentose. Most currently used industrial microorganisms are only able to efficiently metabolise glucose (C6), which results in poor utilisation of the biomass as a whole.
- ✓ Find future enzyme activities that are of interest in the processing of lignocellulosic biomass: For instance, glycosyl transferases or enzymes for lignin modification are increasing in importance. Current, industrially-available enzymes have a very limited range of activities, for instance oxido-reductive enzymes are not truly used on an industrial scale, as problems of functional stability and co-factor regeneration still have to be solved.
- ✓ Decrease impurities and/or their impact on biochemical processes: This implies the use of more sophisticated and less robust pre-treatment or purification methods.

LONG-TERM CHALLENGE FOR BIOREFINERIES

The difficulty of breaking down lignocellulosic material can be explained by the co-evolution of plants and microorganisms. The selection pressure of microorganism activity has resulted in strong plant structures, which resist breakdown in the growing environment, including attack by yeasts, moulds and bacteria. There is therefore a crucial need to develop a new strategy for biocatalyst selection by developing new enzyme functions specifically for industrial applications. This requires a better fundamental knowledge of the microbial world in terms of diversity, metabolism, physiology, ecology etc. and optimisation of existing biotechnology tools using "omics" technologies (metagenomics, proteomics, metabolomics etc.). The possible application of syngas and CO_2 as raw material in biochemical processes should also be considered.

General Challenges

- Increase the yield and productivity of biochemical processes
- Develop processes that result in higher end product concentrations
- Develop downstream processing (the separation and purification steps directly after the actual biochemical process)

Specific challenges for lignocellulose biomass

- Develop an efficient and cost-effective digestion method for the hydrolysis of lignocellulosics to fermentable sugars. Either the method should not generate harmful or inhibiting chemicals, or microorganisms should be developed to be more resistant to such impurities.
- Develop processes that are able to utilise pentose sugars efficiently
- Find and develop future enzyme activities that refine lignocellulosic biomass or its main fractions

Long-term challenge for biochemical processes for biorefineries

- Develop a new strategy for biocatalyst selection

Box 17 Specific bottlenecks and challenges for biochemical processes in biorefineries

R&D needs

GENERAL R&D NEEDS

Biorefinery development would be greatly facilitated both by an increased understanding of the possibilities arising from the enormous, but largely unexplored, range of microbial biodiversity and by further development of biotechnologies applicable to industrial processing. The first of these would greatly increase our knowledge of microbial communities (physiology, metabolism, ecology, interaction with the environment etc.) which would help in the development of better biocatalysts. This work would generate new tools based on strain and gene sequences and continue (in the short-term) the gene-function strategy to screen for new enzymes or new activities. This approach is, however, limited and so, in the longer term, a "systems" approach is needed. The new approach is a combination of the following components:

✓ **Microbiology; a science to discover novel enzymes and microorganisms for biochemical processes.** Microbiology as a fundamental science remains a very important R&D area. There is a need for research and training on basic knowledge, taxonomy, metabolism and microbial physiology in order to understand the development of a microorganism and its interactions with the environment. The general aims are to discover new strains or develop existing ones with enhanced properties (tolerance, productivity and substrate range) and to find new enzymes, which can be applied in the biorefinery for biomass treatment or other processes.

✓ **Metagenomics; data management to predict the function or properties of a protein based on its primary structure.** Metagenomics is the analysis of collective microbial genomes contained in an environmental sample (i.e., not the genome of individual microorganisms), based on sequence and function analysis. The available genomic data represent a great source of knowledge about the metabolism and physiology of microorganisms, and have the potential for use in the development of biochemical processes in biorefineries. We are now living in a post-genomic era, but lack the resources to fully exploit the genomic data available and convert the information into real industrial applications. Research on methodology for data mining in metagenomics is needed to predict the function or properties of a protein based on its primary structure.

✓ **Development of microbial high-throughput screening suitable for the new "systems" approach.** For the next 10 years, special efforts should be directed towards the development of a "systems" approach, based on high-throughput screening and metagenomic techniques, to find novel enzymes and microorganisms with improved properties for use in biorefineries. Understanding their fundamental functions as a part of a system, especially with regards to other enzymes, is particularly important in biorefineries because multifunctional systems will always be used. Metagenomics is an efficient tool, but we need to apply it in a systems approach in order to understand the whole range of possibilities offered by microorganisms. Progress will be possible only by cross-fertilization between different scientific fields. For instance, the use of mixed microbial populations in biochemical processes will increase, which leads to a need for cross-fertilisation between microbial ecophysiology and molecular microbial genetics.

- ✓ **Creation of an European microbial database.** Characterisation of microbial metabolism is well developed, when compared with mammal metabolism. However, thanks to biomedicine, specific tools, have been created to address the physiological complexity of mammalian metabolism, which are not available to microbiology. In Europe, there are small databases containing genomic data, but they are scattered and there is not much interaction between them. Therefore, the creation of a European microbial database is becoming more important in view of the fast development of the field. A database of yeast strains (wild types or recombinant) would represent a very good starting point. European institutions have the ability to do this, including, as they do, those who generated the first yeast genome sequence[28].

R&D NEEDS FOR BIOCHEMICAL PROCESSES FOR BIOREFINING

Much of the current R&D activity is focused on screening microbial populations to discover microorganisms which are able to catalyse specific reactions. A limit of this approach is the fact that selection procedures do not always consider the industrial processing environment, which differs significantly from nature and is much more complicated that typically assumed. Finding enzymes that would efficiently degrade lignocellulosic biomass to fermentable sugars appears to be very difficult using traditional strategies (screening enzymes and mixing the best to find an optimal enzyme cocktail). The challenge is to find an enzyme (or enzymes) that are able to degrade biomass in "extreme" conditions (i.e. low pH, low water activity and high temperature). Combining the aspects of extreme conditions and system specificity turns the future of enzyme development upside down. As far as lignocellulose breakdown is concerned, pentose fermentation, with or without hexoses, is also an issue which must be addressed.

- ✓ **Specific biocatalysts adapted to an integrated biorefinery.** Future biorefineries will often be integrated, and a key point for combining biochemical processes is their adaptation to steps before and after them (carried out with different pH, temperature, solvent, pressure, etc.). The upstreams steps can also result in by-products that inhibit the effect of the biocatalysts. In order to limit their impact and facilitate the integration of biochemical process in a production chain, specific biocatalysts adapted to integrated biorefineries need to be developed.

- ✓ **Design of industrial enzymes: new enzymes or new catalytic properties optimised for industrial applications.** Starting from computer design, new enzymes or catalytic properties from existing proteins can be developed (so called *in silico* development). This requires a molecular dynamics approach. Methods such as directed evolution, site-directed mutagenesis or protein engineering can be applied to improve parameters such as catalytic activity, affinity and specificity, but also to improve technological parameters such as temperature or pH tolerance. Stability is perhaps the main issue as far as enzyme technology is concerned (able to function at extreme pH and/or temperatures, for example). The key point is not the initial enzyme activity, but the overall catalytic work performed by the enzyme during its life.

- ✓ **Water management during the process.** A second issue is the reduction of water content during biochemical processes and the intelligent re-use of process water. The use of biocatalysis and/or bioconversion addresses this issue, which is a serious downside of classical fermentation.

- ✓ **Biocatalytic process design.** Biocatalytic processes give the opportunity to increase concentrations of substrates and products with a decrease of water content to address some of the drawbacks of biochemical fermentation processes compared to classical chemical processes. Enzyme cascades must be developed, although the problem of cofactor regeneration is not yet solved. Enzyme stability is the main limitation in terms of biocatalytic process design. Stability is a key issue, not only during processing, but also for storage and transportation. A new approach is to combine classical catalysts and new biocatalysts. For instance, enzymes immobilised on chemical catalysts give rise to very interesting opportunities. There is a clear need for cross-fertilization between biochemistry and the science of chemical catalysis.

- ✓ **Design of bioreactors.** Reliably consistent processing will require the development of improved reactors for both enzymatic and microbial processing. Efficient utilisation of nutrients and water in fermentation processes represents an important aspect in their economic viability and sustainability. Therefore, research on processes and methodologies with enhanced productivities and reduced waste streams becomes a priority. Also, because there is an increasing interest

28. Goffeau, A. et al. (1997) The yeast genome directory. Nature 387(6632 Suppl), 1-105

in algae, microalgae and photo-heterotrophic microorganisms (such as purple non-sulphur bacteria for hydrogen production), the design of photobioreactors must be addressed, taking account of CO_2 sequestration, fermentation and biofuel production.

- ✓ **Innovation in downstream processing (DSP) for biochemical processes.** Reducing the volume of water and increasing volumetric productivity are key issues in the development of biochemical processes. Interest in the implementation of biochemical processes for manufacturing bulk chemicals needs innovative strategies for product purification. The development of processes with in situ continuous extraction of final products is needed to reduce product inhibition effects and product concentration limitations resulting from thermodynamic equilibrium. Continuous extraction of products can be achieved using membrane-based techniques (permeation, perstraction, pervaporation), carrier materials for adsorption or absorption, liquid-liquid extraction in bi-phasic processes (i.e. non-miscible aqueous phases with organic extractants, such as PEG and polydextran) or by using gases as carriers to remove volatile products (such as alcohols) or gases (CO_2, H_2). Some of these techniques are well established in the chemical industry and it is now time to adapt them also to DSP for biochemical processes.

LONG-TERM R&D NEEDS FOR THE DEVELOPMENT OF FERMENTATION SCIENCE FOR BIOREFINERIES

In the long-term, both systems biology and synthetic biology will play major roles in the development of novel biochemical processes. Systems biology will enable a better understanding of the behaviour of living microbes, in industrial environments as well as in the laboratory. Synthetic biology, on the other hand, will enable completely new biocatalysts to be made, without the laborious task of searching for them in nature. A synthetic biology approach can achieve not only the microbial production of new, synthetic molecules, which is almost impossible with empirical metabolic engineering, but also decrease the delay and production costs.

Improve enzymatic cocktails as part of an efficient and cost-effective process for lignocellulose breakdown

Exploit microbial biodiversity (in a sustainable manner)

- ✓ Develop better tools to find new genes, enzymes and microorganisms from nature (microbiology, high-throughput methods, metagenomics, etc.)
- ✓ Develop a common European microbial database for genomic data
- ✓ Develop methods to better manage and analyse biodiversity data (from data to understanding, so enabling industrial applications)

Develop biocatalysts and biocatalytic processes for future integrated biorefineries

Design new bioreactors

Develop water management systems for biocatalytic processes

Develop new downstream processing techniques applicable for biochemical processes

Develop fermentation science specifically for biorefinery operations

- ✓ Apply systems biology approaches to industrial conditions
- ✓ Use of synthetic biology tools to improve industrial biocatalysts

Box 18 Main R&D needs for biochemical processes

Recommendations for innovation

The main recommendation for innovation in the biochemical process area is for a new strategy that would focus the development of new biocatalysts towards the needs of future integrated biorefineries (see Figure 5). In order to stay cost-competitive, biochemical processes need to be considered as links in the overall product manufacturing process. This link will have other links (biorefinery operations) both upstream and downstream of itself to form the value-chain. To avoid disruption to other parts of the value-chain, the robustness and overall technological properties of bio-catalysts in industrial processes has to be part of the early screening steps.

All the predictive tools developed from "fundamental knowledge" described in this section will be very useful in building future biochemical industrial processes. Future biocatalysts will tolerate high concentrations of final products (with maximum conversion of glucose) and have characteristics allowing their full integration into the process chain (fully compatible with pre-treatment and downstream processes). To realise this objective, synthetic biology will be needed to develop industrial microorganisms (including new enzymes) adapted to future biorefineries.

Synthetic biology will be an area of intense competition in the private sector and Member States and European Union will need to provide strong support to universities and research institutes to provide training and maintain a strong public sector involvement.

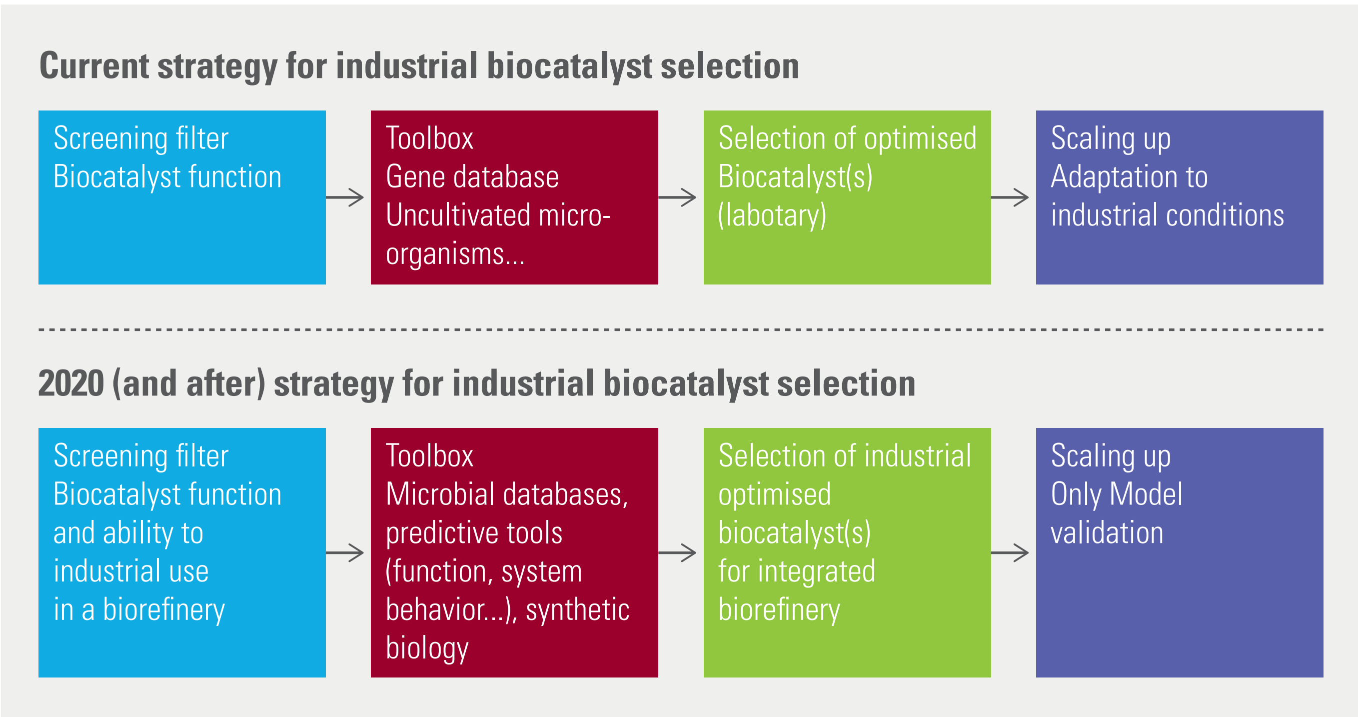


Figure 5: Evolution of biocatalyst selection strategy for biorefineries

Integration

Introduction

The eventual success of the biorefinery concept depends largely on the extent of integration that can be achieved. This has to take place at various levels. Cooperation between farmers or forest owners with processing industries is a very simple example and shows the importance of the integration of the biomass supply sector with all downstream industries. At the processing sites, integration of different technologies and processes is an absolute must for the site to be able to work efficiently. Integration can also take place between two or more processing sites, where, for instance, sharing of utilities and waste treatment are common modes of cooperation, exploiting synergies for mutual advantage. On the highest level, the scale of integration is the whole globalised world, or at least vast markets covering several continents. So, integration is an absolute must for existing, commercial operations, and it will be even more important for emerging and future biorefineries. In this chapter four different integration levels and their R&D needs will be discussed. These will be illustrated in the next sections by looking at two schematic biorefinery value-chains (see Figures 6 – 9).

The success of emerging and future biorefineries depends on win-win cooperation schemes between the various players forming the value-chain. The strategic (business) aspect of this integration and cooperation activity, covering the main part or even the whole of the biorefinery value-chain, is called here '*Strategic cross-sector chain and network development*' (Figure 6), while the technical side at the strategic level is called '*Technical value-chain modelling and optimisation*' (Figure 7).

Interest in the new, biomass-based biorefinery value-chains comes from two opposite directions. One one hand, the current biorefinery players (e.g. the pulp and paper industry or the agricultural industry) are actively looking for new opportunities, either for their current products or for the biomass raw material they process. Meeting either of their objectives will require strategic, cross-sector chain and network integration. On the other hand, new entrants, like companies from the chemical and energy sectors, have become increasingly interested in biomass as a new feedstock for their processing sites. With respect to 'Strategic cross-sector chain and network development', this will mean, amongst other things, new partnerships and business models. With respect to 'Technical value-chain modelling and optimisation', key topics will include identifying the most suitable biomass raw materials, solving logistics problems in respect of biomass supply and working to find the optimal scale of various activities.

'*Process integration*' (Figure 8) refers to integration taking place at the lowest level, within a single processing site, fitting different processes together, but also forming closed loops for on-site material, energy and water usage. Integration is not restricted to the processes of one factory or company. It could also include integrating processes from different companies in the value-chain or between different value-chains, e.g. of neighbouring facilities. However, process integration is geographically more or less restricted to processes on one site, location or restricted area. When biomass or intermediates are exchanged between many sites on different locations, this is more a question of integration throughout the value-chain.

'*Sustainability assessment*' (Figure 9) is the other extreme, where the economic, environmental and societal effects of the whole biorefinery value-chain are evaluated. An integrated sustainability assessment of the whole chain addresses local as well as global effects, people and planet aspects, including nutrient cycles, water management and food-feed-fuel-competition. In order to avoid unequal or unfair sustainability comparisons between different uses of biomass, appropriate, commonly-agreed and practical assessment tools for an integrated sustainability evaluation are needed. These should be based on an appropriate list of generally accepted sustainability premises.

Strategic cross-sector chain and network development

The integration level 'Strategic cross-sector chain and network development' is represented in Figure 6.

Existing biomass processing industries are based on, and optimised for, certain feedstocks or particular downstream value-chains. For instance, the starch and vegetable oil industries, though both catering for very diverse end user sectors, are strongly vertically integrated. Similarly, forestry is mostly organised around the pulp and paper or construction wood value-chains. More recently, new value-chains have emerged to satisfy demand from the transport fuel and energy sectors. However, patterns of cross-sectoral cooperation and integration remain complex, and tend to be limited to support functions (e.g. energy production or water treatment) and on-site integration. Nevertheless, cooperation across value-chains is important to accelerate the optimisation and reduce development risks for new biorefinery operations and value-chains, and can be achieved through better planning and communication amongst stakeholders in the biorefinery field.

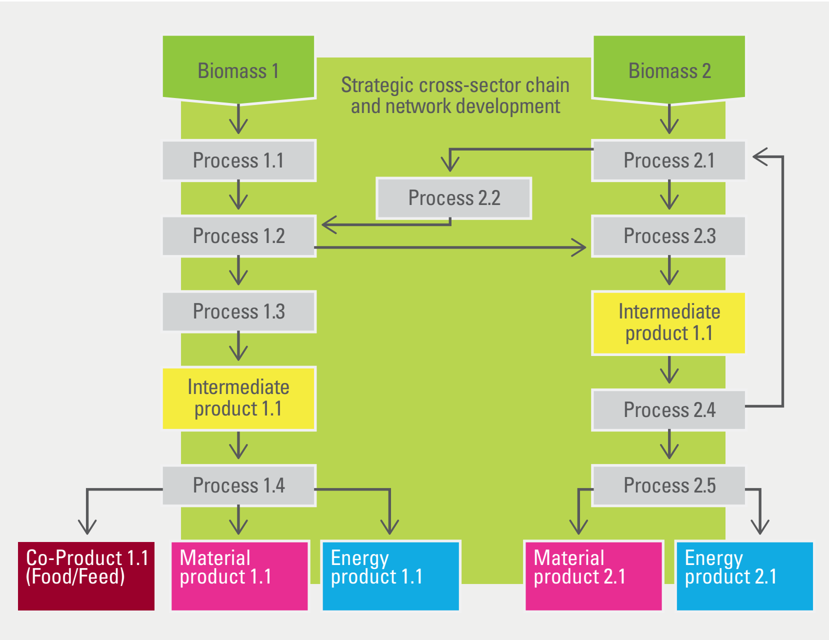


Figure 6: Schematic representation (within the green box) of the integration level 'Strategic cross-sector chain and network development'

Main challenges

Existing commercial ("conventional") biorefineries are typically built around historical value-chains with a low level of cross-sector integration. European examples include starch processing and paper manufacturing. Some production of biochemicals is integrated with papermaking, but in general the level of integration is low. Attempts to integrate food-grade biomass with energy production (including liquid biofuels for transport) have faced great challenges (the "food versus energy" debate is quite controversial). Concepts covering the production of liquid biofuels integrated with the forestry sector and its non-food raw material seem to be on an ethically sounder basis at present (e.g. gasification of forestry residues).

One of the main bottlenecks is the lack of cooperation between different industries. The main challenge will therefore be to establish an optimal degree of cross-sector cooperation needed to support future biorefineries.

Relevant organisational questions are:

- ✓ How are the different links in the chain organised (degree of organisation and cooperation)? Are joint ventures a solution to form links? Promoting links and collaboration between two previously separate industries does not allow top-down management, so what type of management is needed?
- ✓ What is the position of the different industries (e.g. the agro-industries) within the value-chain? Competition could arise e.g. between the chemistry and agro-industry sectors.

- ✓ What are the opportunities for cluster formation (at national or regional scale) versus international sourcing and supply?
- ✓ How can stakeholder interaction methods be used in the process of cross-sector chain and network development?
- ✓ How can the right cooperation partner(s) be found?
- ✓ How can a level playing field be established?
- ✓ What are suitable negotiation mechanisms?
- ✓ What power of negotiation is possible with respect to suppliers and customers?
- ✓ How can intellectual property issues be solved?
- ✓ What education is needed to achieve integration (biorefinery companies need new people and expertise)?
- ✓ What special legal aspects have to be dealt with (e.g. waste regulations)?
- ✓ What other regulatory frameworks need to be considered (standards, REACH, etc.), in addition to environmental criteria?
- ✓ What influence will be possible from partners in the public arena?

Economic sub-questions are:

- ✓ How and where does pricing take place? Is it possible to obtain premium prices for bio-based products to stimulate investment in new biorefineries, and will these higher prices be sustainable in the future?
- ✓ What types of contracts can be used for different patterns of supply of biomass and intermediate products?
- ✓ How should the revenues be divided among the players in the value-chain (farmers, logistics, industry)?
- ✓ What is the best investment choice for a new biorefinery: higher initial investment costs to obtain flexible facilities at start up, or deal with possible up-grading costs later in combination with lower initial investment costs in the beginning for a less flexible biorefinery facility? How should technical and economic issues be balanced?
- ✓ How should specific financing options be developed (e.g. a biorefinery investment fund)?
- ✓ How can investors be provided with good knowledge of policy issues (e.g. policy incentive programmes need to be clear for investors and announce at an early stage that subsidies are valid for a certain number of years and that they will be reduced in stages)?
- ✓ What are the scale issues of investments (e.g. investing in smaller sized sites might have a lower risk than investing in large-scale sites)?

R&D Needs

Promote foresight studies to better understand the "system" in which to the new biorefinery value-chains would operate, i.e. market trends, policy issues with regard to production and use of biomass, the impact of bioenergy goals, customer expectations, etc. Actively disseminate this information.

Promote the development of new business models and integrated biorefinery value-chains (not in terms of the technical aspects, but the business/strategy aspects and transition management). This requires the foresight results as a basis.

Promote necessary "support actions", for example:

- ✓ If needed, develop and initiate new biomass production and management schemes suitable for the most likely future scenarios (availability of raw material)
- ✓ Create suitable new investment mechanisms to catalyse rapid development of cross-sector initiatives
- ✓ Develop investment support tools
- ✓ Improve networking between sectors
- ✓ Be ready to generate the necessary new product specifications, trading mechanisms and other encouraging policies. Some preparatory work could be done in advance.
- ✓ Develop suitable new risk assessment tools
- ✓ Develop specific safety rules for biorefineries
- ✓ Start promoting innovation, innovation management and cross-sectoral innovation in existing traditional biorefinery value-chains

Invest in the development of service businesses (with good technological expertise) that are built around biorefinery activities (equipment and technology providers, engineering companies, etc.). This will also strengthen the position of European companies as biorefinery service providers outside the European Union.

- Promoting foresight studies
- Promoting the development of new business models and integrated biorefinery value-chains
- Promoting necessary support actions
- Investing in the development of service businesses

Box 19 Main research areas for strategic cross-sector chain and network development

Technical value-chain modelling and optimisation

The integration level 'Technical value-chain modelling and optimisation' is represented in Figure 7.

Main challenges

Successful strategic cross-sector integration and networking leads to the need for more specific technical modelling and optimisation within the value-chain. After all, efficient production of the main products is vital for the economics of the biorefinery. Technical value-chain modelling and optimisation also takes place when conventional biorefineries are being improved. Improvement is a continuous activity in any manufacturing process. Hence, most of the conventional biorefineries have already used modelling tools extensively to make their current value-chain more efficient.

Many of the challenges for industry stem from a lack of understanding and predictability of plant component performance and production processes, which is normal at this early stage of development. These constraints lead to limited flexibility in production and meeting market needs, contributing to below par value-chain performance. So, at the moment, biorefinery value-chains are often designed in a sub-optimal way. This could mean, for example, that

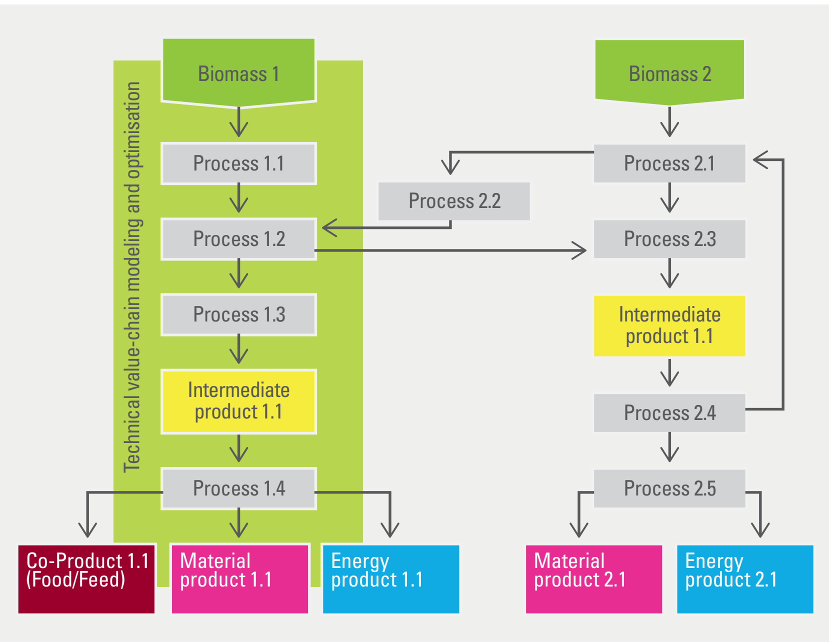


Figure 7: Schematic representation (within the green box) of the integration level 'Technical value-chain modelling and optimisation'

biomass feedstock is (pre-)treated at the wrong point in the value-chain, causing logistical inefficiencies. Another problem might be the partial loss or deterioration of intermediate products because of a poor connection between links in the value-chain. So the main challenge will be to improve the design of the value-chain in situations where it comprises many different players (e.g. farmers, foresters, transport companies and processing companies).

Relevant integrated biorefinery value-chain design questions are:

- ✓ How can new biomass value-chains (e.g. lignocellulosic and algae and seaweed) be optimised and be accepted by all players?
- ✓ How can flexible multi-product systems be developed?
- ✓ How can industrial ecosystems be optimised?
- ✓ How can new perennial crops (e.g. miscanthus) be introduced?
- ✓ How can farmers be encouraged to grow dedicated biomass crops?
- ✓ What is the influence of GMO developments in the whole chain?
- ✓ How can biomass feedstock and intermediate streams be tracked and traced?
- ✓ How can biorefinery types and their variations be effectively benchmarked?
- ✓ How can scaling-up be done effectively, and how can the optimal scale be found in each case?
- ✓ How can risks and benefits be assessed and managed (e.g. applied to issues of scale and complexity)?

Specific questions regarding the modelling and optimization tools to support this value-chain design process are:

- ✓ How can systems design methods be applied and system boundaries determined?
- ✓ How can a complete biorefinery value-chain model be designed (equal to or superior to the oil-based economy)?
- ✓ How can tools like Multi Criteria Decision Making (MCDM) be used?
- ✓ How can tools for designing integrated biorefinery systems using a variety of biomass inputs and producing a variety of outputs be developed (such models should also indicate how value is created at different stages)?
- ✓ How can the overall economic feasibility of biomass value-chains be determined?
- ✓ How can common standardised requirements for raw materials and intermediate products within the value-chain be defined?

R&D Needs

Promote the design of new biorefinery value-chain concepts, and develop and use early modelling tools to estimate the feasibility of these concepts (especially technical and economic aspects, but perhaps even some environmental ones). Existing modelling tools used by the petrochemical and food processing industries can be modified and adapted for this purpose.

Identify preferred areas for agroforestry systems in terms of economic (e.g. land tenure, productivity), ecological (e.g. nutrient cycle, water balance) and social (e.g. diversification of systems) performance. The goal is to introduce new crops (e.g. perennial lignocellulosic crops) into existing agricultural systems and create dedicated, multipurpose biorefinery crop systems.

Investigate the market introduction of perennial cropping systems and analyse the management chain between producers and consumers (e.g. contractual guarantees that feedstock produced will be sold to the biorefinery operators).

Study the possibility of integrating residues from the food- and wood-processing value-chains into new biorefinery systems. This requires sufficient flexibility in the biorefinery value-chain to deal efficiently with varying quality biomass entering the processing site. New waste separation methods have to be developed. Modelling methods have to be used to optimise the biomass feedstock mix of a biorefinery based on various biomass types with widely differing qualities (such as residues).

Study new applications for current biomass-based products (diversification). Potential sectors to cooperate with include electronics (ICT), non-biomass packaging and non-wood building (including also other structural materials). Consumer perspectives and product quality requirements also need also to be studied.

Focus on system architecture for smart and sustainable production. System architecture refers to the hardware components of the system and the communication between them. Further development and optimisation of logistics systems would require modernisation and introduction of integrated automation systems based on high level modelling software as well as new system architecture and machinery drive trains that would enable management, logistics (in-field and downstream), automation and traceability of agricultural and forestry production. This would contribute to sustainability, product quality and the highest efficiency of the total production process.

Invest in scale-up activities and pilot and demonstration sites (covering the whole or part of the new value-chain).

Main research requirements in this area include:

- Promoting the design of new biorefinery value-chain concepts
- Developing and using early-stage modelling tools to estimate the feasibility of these concepts
- Identifying preferred areas for agroforestry systems
- Investigating the market introduction of perennial cropping systems
- Studying the possibility of integrating residues from the food- and wood-processing value-chains into new biorefinery systems
- Studying new applications for current biomass-based products (diversification)
- Focussing on system architecture for smart and sustainable production
- Investing in scale-up activities and pilot and demonstration sites

Box 20 Main research areas on Technical value-chain modelling and optimisation

Process integration

The integration level 'Process integration' is represented in Figure 8.

Main challenges

In a fast changing world, one of the challenges for the biorefinery industry will be to create new value-chains while complying with high sustainability standards. Setting high standards will be very important, so it will be necessary to guarantee green and sustainable processes and apply green chemical principles as widely as possible. One of the ways to achieve this is by putting the emphasis on process integration. At this level, integration aspects between closely interacting processes are very important. Pulping, for instance, would not be a feasible operation without the closely integrated processes of the pulper (digester), the recovery boiler and the limekiln. Successful integration of the unit processes in the sulphate (Kraft) pulping process is a key reason for its dominance over the alternative sulphite process (where the recovery of chemicals is more difficult, even though product quality is better). Process integration could also imply the need for several companies to share safety rules. The integration of new processes in a biorefinery value-chain and the integration of processes for chemical recycling will continue to be key stages on the route to successful biorefineries.

The current state of the art still does not permit wide use of real-time, high-quality model-based predictions in process industries, as the models are too costly and too complex. Further development needs to deliver advanced modelling methodologies not only for complex continuous flow and batch processes but also for lifecycle analysis. Modelling and optimisation are important tools at the process integration level.

The main bottleneck is the current sub-optimal use of biomass, energy, water and nutrients in processing industries, largely due to insufficient process integration. The main challenge is to develop closed loop production processes (and combinations of processes), while still maximizing production.

R&D Needs

Meeting the challenges in plant control and flexible manufacturing requires a step change in integrated process and plant operation modelling, supported by research in process control systems and process analyser technology, together with innovative approaches to plant layout.

Novel research approaches need to focus on a achieving a breakthrough in generic, low cost, fast, first principles-based modelling methodology for complex continuous flow and batch processes and lifecycle management. Together with significant research efforts in plant analyser and process control technology, and novel approaches to plant design and operation, such sophisticated modelling will deliver next generation tools for the demanding tasks of:

- ✓ Computer-aided process and systems engineering for flexible and intensified processes

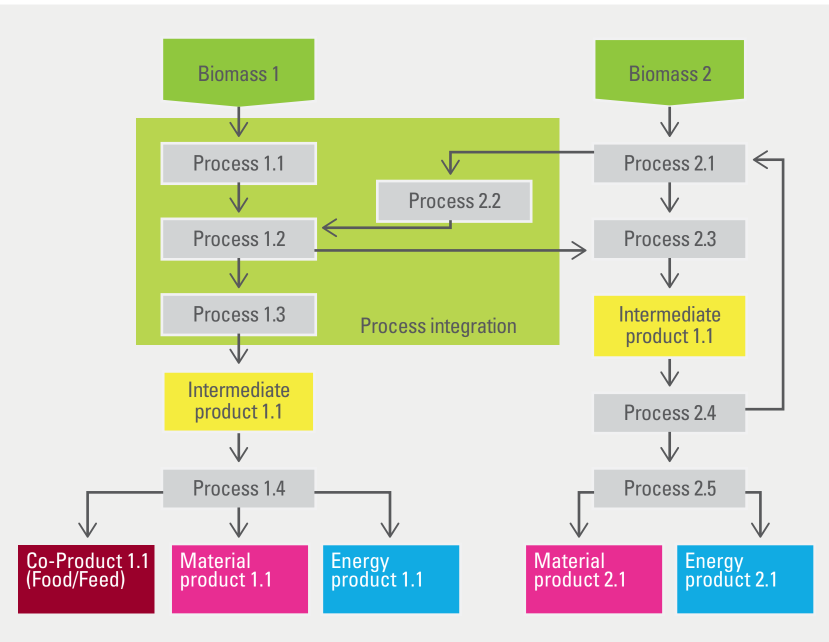


Figure 8: Schematic representation (within the green box) of the integration level 'Process integration'

- ✓ Advanced process performance monitoring based on intelligent, model-based soft sensors and advanced analytical instruments (RMA, NIR)
- ✓ High performance, non-linear process control
- ✓ Integrated supply chain management, bridging the gap between supply chain network planning, detail scheduling and process design and operations.

Main research requirements in this area include:

- Promoting an approach to R&D in which product innovation and process development are better integrated
- Developing methods for (modelling) process integration (closed loops) that maximize product yield (including energy aspects) and lead to the efficient use of biomass, energy, water and nutrients
- Developing adequate recycling methods for residues of the various processes within a biorefinery, e.g. re-usage of water and (organic) nutrients
- Developing methods for usage and recycling of the final products from a biorefinery (material efficiency, cradle-to-cradle, and similar approaches)
- Developing adequate recycling methods for chemicals and catalysts during and after the process (e.g. after pulping or ionic liquid based processes)
- Developing technology to use low-value energy from one process in other processes. Analyse energy streams to discover what processes/companies could fit together.
- Promoting the use of safe design methods
- Developing new concepts for integrated energy production, conversion and distribution
- In the case of advanced biofuels, focussing on specific value-chains such as those identified by the European bioenergy initiatives
- For the sugar platform, studying the integration of enzyme production and enzymatic hydrolysis
- Developing processes that combine biotechnology and chemistry (chemo-enzymatic)

Box 21 Main research areas for Process integration

Sustainability assessments

The integration level 'Sustainability assessments' is represented in Figure 9.

Main challenges

Assessment of the sustainability of biorefinery production is a topic that covers the entire value-chain up to the production and use of the biorefinery end-product. Any sustainability evaluation will have to address local as well as global effects for the people, planet and profit aspects (3P). The biomass production stage is important because a large share of the impact of the whole chain is generated here. But the other stages in the value-chain will also contribute substantially. Therefore, to guarantee the sustainable and socially-desirable development of biorefinery value-chains, a suitable evaluation framework is needed. It is important that there should be a consistent assessment method for different uses of a particular biomass source (e.g. wood or agricultural residues). All biomass uses should be assessed against the same sustainability criteria. However, not many assessment tools are yet available that have a common European or global methodology.

The focus so far has been on Life Cycle Assessment (LCA) which is a standardised approach and estimates the environmental impacts (e.g. greenhouse gas emissions, consumption of primary energy) of biomass production and through the entire biomass life cycle. However, there are significant issues that are so far unresolved and which require further research, such as the development of approaches for the evaluation of emissions from direct and indirect land use change (LUC and iLUC) and the quantification of the impacts of biomass production on regional biodiversity. Besides that, such assessments should be complemented by further approaches like Environmental Risk Assessment (ERA), or certification approaches for good and sustainable agricultural practices like Eco-Management and Audit Schemes (EMAS). Currently, no single approach gives a complete and fair picture.

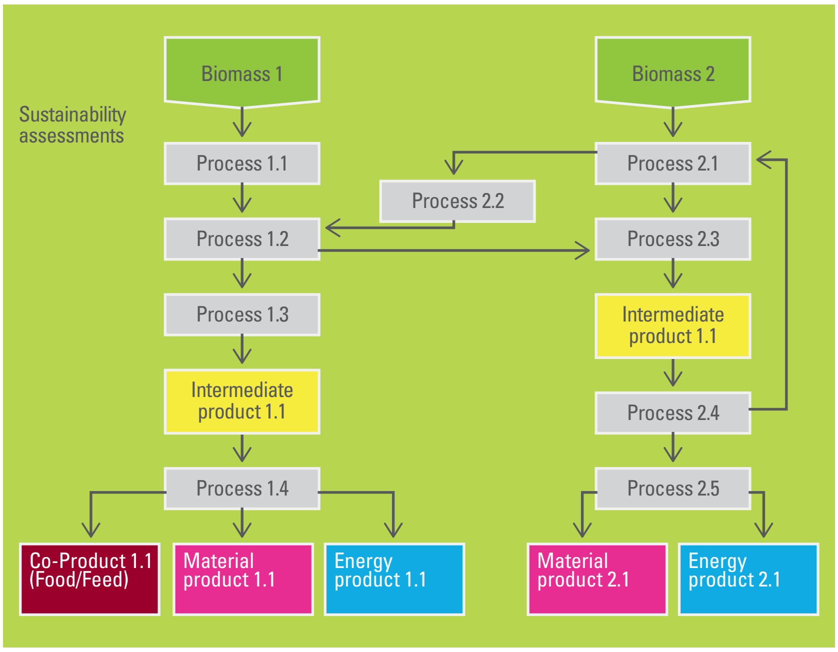


Figure 9: Schematic representation (within the green box) of the integration level 'Sustainability assessments'

But sustainability is a broad term and assessing environmental impact does not tell the whole story. Further research should focus on the development of approaches that include all three aspects: environmental, economic and social. Similarly to what LCA does for environment issues, the economic and social impacts of biomass production should be investigated, for instance through Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), respectively. Those approaches are not standardised and research is needed for their implementation at the biomass production level. This would lead to an integrated approach, which could be described by the term Life Cycle Sustainability Assessment (LCSA).

Different sustainability criteria for biomass production together with certification schemes that would confirm compliance with sustainability standards have emerged in recent years (e.g. the Roundtable for Sustainable Biofuels, International Sustainability and Carbon Certification). While carefully considering background objectives and regional circumstances, harmonisation of the different approaches and development of uniform terminology should be priorities, to facilitate sustainable production, trade and use of biomass sources.

This means that further work will be needed to develop commonly-agreed appropriate and practical tools for sustainability evaluation. Sustainability tools and data collection will be essential to ensure that relevant legislation, standards and certification schemes are based on sound science, using transparent and relevant data that can be assessed using practical tools. Comparisons of the sustainability of bio-based and fossil-based products, and comparisons between bio-based processing routes, are also important for decision making at a company or policy level. Potential combination with CO_2 sequestration and greenhouse gas emissions reduction data will also be relevant.

This key integration theme is relevant for public appreciation of biorefineries and bio-based products, and also for political approval, which will lead to government incentives for biorefinery development. Social appreciation of the biorefining sector can be improved by strengthening the communication channels among the relevant stakeholders, especially the farming and forestry sectors, with the respective down-stream sectors, as well as open communication with society.

Safety management must also be considered as a true sustainability topic, with its own set of criteria and related metrics.

Therefore, the main challenge at the moment is that we have only limited possibilities to perform an integrated sustainability assessment of the whole biorefinery value-chain (including biomass, logistics, processes and products) to describe the influence of a biorefinery on the whole system (e.g. the iLUC problem). The overall effects of biorefineries could be assessed with systems modelling (e.g. energy market models, land use models) but this can be very challenging and still leaves various uncertainties.

R&D Needs

Since sustainability is still a loosely defined topic from a scientific point of view, it is essential to accelerate the development of science-based, rational and transparent criteria, indicators, methodology and data. Such methodology should be applied to the full value-chain (from feedstocks through conversion processes to end uses), to EU-relevant geographies (production in places relevant to EU-markets for both domestic and imported feedstocks and biofuels) and to the three dimensions of sustainability (environmental, social and economic). Thus, it is necessary to:

- ✓ Develop standards and valid sustainability criteria. Harmonisation of aspects of the evaluation tools within the EU is a must.
- ✓ Develop an integrated, science-based, rational and transparent framework for sustainability assessments on all three aspects of sustainability (people/social, planet/environment, profit/economics) which could be termed Life Cycle Sustainability Assessment (LCSA). This means both the development of new tools and the integration of existing ones such as Life Cycle Assessment (LCA), Environmental Risk Assessment (ERA), Eco-Management and Audit Schemes (EMAS), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) into an integrated methodology. The goal is to help evaluate the implementation of legislation and to facilitate policy and investment decision-making.
- ✓ Collect reliable data needed for the assessments.

Sustainability comparisons of different biorefinery options must be performed with the newly developed integrated evaluation framework (LCSA). A better understanding of the sustainability aspects of the biorefinery value-chain versus other economic value-chains as well as non-market public goods is needed, which should include systemic impacts over both short and long timescales. Generating and using sustainability-related tools and data should be a priority for public R&D funding at EU and national level.

Biorefinery sustainability requirements will restrict effective biomass availability, as competing usages (food, feed and fibre) already do. It is also recognised that fulfilling basic sustainability requirements is critical in ensuring the long-term availability of biomass, maintaining an appropriate equilibrium between different biomass uses (with priority for food supply), and reducing environmental impact. Therefore certification schemes need to be developed for different feedstock and process combinations.

Main research requirements in this area include:

- Developing standards and valid sustainability criteria
- Developing an integrated evaluation framework for sustainability assessments
- Collecting reliable data
- Making sustainability comparisons
- Developing certification schemes for different crop-process combinations

Box 22 Main research areas for sustainability assessments

From research to markets

Main challenges for translating research into products

The innovation challenge: bridging the gap from research to product

The European Research Area shows great potential for innovation in science and technology, thanks to its growing number of well educated researchers and engineers, good research infrastructures and high-quality research programmes, amongst other assets. However, one of the key challenges for Europe is to translate this high-quality research into innovative products. Several studies and reports, such as the Lead Market Initiative Ad Hoc Advisory Group report, have looked into this innovation challenge, but a number of hurdles must still be overcome to bridge this major gap.

The Key Enabling Technologies High-Level Group (KET HLG) highlighted the crucial importance of cooperation between academia and industry. Pilot- and demonstration-scale activities are needed when turning a research concept into a commercial product, and researchers often lack access to industrial demonstration plant, which means that R&D concepts cannot always be tested for feasibility on a larger scale. There is also a high risk of European research being used in products launched by European companies only in other parts of the world, where conditions are more favourable to innovation, product development and entrepreneurship. Intellectual property costs and complex regulatory frameworks also contribute to this phenomenon, along with low numbers of start-up businesses compared to other regions of the world, such as the United States. The innovation challenge is coupled with an information challenge: it is crucial to inform consumers about the benefits of bio-based products and enhance public awareness of them.

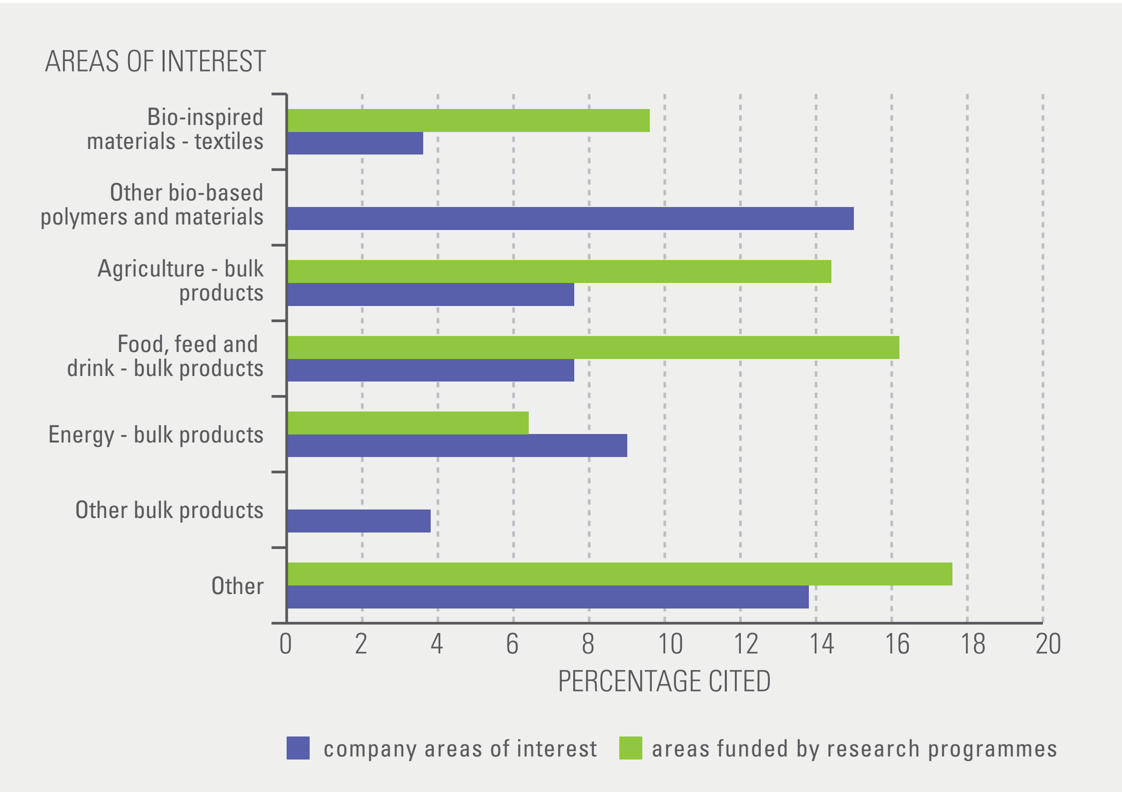


Figure 10: Status quo on Company area of interests vs. areas funded by Research programmes[29]

The World Economic Forum's (WEF) report on Industrial Biorefineries[29] draws attention to integration into existing value-chains as a key commercial challenge, for two specific categories of product. The first category is bio-based products that replace compounds in existing value-chains (e.g. bio-based succinic acid that replaces its petroleum-derived equivalent in polyester manufacturing); the second is bio-based products that are novel or that cannot easily be integrated into existing value-chains. In the first case, a competitive price and equal or better quality are central to the viability of bio-based products. In the latter case, there are specific challenges related to the uncertainty of translating research into novel products which do not fall into conventional value-chains and for which no demand already exists.

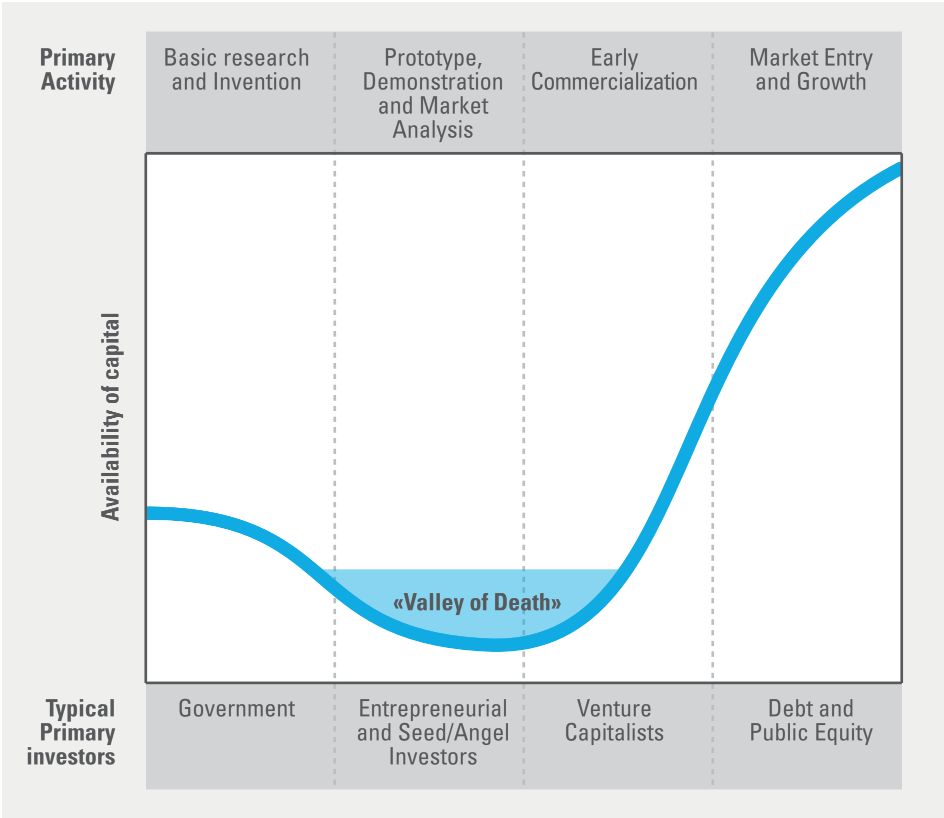


Figure 11: Valley of Death for innovation[34]

The funding challenge: turning research results into commercially viable products

The European innovation challenge goes hand in hand with a range of funding-related challenges. European expenditure on R&D is rather low compared to other regions of the world. The latest Eurostat data[30] shows that the 3% of GDP target of the Lisbon strategy was missed by a considerable margin: Europe dedicated 1.85% of its GDP to R&D in 2007, which was way below the US rate of 2.67%. The KET HLG report highlights that Europe's relatively poor record on innovation is partly due to this inadequate investment in research and development.

More specifically, when it comes to biorefinery outputs, actual R&D expenditure is not always in line with apparent company interests. As highlighted in the ERA-IB[31] status quo report, company interest in high added-value bio-based polymers and materials is significant, whereas few or no research programmes are dedicated to them.

According to the WEF[28], KET and LMI[32,33] reports, the financial crisis has resulted in growing difficulties in accessing venture capital and private equity funding, thus making it extremely hard to finance the early stages of product development (pilot-scale) and to obtain follow-up bank loans. In fact, this type of financing in the biorefining sector has been decreasing, as large amounts of capital are needed to bring technology to the market. Overall, the high cost of up-scaling processes results in a lack of prototypes, demonstration activities and concrete market analysis, as highlighted by the KET HLG. Consequently, knowledge in the biorefinery sector generated by European industry and academia is moving overseas because of the lack of development opportunities in Europe. It is well known that Small and Medium Enterprises (SMEs) are key drivers of innovation, but their ability to market innovative products is threatened by high market and financial risks. To compound these difficulties,

29. World Economic Forum: the Future of Industrial Biorefineries, 2010:
http://www3.weforum.org/docs/WEF_FutureIndustrialBiorefineries_Report_2010.pdf
30. Eurostat news release September 2009 :
http://epp.eurostat.ec.europa.eu/cache/ITY_PUBLIC/9-08092009-AP/EN/9-08092009-AP-EN.PDF
31. ERA-IB report: Status quo on Industrial Biotechnology – http://www.era-ib.net/default.asp?cid=86&pid=71
32. Lead Market Initiative on Bio-based products: Taking bio-based from promise to market, November: 2009:
http://ec.europa.eu/enterprise/sectors/biotechnology/files/docs/bio_based_from_promise_to_market_en.pdf
33. Lead Market Initiative on Bio-based products: Ad-Hoc Advisory Group Financing Paper, February 2011
34. High-Level Group Key Enabling Technologies Working document: Mastering and deploying KETs: building the bridge to pass across the KETs "Valley of death" for future European Innovation and competitiveness:
http://www.kowi.de/Portaldata/2/Resources/fp7/HLG-Working-Document.pdf

the EU faces a regulatory challenge: it could improve investment rates and market certainty by establishing a reliable, holistic and uniform regulatory framework, without increasing the administrative burden for companies.

Despite the increasing efforts of Europe to cope with this, research funding is still fragmented and lacks coordination. These funding challenges together produce the picture of the 'Valley of Death' (Figure 11), which is defined by a lack of financing at the scaling-up stage, coupled with other factors such as the lack of entrepreneurship.

What is needed to bridge the Valley of Death?

Innovation side

ENHANCED COOPERATION BETWEEN ACADEMIA AND INDUSTRY: PUBLIC PRIVATE PARTNERSHIPS

In order to bridge the 'Valley of Death' in Europe, cooperation between academia and industry is crucial and must be given greater attention, in order to generate innovative products. Public Private Partnerships between top-level research institutions, industry and public institutions will be critical to achieve the 2030 vision on biorefineries, by reducing fragmentation of research funding and efforts in Europe, and sharing the risk of developing innovative biorefinery outputs. Cooperation through biorefinery clusters is already boosting the development of innovative technologies and industrial development of products.

SUPPORT KEY ENABLING TECHNOLOGIES SUCH AS INDUSTRIAL BIOTECHNOLOGY AS ESSENTIAL DRIVERS FOR DELIVERING INNOVATIVE PRODUCTS WITH HIGH ADDED-VALUE

It is crucial for Europe to focus on products of high added-value to utilise biomass in the best possible way, favouring quality over quantity. For example, Europe has great potential to develop its share of the industrial biotechnology products market, ranging from bio-based polymers to cosmetic ingredients. Industrial biotechnology is a very broad sector which facilitates connections and cooperation between different sectors (e.g. utilising waste streams from food production, paper production etc.) and creates mutual benefits. New applications should be supported, and current applications should be improved further through R&D.

Funding side

FUNDING FOR DEMONSTRATION BIOREFINERY INFRASTRUCTURES AND ACTIVITIES

It is important to look at the funding of Public Private Partnerships and of demonstration plants as a means of bringing research and industry together, in order to close the gap between scientific feasibility and industrial application in the value-chain. This means that building new demonstration plants in the most appropriate areas should be considered, and that access to existing infrastructures to develop and test new products and processes should also be improved. Stimulating the construction of demonstration plants via public-private partnerships is therefore one of the most important steps that can be taken in the development of the bioeconomy, enabling the translation of knowledge into marketable products.

FUNDING NEW PRODUCT DEVELOPMENT AND ATTRACTING INVESTORS TO THE END OF THE BIOREFINERY VALUE-CHAINS

Financing is a major challenge when translating research findings into products, especially during the pre-industrial testing phase. Attracting venture capital and business angel investment during this phase would increase product development and contribute to bridging the 'Valley of Death'. This type of funding should also be made more accessible to the SME sector, which is the largest employer in Europe and a main driver of innovative concepts. A recent report by the World Economic Forum highlighted the fact that converting biomass into products has the potential to contribute more than $230 billion to the global economy by 2020, so awareness should be raised within investment communities. A full list of financing recommendations can be found in the Lead Market Initiative Financing Paper.

R&D needs and priorities

Some key areas need further research in order to drive the development of marketable, innovative, added-value products and ensure their successful market penetration. There are two main areas: market and socio-economic research, and product development.

Market and socio-economic research

As highlighted in the ADEME roadmap[35], Member State governments have set binding targets for the increased use of renewable energy, including biofuels, but there is no such target for other categories of bio-based products. Bio-based products are often more costly than their petroleum-based equivalent, which is an issue for their market appreciation. Given this, demand for innovative bio-based products will be driven by their fulfilment of societal needs. Tools to assess appreciation need to be developed, in order to better evaluate market penetration and growth.

Foresight studies and surveys should be undertaken when developing new bio-based products, or alternatives to petroleum-based ones, in order to assess consumer behaviour, understand specific market needs and identify promising future business areas. Specific market research is needed for bio-based products (product type, placement, price, promotion, etc.), in order to determine how these products should be positioned on the market: will they be sold as green alternatives to petroleum-based products, as green products, or simply as new products? These market studies will help the introduction of new products to the market, and the creation of new value-chains.

It is important to distinguish two main types of market research as far as biorefinery outputs are concerned: on the one hand business-to-business studies, which should mainly aim at defining the right properties for molecules and positioning them on the B2B market. On the other hand, consumer market research would mainly be centred on final products rather than building blocks, with a focus on green product positioning and marketing tools such as pricing.

Alongside market studies, a bottom-up approach is needed to encourage participation along the whole value-chain, engaging stakeholders (e.g. retailers) on the benefits of bio-based products and raising farmers' awareness of the possibility of diversifying their incomes by cultivating non-food crops for the bio-based economy. It is crucial to support research on products through studies on bio-based alternatives and how to position them on the market.

A bottom-up approach could also allow marketing goals to be translated into research priorities, thus providing support to companies in ensuring a better transfer of research and innovation into successful products.

35. ADEME – Feuille de route R&D de la filière Chimie du végétal - www2.ademe.fr/servlet/getBin?name...tomcatlocal1306328226244.pdf

Product development

Last but not least, European R&D priorities in the field of biorefineries should have a strong emphasis on the development of excellent bio-based products (application research).

When replacing 'traditional' products by novel, bio-based products, the focus should be on developing new products on the one hand, and improving properties of existing products on the other, to increase the competitive advantage of these products versus their petroleum-based counterparts. Product design should focus on the properties of bio-based products, using natural formulations to achieve desired effects. For instance, substitution of 'greener' products should not lead to more complex formulations, which can be detrimental to market appreciation. To avoid difficulties, more links should be created along the value-chain, in particular with those who work further downstream, and any change of formulation should not lead to more complication.

Market-driven research should aim at creating products that consumers want, and it is essential that bio-based products reach at least the same level of quality as their fossil-based counterparts. New bio-based materials with equal or superior levels of performance need to be developed. Rather than just mimicking properties of fossil-based products, bio-based products should aim for specific functionalities, taking full advantage of the native properties of biomass and its components.

The gap between building blocks and final products also needs to be addressed. Indeed, studies on how different bio-based materials and building blocks fit in different applications and value-chains need to be undertaken, in order to find more uses and markets for the various intermediates and products. This approach should be coupled with a 'cradle to grave approach', taking into account the whole value-chain, including recycling.

To sum up, an application-driven approach is needed to allow the full deployment of bio-based products and biorefineries, favouring products of high quality to ensure they are competitive in European markets.

Integration and innovation

- Focused targets for innovation that are sensible for European bio-industries
- Demonstration of technologies, and combinations of technologies, in flexible, integrated biorefineries (multi-product, multi-process, for multiple types of biomass)

Market research and socio-economic research

- Monitoring, including impact assessments of market developments and international and national regulations
- Develop tools to assess appreciation of bio-based products
- Foresight studies and surveys should be undertaken when developing new bio-based products
- Specific market research is needed for bio-based products
- A bottom-up approach could also allow marketing goals to be translated into research priorities

Product development

- Application-driven approach with a focus on the development of excellent bio-based products of high added-value
- Developing new bio-based products with specific functionalities, taking full advantage of the native properties of biomass
- Improving properties of existing bio-based products, giving at least the same level of quality as their fossil-based counterparts
- Collaborative approach throughout the value-chain: how different bio-based materials and building blocks fit in different applications and value-chains
- Develop products matching consumer needs and wants

Box 23 Main R&D needs and priorities for integration and innovation, market research and socio-economic research and product development

Recommendations

By 2030, the Biobased Economy is expected to have grown significantly in Europe. A pillar of this, both now and in the future, is biorefining, the sustainable processing of biomass into a spectrum of marketable products and energy. The European sector of 2030 will evolve from the established biorefinery operations for products like food, biofuels, paper and board, to a broader, more mature sector. In 2030, biorefineries will use a wider range of feedstocks and will produce a greater variety of end-products compared to the situation today.

The European Biorefinery Vision 2030 can only be achieved if several bottlenecks along the value-chain have been removed. To address these challenges, several strategic research areas must be developed by 2020. In this context, the main key research area requirements and recommendations for innovation are listed below.

Strategic Research recommendations for 2020

The most important biorefinery R&D needs in the period from 2012 to 2020 have been analysed in specific sections (biomass, pre-treatment, conversion processes, markets and integration). The most important recommendations arising from these chapters are:

Biomass

1. Due to limited land availability for biomass production (both food and non-food) in the EU, the production of higher yielding biomass crops that can be grown in a sustainable way is a key priority. Studies in this area should be performed and should be combined with research on biomass crops suited to the differing soil and climatic conditions within Europe, as well as those adaptable to climate change scenarios and with good resistance to stress (water, nutrients) and diseases.

2. The basis for biomass refining is a fundamental knowledge of biomass structure and composition. Thus, it is of the utmost importance to study the structure of various biomass types further, with an emphasis on the most important potential feedstocks and especially lignocellulosic biomass. In addition to structure, development of improved breeding methods for all crops is proposed, applying fast-track modern breeding technologies.

3. There has been useful public investment in identifying potentially valuable new plant varieties producing biomass more suited to conversion into biofuels, and these have the potential to make a step-change in the costs of processing biomass. It is important to ensure that there is research support to allow this work in model plant species to be translated into arable and biomass species and that these are field trialled at sufficient scale to allow pilot scale processing.

4. As biomass has a low density, logistics — from harvest to the industrial plant gate — is a crucial issue. Improvements are necessary at the different steps but especially at the field level (e.g. harvesting, densification, drying, storage, transport) in order to significantly reduce the costs and adapt harvested biomass to meet industrial quality requirements.

5. The future business environment for biorefineries still has too many risks and uncertainties, and this slows investment in the sector. Careful consideration needs to be given as to how the most enabling policy framework can be developed to give investors sufficient security to get this industry off the ground. There should also be investment in foresight analysis at a European and global level to generate a better understanding of the risks and opportunities of the business environment. The analysis should include an evaluation of the potential future production and availability of biomass, taking into consideration food security and price.

Pre-treatment processes

6. The industrial processes available to fractionate lignocellulose are not optimal for the future needs of an integrated biorefinery. In future, the same biorefinery must be able to use a much wider variety of raw materials. Novel biomass-derived components or fractions are also needed as the starting point for new value-chains. New biomass pre-treatment processes should thus be developed, and these should be flexible and

tailored to suit improved biomass feedstocks as they are developed. One of the main goals of the technologies is to separate the carbohydrates, cellulose and lignin into separate fractions while maintaining their native structure and activity.

Biorefinery conversion processes

7. Thermo-chemical conversion processes have a long history of industrial applications e.g. gasification in heat and power production. A main issue for their application in biorefinery concepts is the scaling-up and development of industrialised, reliable design and components and their integration into existing industrial units. Secondly, end-product quality improvement, e.g. syngas purification for catalytic conversion and pyrolysis oil upgrading and fractionation, is essential for market penetration of these products.

8. Current chemistry has been mainly developed based on oil as raw material. With biomass as the new feedstock, the main R&D needs are for the development of new catalysts that are well adapted to biobased molecule properties (oxygen-rich, nitrogen containing and highly reactive) and that are especially able to work in aqueous media (green chemistry). The development of high throughput technology for catalyst development would give a considerable advantage.

9. Current research on lignocellulose breakdown must be accelerated. The strategy is to improve existing technologies to develop efficient and cost-effective enzyme cocktails.

10. The key issue for biochemical processes is to develop new tools in order to design new and specific biocatalysts for the future integrated biorefinery. These new tools are based on a better knowledge and understanding of microbiology in an industrial context and the introduction of industrial performance criteria in the first steps of the selection process.

11. Reducing the volume of water and increasing overall productivity are crucial issues in the development of industrial biochemical processes. Therefore, it is recommended that research focuses on downstream (separation and purification) processes.

12. As the development of (bio- and chemical) catalytic processes in aqueous environments will be important over the next years, the recommendation is to focus public funding on the development of a new science involving both chemical and biochemical catalysis.

13. To strengthen the biomass conversion toolkit, which is well developed for carbohydrates (and will be further improved by industry), it is recommended that public funding should focus on the development of conversion technologies applicable for lignin (development of lignin-based chemistry).

14. Fatty acids conversion technologies need to be developed, including chemistry (metathesis, for example) and biotechnology (including microbial conversion of sugars to lipids/fatty acids).

15. Fractionation and extraction technologies will offer the possibility of preserving the structure and activities of macromolecules such as fibres and natural polymers. There is a need to develop the scientific background to characterize these molecules as well as conversion tools to add new functionalities.

16. Research should be encouraged into advanced fermentation for the production of "drop-in" biofuels such as alkanes, using systems and synthetic biology approaches.

Integration

17. The key conversion processes should not be developed in isolation. Future process solutions will need process integration modelling, taking into account recycling and waste management.

18. Demonstration of technologies and combinations of technologies is needed, in flexible integrated biorefineries (multi-product, multi-process, for multiple types of biomass).

19. In order to promote the development of new business models and integrated biorefinery value-chains (in terms of the business/strategy aspects and transition management), we recommend commissioning foresight studies to better understand the "system", including market trends, biomass related policy issues, the impact of bioenergy goals, customer expectations, etc.

20. Develop an integrated, science-based, rational and transparent evaluation framework for sustainability assessments — Life Cycle Sustainability Assessment (LCSA) — based on a common methodology.

21. Rural biorefineries are an integral part of their supply area, and help to optimise resource flows (mass, energy, water, nutrients, waste, etc.) within a closed loop system. Research is needed to understand the impact of the integration of biomass cropping systems and biorefineries in specific regions on biodiversity, water and soil quality, landscape, etc. Biorefineries could be used as a tool for rural economic development.

22. Given the complexity of the network of stakeholders (including farmers, local and national authorities, industry and citizens) involved in biomass supply, research in social science is required to develop innovative strategies to facilitate cooperation between them in a sustainable way.

From research to markets

23. Market-driven research is needed in order to develop excellent bio-based products that are attractive to consumers, replacing traditional products, or developing new markets.

24. Adopt an application-driven approach: address the gap between building blocks and final products in order to find new applications and possibilities for these bio-based building blocks.

25. As demand for innovative bio-based products will be driven by their capacity to fulfil societal needs, we recommend the development of tools to assess acceptance of bio-based products, in order to improve evaluation of market penetration and growth.

Recommendations for Innovation and Support Actions

- Support key enabling technologies (such as the conversion technologies mentioned above) and their combination as key drivers for delivering innovative products with high added-value.
- To reduce duplication of effort and fragmentation of research funding within the EU, we recommend stronger links and cooperation between European Commission directorates, national and regional governments (following the example of initiatives such as the Joint Biorefinery Call).
- A holistic approach is needed for the EU policy landscape to take into account the full scope of the biorefinery sector: cooperation and communication is needed at all levels, covering a wide range of policy sectors, from agriculture to industry. This could be done under the umbrella of the bioeconomy strategy.
- Promote incentives supporting the market uptake of bio-based products (e.g. chemicals) and encourage stakeholder engagement at the end of the value-chain.
- Support enhanced cooperation between academia and industry (Public Private Partnerships) and especially cooperation through biorefinery clusters and between existing facilities. In particular, public funding should help to encourage big companies and SMEs to work together.
- Funding for first of their kind biorefinery demonstration plants, up-scaling facilities and activities.
- Funding new product development and attracting investors to the end of the biorefinery value-chains.
- Improve the attractiveness of the new Integrated Bioeconomy through education and training. Support cross-fertilisation between bioeconomy sectors and beyond (e.g. attract skills and experts from the "fossil carbon world").
- Ensure access to consistent quality renewable feedstock in sufficient quantity, at competitive prices, to allow full deployment and market uptake of bio-based products.

List of boxes

Electronic versions of our Joint European Biorefinery Vision for 2030 and our European Biorefinery Joint Strategic Research Roadmap to 2020 can be found on our website at:

http://www.star-colibri.eu/publications/

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SEVENTH FRAMEWORK PROGRAMME

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