Industrial Biotechnology and Climate Change

OPPORTUNITIES AND CHALLENGES
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Executive summary

Carbon dioxide (CO₂) has the second-largest direct contribution to the greenhouse effect of all gases. Since the beginning of the Industrial Revolution, the burning of fossil fuels has contributed to the increase in carbon dioxide in the atmosphere. Moreover, national CO₂ emissions are strongly linked to wealth, and a global strategic goal should be to prevent growth at the expense of sustainability. A large proportion of CO₂ production arises from industrial activities. Therefore, meeting market demands whilst reducing the impact on climate change is critically important for industry.

To meet the challenge of greenhouse gas (GHG) emissions reductions, industry has responded in most countries, and as a result GHG emissions from industry have substantially decreased in recent years. However, the targets for reductions are very ambitious, and more remains to be done. Thus the idea of “sustainable growth” has taken hold. New technologies are being developed to counter GHG emissions, and the new industrial biotechnology should be seen as part of the technology toolkit.

Industrial biotechnology, based on renewable resources, can save energy and significantly reduce CO₂ emissions. It is an embryonic industry, but has already proven its worth in climate change mitigation. It holds much greater promise for the future by avoiding the use of fossil raw materials. It involves the use of enzymes and microorganisms to make biobased products in a diverse variety of industry sectors. The feedstocks are agricultural biomass and organic waste materials, even wastewaters.

The new industrial biotechnology arose from international interest in the production of biofuels from a variety of feedstocks. Many countries now have bioenergy strategies and targets. In short order, many supportive policies were developed for the production and utilisation of biofuels, particularly bioethanol. However, very quickly the biofuels boom courted controversy, especially the food versus fuel debate. Now there is a shift in policy towards second generation biofuels using non-food crops as feedstocks.
Besides biofuels, industrial biotechnology can contribute to climate change mitigation through diverse products in the plastics and chemicals sectors. These products are less controversial, some are closer to market than second generation biofuels, and yet do not enjoy the wealth of supportive supply and demand policies as seen with biofuels.

Several sources predict that biobased chemicals could in the near future occupy a much larger market share than at present. As befits the remarkable biodiversity of microorganisms, the diversity of potential biobased chemicals is wide. In many cases, organic chemistry has no feasible replacement; in other cases, biobased chemicals can replace their fossil-based counterparts with significant GHG emissions reductions.

Plastics from fossil fuels have grown faster than any other group of bulk materials for several decades. By 2100, a predicted 1 billion tonnes annual plastics demand would require 25% of current oil production. Biobased plastics are potentially attractive in terms of specific emissions and energy savings. In recent years biobased plastics have been developed for increasing types of applications, way beyond simple packaging applications as once envisaged. Estimates of total technical substitution potential for petro- with bio- plastics is 33-90% and yet global bioplastics consumption is a mere 0.4% of total plastics. As biobased plastics become proven in GHG emissions reductions, they should become an obvious target for supportive policy.

This paper explores the potential role of industrial biotechnology in the biobased economy. Along the way it examines emerging trends, the impact of innovation, the convergence of technologies, and goes on to identify the challenges involved. It concludes with a need for an integrated and strategic approach to allow industrial biotechnology to fulfil its potential as a force for good, not a panacea, in the struggle with climate change. Industrial biotechnology has suffered a lack of investment at all levels, and there is a serious mismatch between future expectations of this industry and this low level of investment. Policy intervention is seen to be required across three broad criteria – social/environmental, industrial performance and economical. To make this all happen requires not only national but international policy in a rapidly globalising world.
Introduction

Climate change is challenging almost all human endeavours, including the future ways in which energy will be generated and consumed. It could adversely affect water supplies and agricultural productivity, and the need to cut CO₂ emissions to avoid harmful environmental degradation has made the transition from conventional fossil fuels to alternative and renewable resources a global priority. The United Nations Environment Programme (UNEP) (2010)¹ has noted that “doubling of wealth leads to 80% higher CO₂ emissions”. Therefore there is a need to break the link between growth and increasing emissions at the expense of sustainability.

Meeting market demands whilst at the same time reducing the impact on the climate is of critical importance to industry. Although past discussions have centred around the causes of climate change, society, industry, governments and other stakeholders are now searching for solutions to mitigate the impacts on health and the environment. In most countries, industrial greenhouse gas (GHG) emissions have substantially decreased over recent years. Both regulators and industry have responded to the need to work towards a sustainable future and have focused on developing and innovating technological improvements for the benefit of the environment. However, in spite of these endeavours, current practices and technologies will most likely be insufficient or inadequate to achieve the ambitious objectives set by countries to tackle climate change. Industries should take bold steps towards establishing more sustainable growth and should be given the opportunity to implement new technologies including the use of biotechnology to reduce the carbon footprint.

With the Kyoto Protocol due to expire in 2012, parties to the United Nations Framework Convention for Climate Change (UNFCCC) are currently in the process of negotiating a new treaty. It is critical that current and emerging uses of biotechnology are recognised by stakeholders as being part of the toolkit necessary to achieve sustainable solutions to climate change. Furthermore, it is also of vital importance that a new worldwide climate change agreement both supports and enables the implementation of eco-friendly innovations.

The over-arching goal of this paper is to explore how industrial biotechnology can be used as part of the toolkit in the struggle to control climate change. For this to happen, the products of industrial biotechnology (biofuels, biobased chemicals and bioplastics) have to be demonstrated to produce less GHG emissions than their non-biological counterparts, whilst maintaining product performance.
Industrial biotechnology as part of the solution to climate change

Since the industrial revolution, economic growth has been inextricably linked with accelerating negative environmental impact. Industrial biotechnology challenges this pattern and has the potential to break the cycle of resource consumption by allowing for a rethinking of traditional industrial processes. Industrial biotechnology, by providing a range of options for competitive industrial performance in selected sectors, could enhance economic growth, while at the same time save water, energy, raw materials and reduce waste production.

Industrial biotechnology, based on renewable resources, can save energy in production processes and significantly reduce CO₂ emissions. The impacts of biotechnology on industry are confirmed by scientific studies and reports, such as the OECD’s report on the application of biotechnology to industrial sustainability and, more recently, by a EuropaBio report (2009) on the potential of industrial biotechnology to help mitigate climate change. Even though the industrial biotechnology sector is still embryonic, it globally avoids the creation of 33 million tonnes of CO₂ each year through various applications, without taking ethanol use into consideration, whilst globally emitting 2 million tonnes of CO₂.

It has been claimed that the full climate change mitigation potential of biotechnology processes and biobased products ranges from between 1 billion and 2.5 billion tons CO₂ equivalent per year by 2030. To put this in context, it represents more than Germany’s total reported emissions in 1990.
The role of industrial biotechnology in the biobased economy

Industrial biotechnology, also known as white biotechnology, uses enzymes and micro-organisms to make biobased products in sectors as diverse as chemicals, food and feed, healthcare, detergents, paper and pulp, textiles and energy. Agricultural products, biomass and organic waste, including food processing waste and effluents (also referred to as renewable raw materials) are transformed into other substances, in the same way as crude oil is used as a feedstock in the production of chemicals.

Existing energy infrastructure and production processes are largely based on fossil fuels, which result in high levels of GHG emissions. In a biobased economy society is no longer wholly dependent on fossil fuels and industrial raw materials.

By contrast, industrial biotechnology holds promise by avoiding the use of limited fossil resources as starting materials, but in some instances it competes with edible feedstocks. This important issue, specially raised in the case of biofuels, can be solved by the introduction of second generation biofuels using non-edible biomass as a sole feedstock. Besides biofuels, the wide variety of intermediate products that may enter at different stages in different value chains introduces complexity when analysing biotechnological products. The OECD predicts the following industrial biotechnology applications have a high probability of reaching the market by 2030:

- Improved enzymes for a growing range of applications in the chemical sector.
- Improved micro-organisms that can produce an increasing number of chemical products in one step, some of which build on genes identified through bioprospecting.
- Biosensors for real-time monitoring of environmental pollutants and biometrics for identifying people.
- High energy-density biofuels produced from sugar cane and cellulosic sources of biomass.
- Greater market share for biomaterials such as bioplastics, especially in niche areas where they provide some advantage.
The value of biochemicals (other than pharmaceuticals) could increase from 1.8% of all chemical production in 2005 to between 12% and 20% by 2015, and biofuel production could partly shift from starch-based bioethanol to higher energy density fuels manufactured from sugar cane, algae or to cellulosic ethanol from lignocellulosic feedstock such as straw, grasses and wood. In addition, significant growth in the biobased polymers sector will result from the development of new polymers with new properties, greater incentives to reduce costs through the use of renewable materials, and increasing regulatory pressure to reduce carbon footprint (for example for packaging applications). In addition, enzymes will be used increasingly in a growing range of applications, due to improvements and advantages, particularly in the food, cosmetic and textile industries, in line with customer requirements and stricter environmental regulations.

**Technological progress in industrial biotechnology: Greening the economy**

**Current trends in technology applications**

Industrial biotechnology has been established for decades in the production of biofuels, biochemicals for the pharmaceutical markets, food and feed, fine chemicals, detergents and hygiene products. Bioethanol production is increasing for biofuel, with world-wide annual growth rates of more than 10%. The United States has overtaken Brazil as the world leading bioethanol producer since 2008 due to a strategic desire to achieve energy independence. Europe is lagging behind these developments. Biopolymers (e.g. poly-lactic acid, PLA) are emerging products with diversifying applications. The global annual sales volume of products produced by industrial biotechnology is about EUR 2.535 billion (2008) — equivalent to 6% of the worldwide chemical sales. Most of these established products are available only through biotechnological processes because chemical synthesis offers no alternative.

**Emerging trends**

Chemical or biochemical products obtained using biotechnological processes need not only to be developed but their quality, production capacity and share of the market have to be assured and improved. Certain building block (platform)
chemicals derived from sugar sources may potentially replace petrochemical building blocks; this means the development of biotechnological platform intermediates based on renewable carbon sources as shown in Figure 1.

*Figure 1. Biological intermediates substituting petrochemical building blocks*

![Figure 1](https://example.com/figure1.png)

*Source.* Adapted from M. Kircher, OECD Workshop on “Outlook on Industrial Biotechnology”, 2010.

Future synthesis of polyesters and biobased biodegradable polymers may be achieved by using building blocks such as fumaric, succinic or malic acid, among others, which are used at present in the food industry.

Ethanol and succinate are good examples of precursors which, after they are fermented, isolated and purified, may enter into synthetic processes to be transformed into ethylene and subsequently polyethylene products, and polyesters, polyurethanes and polyamides, respectively. Thus the combination of biotechnological and chemical technologies may be critical in the future.

When and if these biotechnology processes and applications become more economically and environmentally sustainable, the industrial relevance of biotechnology will change dramatically. This development opens not only a potentially broad field of new applications, but would also require a combination of biology and clean chemistry processes. For example, one area of great interest currently is the field of biopolymers.
It can be predicted that the growing sugar consumption for the production of (bio)-chemicals will compete with the food and increasingly the biofuel industry. The industrial biotechnology industry should avoid competing with biomass intended for food production. Lignocellulose as carbon source from biomass, plant breeding for industrial purposes and algae production may represent ways to prevent this competition. The concept of biorefineries as a combination of integrated plants addressing:

- Processing and fractionation of renewable raw materials.
- Transforming feedstocks to various products.
- Recycling and integrated valorisation of the products after use where possible is becoming a promising strategy.

Finally, synthetic biology represents a very important step forward, since it allows designing chemicals that would not occur by natural pathways. In this sense the tailor-made synthesis of products by modified microorganisms opens new possibilities for the production of chemicals for widely differing purposes. There are compelling reasons to believe that synthetic biology will strongly influence the bioresearch agenda in the 21st century and in fact may be the vehicle that moves biotechnology into the economic mainstream.

From incremental to radical innovation

During the last decade there has been a tangible shift from incremental innovation in the industrial biotechnology field, where some specific steps in existing technologies were replaced to save energy or to make the overall production process more efficient, towards more radical innovation with the development of new production processes entirely based on renewable resources. This makes industrial biotechnology today one of the rare technologies which might help to radically change production chains in terms of sustainability along the whole product life cycle.

Industrial biotechnology techniques were first introduced within traditional industries, such as the food industry, where enzymes and yeasts are used in many food processing techniques, resulting in an increased efficiency and reduced environmental and GHG impact. The experiences developed in the food industry have found application in a number of traditional industries, such as the pulp and paper, leather and textile sectors. Enzymes and microorganisms can carry out processes that traditional manufacturing systems would perform
with much higher quantities of energy, using aggressive chemicals, and producing significant amounts of potentially hazardous waste products. In addition, the biotechnological alternatives can deliver productivity improvements and can help to reduce the impact of GHG emissions.

The feedstock processing and fermentation technologies developed in traditional industries were essential tools for the development of industrial biotechnology solutions for the transformation of agricultural feedstock into biofuels such as bioethanol. The largest share of ethanol production is obtained from sugar cane and corn, which are the crops most utilised by the world's largest ethanol producers: Brazil and the United States. Today, new technologies are being developed to extract sugars from lignocellulosic biomass. The so-called cellulosic ethanol is bioethanol made from lignocellulosic feedstock, meaning agricultural residues such as straw or corn stover.

This has significant economic and environmental potential, as biotechnological processes using highly specific biocatalysts and fermentation systems can produce cellulosic ethanol in high yield with GHG emission reductions of almost 95% compared to fossil fuels. In addition to the transport sector cellulosic ethanol can play an important role as a platform compound in the production of green chemicals. For example, ethanol can be converted into ethylene which is the source for one of the most commonly used plastics polyethylene (PE). In Brazil, one of the leading ethanol producing countries, green polyethylene is already being made from bioethanol made from sugar cane. Much of the biofuel growth in the market is driven by supporting policies and measures, such as the establishment of some targets for biofuel use.

Although currently the market share of biotechnology-produced biobased chemicals is relatively small, the importance could grow very quickly depending on the substitution potential that biobased materials have compared with their petrochemical counterparts. Some industrial biotechnology processes create the same molecules that are produced petrochemically. In these instances, the substitution could be complete, given that they are price-competitive. Other biotechnological processes lead to the creation of different compounds that have similar functionalities to petrochemical products, and in this case the biotechnology-derived molecules may not be suitable for a complete substitution of their petrochemical counterpart. They may nevertheless occupy or even create a niche within the overall market.
Other factors driving the uptake of industrial biotechnology products are: the relative price of feedstocks compared to the price of crude oil; the technological progress; and the relevant policies and measures put in place.

Insightful companies have already discovered the potential of biotechnology to cut GHGs emissions (Figure 2). However, as with most technologies, the potential to achieve sustainability goals does not automatically translate into such goals being realised. There are still numerous challenges for industrial biotechnology — including technical, commercial and sustainability challenges — inhibiting large scale diffusion and commercialisation. The impact of industrial biotechnology on global GHG emissions will depend on the framework conditions in which this technology is applied. In the short term industrial biotechnology will mainly increase process efficiency and reduce emissions. In the longer term however, the impact of industrial biotechnology on GHG reductions will not be determined by the development of the technology alone, but by the supporting socio-economic environment and policy context, and proactive effort from both industry and policy makers, as well as by the main actors of the biobased value chain.

Figure 2. Process inputs in terms of energy, chemicals and natural resources as well as emissions to water and air were reduced

The importance of converging technologies

Researchers and policy makers all have recognised the potential of converging technologies to transform major sectors of the economy, and industrial biotechnology, nanotechnology and information technology are implicit in this potential. Rapid advances in these convergent technologies have the potential to enhance human performance and productivity, e.g. industrial efficiency, revolutionary changes in healthcare, attaining sustainable development, and the mitigation of climate change. Due to the current clean technology boom and the reaction of the market and consumers, the development of “green technologies” that improve energy efficiency, are less polluting and less consuming, is being stimulated. An example is the so-called bio-inspired catalysis, at the boundary between biology and green chemistry.10

Enabling industrial biotechnology at industrial scale:
The importance of biorefineries

Biorefineries are similar to petroleum refineries in concept. However, biorefineries use biological matter (as opposed to petroleum or other fossil sources) to produce transportation fuels, chemicals, and heat and power. Plastics and ethanol were among the first chemical products to use biorefining methods for production. As the technology advanced, methods using bioconversion entered the arena and advanced methodologies were developed to produce a variety of biochemicals. The latest enabling technologies include synthetic biology and systems biology which bring new production methods to biofuels, renewable chemicals, specialty chemicals, and other bioproducts. The discovery tools of metagenomics and quantitative proteomics are now reaching maturity and are starting to be rolled out from large research institutions to smaller universities and research organisations.

A crucial step in developing this industry is to establish integrated biorefineries (Figure 3) capable of efficiently converting a broad range of industrial biomass feedstocks simultaneously into affordable biofuels, energy, and a wide range of biochemicals and biomaterials. Integrated biorefineries are similar to conventional petrochemical refineries in that they produce a range of products in order to optimise use of the feedstock and improve process economics. However, for integrated biorefineries to utilise a range of feedstocks efficiently, significant technology development and financial risk is implied, which increases the capital costs considerably, with the ultimate objective of lowering the operating costs.
A recent report by the World Economic Forum (WEF) concluded that converting biomass into fuels, energy, and chemicals has the potential to generate upwards of USD 230 billion to the global economy by 2020. The report also identified industrial biorefineries as one possible solution that may help mitigate the threat of climate change and the burgeoning demand for energy, fuels, chemicals and materials. The report also concludes that there are still numerous large technical, commercial and sustainability challenges inhibiting – including both technical and commercial as well as sustainability challenges – large scale commercialisation.

Bloomberg New Energy Finance recently calculated that the development of this new industry could stimulate innovation and spur economic growth, generating up to EUR 31 billion of revenues per year in Europe by 2020, creating 230 000 man-years of employment.

**Figure 3. The integrated biorefinery concept**

![Biorefinery Concept Diagram](image)


### Challenges and recommendations

#### Feedstock competition and land availability

Rapid development of first generation biofuels was accompanied by significant and public controversy as the feedstock is the same raw material (e.g. sugars and plant oils) as for food production. In addition biofuels received some of the blame for the food price increase mid-2008, resulting in the “biomass: food versus fuel” slogan. And although agriculture has supplied biomass and crops,
which have provided products for non-food applications for a very long time (e.g. cotton or linen for clothing, wood for building, paper and energy, rubber), producing biobased products in huge quantities is a relatively recent trend. A generally accepted priority list for the different applications of biomass has recently been defined, known as the 5 F-cascade:

- Food and feed.
- Fine and bulk chemicals, pharmaceutical ingredients.
- Fibres and biomaterials (wood, pulp and paper).
- Fuels and bioenergy.
- Fertilizer and soil conditioners (e.g. compost).

Although it is crucial to secure a sustainable supply of feedstock for industrial uses, there are concerns about resource availability in the long term: both on the potential of biomass feedstock to deliver sufficient raw material for all future applications (chemicals, biomaterials, bioenergy), as well as on its long term price level. The Nova Institute in Germany estimates that 500 million hectares of land are available world-wide (and this without cutting down forest or using artificial irrigation) to produce biomass in a sustainable way in response to growing food, chemicals, materials and energy needs. Securing a sustainable supply of feedstock for the biobased economy requires further research into methods of improving feedstock yields and/or the composition of biomass for optimal conversion efficiency. This research will involve plant genomics and new breeding programmes, and also research into efficient crop rotation, land management and land-use change issues. In addition feedstocks must be produced according to broadly supported sustainability criteria.

Although climate change mitigation is one of the main drivers of industrial biotechnology and the biobased economy, it should not be forgotten that climate change will also impact upon productivity, yields, water and land availability. While yields in forests, for example, might increase in parts of the world such as Northern Europe, the factors destabilising forest ecosystems (insect attacks, changing weather conditions) will have growing impacts. In agriculture, IFPRI\textsuperscript{11} noted that yields, especially in developing countries, will likely decrease, and South Asia will be especially hard hit.

To avoid competition with food, the use of agro-food by-products and wastes should be strongly encouraged. They represent huge amounts of biomass already available and at low costs. However investments in developing and
optimising infrastructures and logistics capacities are crucial to ensure that all the biomass that can be mobilised in a sustainable way (both from environmental and economic points of view) is actually used. Incentives are also needed for farmers to collect agricultural residues.

Another important discussion, although mainly related to biofuels, is the inclusion of GHG emissions-related land use change, both direct (dLUC) and indirect (iLUC), as land conversion can cause large changes in carbon content of the soil and the upper soil vegetation. The principle of iLUC is as follows: when biofuels are grown on existing arable land, current demand for food and animal feed may push these production activities into new areas such as forests or grasslands. Conversion of forest or grassland to agricultural land can lead to very significant releases of carbon to the atmosphere. When this indirect change is also allocated to biofuels, this can have an important effect on the overall GHG balance, when compared to fossil fuels. However the methodology for calculating iLUC emissions is still under discussion as most of the current calculation methods base their reference on a status-quo (e.g. poor agricultural policy in developing countries, lack of protection of valuable nature areas, inefficient use of food and feed products). If real improvements in agricultural policy, and subsequent yield increases in the developing world, or a stricter protection of valuable natural areas and rainforest (for all applications of biomass) are taken into account, this could significantly reduce these iLUC effects.\textsuperscript{12} e.g. CO\textsubscript{2} fixation by bacteria or algae as well as CO\textsubscript{2} fixation by microorganisms in soils.

\textbf{Objectives}

In order to develop and secure a supply of feedstock for industrial biotechnology and the biobased economy, without hindering the production of food for a fast growing world population and without negatively impacting the environment and biodiversity, the following measures are interesting additional pathways by which biotechnology can help mitigate climate change:

- Optimise production per hectare of land through increased crop productivity by developing the crops themselves (traditional crops as well as ‘energy’ or ligno-cellulosic crops), the cropping system and new biorefining technologies to make better use of the biomass.
• Develop and support a reliable upstream supply chain able to mobilise a sufficient level of feedstock for conversion, by investing in local and regional infrastructures and logistical capabilities to allow all biomass, including agricultural, forestry and waste-based raw material, to be utilised.

• Introduce specific financial incentives to improve the logistical capabilities to collect and stabilise biomass residues (e.g. agricultural residues and forestry waste).

• Develop policy instruments which could secure access to sustainable renewable feedstock, well balanced between bioenergy and biobased products. A higher focus should be put on resource efficiency and climate protection regarding the use of land and biomass flow. Cascading utilisation (the sequential utilisation of renewable raw materials for material and energy uses) could be one option for future support.

Research and innovation

For industrial biotechnology to meet its promise in climate change mitigation requires large-scale public and private investment in R&D. There is a serious mismatch between the level of private sector investment in industrial biotechnology R&D and the potential market opportunities for the sector. Only 2% of biotechnology R&D went to industrial biotechnology in 2003, while the OECD expects industrial biotechnology to contribute up to 39% of biotechnology’s gross value added (GVA) in 2030. Furthermore, since this figure excludes the potential contribution of biofuels, there is a clear underestimation of the potential share of GVA that industrial biotechnology — and biobased products in general — could deliver. Therefore there is a pressing need to boost research in industrial biotechnologies by increasing public research investment, reducing regulatory burdens to bringing products to market, and by encouraging public-private partnerships.

Industrial biotechnology is still a relatively new field and therefore immature; there are major areas of knowledge still to be explored. This presents a bottleneck to greater exploitation, but also offers tremendous opportunities for further research and break-through innovation. Both basic and applied sciences are essential: basic science to develop our fundamental knowledge base, and applied science to introduce innovative products and processes based on this knowledge. In addition, industrial biotechnology is by nature a multi-disciplinary area, comprising biology, microbiology, plant sciences, biochemistry, molecular
biotechnology, chemistry, bioinformatics, engineering, and fermentation technology.

Special attention should also be placed on specific key areas, such as:

- Synthetic biology and metabolic pathway engineering are examples of emerging technologies that will significantly increase the diversity of biotechnological processes and products, driving the development of innovative products.

- Some biobased products will require further chemical processing and unless these chemical processes are made available there will be no market for these precursors. Therefore dedicated research on the combination of technologies such as biochemical and chemical processes should also be given special attention.

- Another important field is the development of efficient and robust enzymes, particularly for the conversion of lignocellulosic material. This should enable the conversion of a variety of feedstock.

- Specific research is also needed to improve feedstock yield and/or the composition of biomass involving both plant genomics and new breeding programmes, and also incorporating further research into efficient crop rotation, land management and land-use change issues.

In Europe, ERA-Net Industrial Biotechnology\(^{13}\) as well as the EU projects Becoteps\(^{14}\) and Star-Colibri\(^{15}\) recently organised a survey on national research programmes, and the current and future use of industrial biotechnology by manufacturers. Comparing the areas of interest of industry and research programmes (Figure 4), it was concluded that there are areas where funding is not compatible with industry needs.

One of industry’s remaining major challenges is to translate research to products, including the development of new product applications. Setting up public-private partnerships would result in a pooling of resources, thus allowing more ambitious goals to be set in terms of reducing the time-to-market. This would also enable industry to adopt longer-term investment plans in the field of the bioeconomy, taking into account the market perspective.
Lessons learned from existing biorefineries show that the construction of demonstration facilities is a crucial step towards developing a fully-fledged biorefining industry. Demonstration activities are able to close a critical gap between scientific feasibility and industrial application. They enable the measurement of actual operating costs, and specific strengths and weaknesses of technological processes before costly, large-scale facilities are built. They dramatically reduce the risk of introducing new technology on an industrial scale and therefore make a biorefinery venture much less risky for investors. Stimulating the construction of demonstrators via public-private partnerships is therefore one of the most important measures that can be taken in the development of the bioeconomy.

The initial construction of biorefinery demonstration plants is not only a costly undertaking but it also involves bringing together market actors along new and highly complex value chains. This includes the diverse suppliers of biomass raw materials (farmers, forest owners, wood and paper producers, biological waste suppliers, producers of macro- and microalgae), the industrial plants that convert the raw materials and industries providing them with the necessary technologies, and the various end users of intermediate or final products. Countries like the United States, Brazil, China, the Netherlands and others are...
increasing investment into research, technology development and innovation, and are supporting large scale demonstrators.

Objectives

In order to make a fast and efficient shift towards more integrated and sustainable production and processing systems, the following measures are proposed.

- Support technological progress and increase public and private R&D investment in industrial biotechnology and related technologies, through multidisciplinary research programmes at both national and international level.
- Build networks between industry and academia to overcome the competence hurdle and knowledge gap.
- Mobilise sufficient resources to support large co-ordinated research initiatives, focusing on the market perspective covering the whole value chain.
- Stimulate and support technology transfer in the area of industrial biotechnology and green technologies.
- Establish programmes to accelerate and alleviate risks of transforming knowledge into commercial products, by financially supporting access to pilot and demonstration facilities and by integrating production processes.

Dedicated policies and incentives to promote the use of biobased products

Specific policies for the development of biobased products are more extensive for bioenergy (including liquid biofuel use and solid biomass applications) than for biochemicals or biomaterials. Worldwide, many governments support their emerging biofuel industries far more than other sectors via subsidies, mandates, adjustments to fuel taxes and incentives for the use of flex-fuel vehicles (e.g. United States, European Union, Brazil, China), and several countries have started to develop extra incentives for the so-called second generation biofuels.16
The other biobased products however, in contrast to biofuels, suffer from a lack of tax incentives or other supporting regulations. Although research and innovation have reached a stage where products are ready for market introduction, renewable raw materials are only used in certain product categories. A few examples of specific policies that have been developed to promote the use of biobased products include:

- In Europe, the European Commission is developing a demand-based innovation policy for biobased products. The aim of the so-called Lead Market Initiative (known as LMI) for biobased products is to promote and stimulate innovation by strengthening the demand base. The added value of the LMI is about developing a prospective, concerted and tailored approach of regulatory and other policy instruments, including legislation, public procurement, standardisation, labelling, certification, and complementary instruments. Although an advisory group has developed a series of recommendations to stimulate market uptake and development, these measures still have to be implemented. Other national demand-driven policies often focus on the sustainability agenda (including green public procurement) and are often implemented as a mix of public procurement procedures, legislation and direct financial incentives.

- In the United States, the BioPreferred programme aims to increase the purchase and use of renewable, environmentally friendly biobased products.

- In Japan, in 2002 the government initiated the Biomass Nippon Strategy, requiring that 20% of all plastics consumed in the country be sourced renewably by 2020. This prompted Toyota, NEC and others to accelerate levels of R&D into biobased plastics and to raise the biobased content of their products. Biobased chemicals and bioplastics benefit from usage, waste management, and labelling legislation.

- In China, support for biobased chemicals includes numerous incentives for producers and a preferential tax treatment for selected firms in emerging biochemical industries. In addition, since 2005, a specific programme promotes production and consumption of biodegradable plastics.

- In Korea, the government supports the use of biodegradable materials in refuse bags and fishing nets. One-time use products cannot be made from conventional plastics, and polystyrene is banned in food packaging.
Objectives

- A framework of incentive-based and demand-stimulating policies, such as mandates, public procurement, subsidies and other incentives to stimulate the demand for sustainable biobased products, should be implemented.

- The implementation of a source-separated, high quality composting system for organic waste treatment could also help boost the market development of biodegradable and compostable plastics. The organic recycling of biodegradable and compostable plastics would offer many benefits to boost the market as composting is cost-efficient and is a concept that consumers can easily engage with and participate in. For short life products such as fresh food packaging, biowaste, shopping bags or disposables such as compostable packaging for catering, composting is the best method to recover and recycle biodegradable and compostable plastics.

Standards for measuring sustainability and GHG savings

Addressing sustainability issues through all segments of the value chain of biobased products (from biomass production to end-use) in a fair, evidence-based regulatory framework, represents an enormous policy challenge. Addressing these sustainability concerns is a major challenge for biofuels and other biobased products, and the sector must demonstrate that it possesses sustainability credentials in order to gain a strong “license to operate” from governments and consumers, especially if supporting policies are to be developed. Unfortunately the lack of a widely-accepted mechanism to assess and confirm sustainability is an important barrier to consumer and government confidence. The OECD is currently developing best guidance to assess the environmental and economic sustainability of biobased products. This best guidance is based on an analysis of existing approaches and on the identification of key elements of best-practice assessment methodologies.

Consumers increasingly demand products with low environmental impacts. While the primary focus is currently on carbon, impacts on biodiversity are less frequently taken into account. In addition, there is currently no standard procedure available to measure this criterion as a part of Life Cycle Analysis.
Sustainability criteria should aim to, if possible, measurably reduce the key impacts associated with feedstock production, consumption and use. While dependency on the feedstock variations will persist, it is likely that key aspects to consider for the future will be biodiversity, soil protection, water conservation, carbon dioxide emissions reductions, air quality and social sustainability.

**Objectives**

- Production and processing of materials should be done using best management practices.
- Sustainability filters should be integrated into lending policies.
- Sustainability requirements should be addressed through public/private partnerships. Feedstock producing countries – especially in the global South – will also need significant technical and financial support to implement adequate safeguards.

**Communication and education**

Biobased products comprise a great variety of innovative products in many applications. However most of these products cannot be easily recognised by users and consumers, due to the fact that no external, perceptible characteristics differentiate biobased products from traditional products made with petrochemicals. Thus the specific features of biobased products are mostly invisible to the purchaser. This lack of awareness and knowledge of the potential of industrial biotechnology, in manufacturing industry and amongst policy makers, consumers and even investors\(^7\) represents a major obstacle to increased market uptake of biobased products. In its recent bio-economy report, the OECD\(^8\) suggested creating an ongoing dialogue between regulators, citizens and industry, as many of the policies to support the bio-economy and its sustainability will require the active participation of these groups. Sustainability should be made more visible as the core value driving the development process. As environmental awareness grows, the demand for products from sustainable manufacturing processes, including biobased products, is likely to grow.
Consumers are increasingly making purchasing decisions based on environmental considerations. Such buying patterns also give signals to retailers and manufacturers that factors in addition to quality and price are important. However in order for the consumer to make an informed choice, communication with the public has to provide simple and clear information. Consumers have limited knowledge of biobased products in the market place. If the aim is to create a market-pull effect by information and specific campaigns, then brand owners and retailers are a very important target group. Such business to business (B2B) information should be based on standards and certification schemes. Meaningful information campaigns can increase consumer awareness and understanding.

The challenge in communicating about biobased products is their diversity. Though they are all created at least partially from biomass or the transformation of biomass components, they fall into many product categories, ranging from pharmaceutical ingredients to consumer products, from bulk materials to chemicals. The main characteristic of biobased products is their biobased carbon or biomass content, while other important characteristics related to climate change are environmental performance and carbon footprint.

The public needs simple and easy-to-recognise information such as labels. Labels are frequently used to inform consumers about characteristics of the products, options for disposal (recyclable, biodegradable), or provide a quality indicator (e.g. EU Eco-label, Nordic Swan, Blue Angel). However the efficiency of a label is limited by two factors:

- First, with the multiplicity of labels and information tags on products, consumers tend to be overwhelmed by information. Thus it is important to review the efficiency and coherence of the labelling system, and evaluate the need for consumers to have labels and their actual impact on consumer behaviour.

- Second, in driving a value chain towards increased sustainability, a label is only as efficient as its adoption by the market — especially if the label is not compulsory — and its recognition and understanding by consumers.

Labels can be used for improving information and transparency for consumers regarding the renewable origin of products and promoting these products. However as the biobased or renewable nature of a product is not sufficient to prove its sustainability, communication to consumer should also include a range...
of other factors. Starting from industrial standards, the development and communication of (independent or third party) certification and labelling programmes (e.g. eco-labels, environmental product declarations) are a precondition for communication of verifiable claims. If such tools are not well developed or improperly used, they can lead to mistrust in the public and damage the reputation of the industry.

At the beginning of 2011, The US Department of Agriculture\textsuperscript{19} launched a specific label for biobased products which is intended to better inform consumers purchasing biobased products. Products made of “wholly or significantly biological ingredients — renewable plant, animal, marine or forestry materials” are eligible for a USDA-certified biobased label. Products need only be 25% biobased to warrant the label, but the percentage might be increased in the future.

\textbf{Objectives}

- Dedicated information and communication campaigns should be developed.
- An understandable label based on simple, harmonised criteria and standards should be created.

\textbf{Conversion towards low-carbon renewable-based production systems}

One of the main questions is how we can economically valorise GHG emission savings or avoidance. Producing chemicals through biochemical routes is currently still more expensive compared to traditional production routes. In addition, existing production facilities for chemical syntheses cannot be converted to biotechnological production without massive new investments, and, in many cases, there are clear economic restrictions in biotechnological production processes due to higher operating costs and higher levels of R&D costs and investments. When competing against an existing process based on fossil carbon sources, the alternative bioprocess must also show competitiveness in scenarios with high energy- and feedstock-cost volatility.

Investments required for building a new bio-industrial facility, especially if it competes with the conventional one, might present a significant barrier. In addition, it has become even more difficult to obtain financing for investing in building new, full-scale commercial plants and infrastructure as result of the
recent worldwide financial crisis. Governments tend only to provide financial support and incentives on a relatively short-term basis, while the pathway to success for many enterprises is a long term proposition. Governments interested in supporting biorefineries for reasons of environmental protection, energy security and innovation leadership need to support market growth, in order to trigger private sector investments.\textsuperscript{20}

In the United States — at federal as well as at state-level — several programmes have been set up to stimulate the construction of new plants (producing biofuels and biobased products) and/or new biorefineries. The United States is currently evaluating the feasibility of bioenergy and biofuel tax policies, programmes and carbon legislation for other biobased chemicals and products.

\section*{Recommendations}

- Authorities should develop support mechanisms for the construction of new bio-refineries (including grants, loans and tax incentives).

- Authorities should ensure that biobased products are incentivised in existing and new climate change/carbon legislation.

\section*{Need for an integrated and strategic approach}

According to the OECD,\textsuperscript{21} in order to achieve a competitive bioeconomy, broad approaches, such as creating and maintaining markets for environmentally sustainable products, funding basic and applied research, and investing in multi-purpose infrastructure and education will be necessary. In addition, these will need to be combined with shorter term policies such as the application of biotechnology for improving plant and animal varieties, improving access to technologies for use in a wider range of plants, fostering public dialogue and increasing support for the adoption and use of internationally accepted standards for life cycle analysis together with a range of other incentives designed to reward environmentally sustainable technologies. EuropaBio\textsuperscript{22} and the Biotechnology Industry Organisation\textsuperscript{23} in the United States, recently published policy guides setting out similar requirements, and called for a more integrated and strategic approach, with supportive policies in the areas of climate change, energy security, renewable feedstock supplies, research and innovation, the environment and trade.
It can be assumed that the net GHG impact of industrial biotechnology will be strongly influenced by the overall socio-economic environment and the policy landscape promoting the dissemination of these technologies. In many instances, current policies and private sector strategies are neither strong nor efficient enough to fully develop and harvest the GHG emissions reduction potential of industrial biotechnologies. A significant effort is therefore required to achieve the socio-economic environment and policy landscape that would nurture such potential. The following figure illustrates policies proposed by Bang et al. (2009) that can maximise the impact of industrial biotechnology on climate change.

**Figure 5. Policies for a low GHG path**

Concluding remarks

At the heart of the climate change debate is GHG emissions. There is a strong linkage between economic growth and increasing CO₂ production. The problem then becomes one of how to break this linkage i.e. to continue economic growth but in a sustainable manner that leads to GHG emissions reductions. Industrial biotechnology is one part of the solution to the problem.

It is incumbent upon any new environmentally competitive technology to be also performant and cost-competitive. In its early years industrial biotechnology must be supported financially at a very high level as it competes head-to-head with the oil and petrochemical industries. These are very well established industries that benefit from large economies of scale that would make industrial biotechnology processes and products uncompetitive. The level of support required needs to come from both government and private industry in partnership.

To date the United States first generation bioethanol industry provides a good example of how policy measures can change the landscape for a promising technology. Bioethanol has been massively supported by regulation, volume and GHG mandates, public procurement, and private industry has responded positively. For biofuels to continue to be a success requires, amongst other challenges, that the technical challenges associated with the use of agricultural waste materials as feedstock be overcome. The maturation of the integrated biorefinery will go a long way to addressing economic issues. Biobased chemicals and bioplastics lack the national and international policy frameworks at present that have made first generation bioethanol successful.

It is assumed that producing chemicals, polymers and liquid fuels by biological processes rather than petrochemical ones, or by including biobased ingredients, should lead to a reduction in GHG emissions as:

- Biological processes are more benign than most petrochemical processes (lower temperature and pressure, low water and energy consumption as well as lower CO₂ and waste production).
- The raw materials for biological processes are renewable, and therefore the products are more likely to be carbon-neutral.
The assumption needs to be proven on a case-by-case basis, using techniques such as life cycle analysis and carbon footprint testing. To produce such proof requires standardisation of techniques used. To create a globalised industrial biotechnology industry requires harmonisation of those techniques to prevent trade barriers developing. Best practices are an essential prerequisite. Great care is required in determining what are the most useful sustainability indicators, and then making sure that there is great clarity in their application to prevent confusion. For example, when biodegradable plastics started entering the market, there were a series of misconceptions about the term degradable and biodegradable (Mohee et al., 2008). Designing appropriate labels, by consequence of such misconceptions, is therefore a complex problem.

Industrial biotechnology has suffered a lack of investment at all levels e.g. R&D, demonstrator plants, full-scale process development, feedstock development, land use issues. There exists a serious mismatch between future expectations of this industry (high) and the level of investment (low). Part of the problem is the lack of visibility of a biobased product compared to, say a pharmaceutical product. It is difficult for industrialists, investors and the public to visualise industrial biotechnology products, and therefore to understand their benefits. Part of the policy mix therefore is communication and education.

The stakes involved environmentally and financially are very high indeed. Industrial biotechnology offers the promise to be a force for good, not a panacea, in the on-going climate change struggle. Policy intervention is required across the three broad criteria — social/environmental, industrial performance and economical. To make this happen requires policy to be both national and international if industrial biotechnology is to fulfil its promise in a rapidly globalising world.
Annex

Impact of industrial biotechnology in different industrial sectors

Overall impact

Several studies outline the potential of industrial biotechnology and biobased products to lower the impact of industry on the environment, with particular regard to lowering GHG emissions. This annex looks at some specific industrial sectors, and it should be pointed out that the product specific claims on impacts were measured via transparent life cycle analyses (LCA). The studies indicate that — in most cases — bio-based products consume less energy and emit less carbon dioxide (CO₂) than products from fossil resources. This is mainly due to the fact that fermentation or bioconversion processes occur at or near room temperature and atmospheric pressures, resulting in lower combustion energy requirements and fewer associated emissions than in conventional chemical processing.

According to Ademe,²⁶ biobased products can create 40-80% savings in non-renewable energy consumption and at least 50% lower CO₂ emissions. In another study co-ordinated by the University of Utrecht,²⁷ the non-renewable energy savings of biobased production are estimated at 30%. The same study estimates that up to one third of the current non-renewable energy use for the production of all organic chemicals could be saved by 2050 if substantial progress is made in industrial biotechnology and if the use of lignocellulosic feedstocks is successfully developed.

In a more recent report, Bang et al. (2009)²⁸ claimed that the industrial biotechnology sector today globally avoids the creation of 33 million tonnes of CO₂ each year through various applications (without taking ethanol into consideration), whilst globally emitting 2 million tonnes of CO₂. The same report concludes however that the full climate change mitigation potential of industrial biotechnology ranges between 1 billion and 2.5 billion tons of CO₂ emissions per year by 2030, compared with a scenario in which no industrial biotechnology applications are available.

However, it is clear that the effects can vary considerably from one application to another. In addition larger savings are expected if lignocellulosic feedstocks or fermentable sugar from sugar cane can be used in the future: respectively up to 75% and 85% non-renewable energy savings.

The application of industrial biotechnology is benefiting a diverse range of industries, including food processing, pharmaceuticals manufacturing, plastics,
fuels and specialty chemicals manufacturing, textiles and paper, advanced materials and beyond.

Impact per sector: case studies

Textiles and detergents
Laundry and dish washing are among the most energy intensive household activities, requiring the heating of large quantities of water and the consumption of electricity to drive the wash process. Washing machines are one of the biggest consumers of household electricity, and 80% of the electricity for washing laundry is used to heat the water. So reducing the temperature required to effectively clean soiled clothes or dishes can result in significant energy savings and reduced CO₂ emissions. Detergent enzymes represent in fact one of the largest and most successful applications of modern industrial biotechnology as one of the main environmental advantages of enzymes is that clothes can be washed at a lower temperature.

With the new generation of cold water enzymes, washing temperatures can be reduced to 30°C, without sacrificing cleanliness. Studies show that CO₂ emissions can be reduced by 100 g per wash by washing at 30°C rather than 40°C.²⁹ By washing at 30°C rather than 40°C or 60°C, the CO₂ savings potential in the United States and Europe alone is around 32 million tons annually, equivalent to the emissions of 8 million cars.³⁰

Natural fabrics such as cotton are normally bleached with hydrogen peroxide before dying. In the classical process, bleaching was followed by at least two rinses in hot water (80-95°C). With the use of an enzyme that degrades residual peroxide during the second post-bleach rinse, water heated to 30-40°C can be used resulting in lower non-renewable energy consumption.³¹ Another application of enzymes in the textile industry is in the treatment of cotton fibres. Scouring is a cleaning process that removes pectins and thereby assists with the removal of impurities such as waxes and mineral salts from cotton yarns and fabric before dying. Traditionally, scouring involves a number of high-temperature steps with a large consumption of chemicals. Enzymes enable a faster and gentler scouring process with lower energy and chemical consumption. Compared to the traditional chemical process, the enzymatic process reduces temperature from 95°C to 55°C, meaning that there are important energy savings.³²
Plastics production

Plastics in general are important materials contributing significantly to environmental protection: due to their tailor-made properties (e.g. light weight, excellent insulation ability, tuneable properties for optimum food protection, etc.) they reduce energy use by 26% and GHG emissions (GHG) by 56% across a variety of applications compared to alternatives.\(^{33}\) Besides crude oil, natural gas and coal, biomass is an additional raw material source for plastics (biobased plastics). Depending on the type of biobased plastic, they may contribute up to a 50% decrease in terms of energy consumption and up to 67% savings of CO\(_2\) emissions during the production process.\(^{34}\) Depending on the extent to which policies and measures supporting biobased plastics are implemented, the potential GHG emission reductions range between 3.0 and 8.5 million t CO\(_2\) eq. by 2020.\(^{35}\)

Polylactic acid or PLA, produced from corn starch as a renewable feedstock, is being used in fibres, films, food and beverage containers, textiles, coated papers, and many other applications. LCA data indicate that from cradle to polymer factory gate, PLA requires 30-50% less non-renewable energy and releases 30-60% less GHG to the atmosphere than the most common traditional plastics.\(^{36}\)

Pulp and paper production and bleaching

Converting wood into paper is an energy, water and chemical intensive process. The conventional chemical process requires boiling wood chips at around 160 °C before bleaching the pulp with chlorine dioxide. With the application of new biotechnology processes, it is now possible to reduce the energy consumption by 32% used during the bleaching process.\(^{37}\)

Chemicals

Biotechnology can be used to produce various bulk and fine chemicals that are currently produced from fossil fuel based feedstocks (Figure A1). Biobased substances can also act as building blocks for many other materials provided that they are cost-competitive.

Recently a company has developed a patented process to manufacture 1,3 \textit{propanediol}, the so-called bio-PDO\textsuperscript{TM}, from renewable resources instead of petrochemicals. Bio-PDO\textsuperscript{TM} is one of the first commercial-scale industrial applications of metabolic engineering designed to make a 100% renewable
resources based material from corn starch, and is the key element for many materials in use every day. The production of Bio-PDO™ has a much smaller impact on the environment than its petroleum-based equivalent. The production of Bio-PDO™ consumes 40% less energy and reduces GHG emissions by 20% versus petroleum-based propanediol. It has a broad range of applications in fibres, films, thermoplastics, detergents, cosmetics products, ink and several other industrial areas.

Vitamin B2, also known as riboflavin, plays a very important role in maintaining human and animal health. Vitamin B2 is central to energy metabolism, and is required for the metabolism of fats, carbohydrates, and proteins. Industrial biotechnology replaced a laborious and costly traditional multi-step chemical synthesis and purification process by a one-step fermentation process whereby...
a micro-organism directly transforms vegetable oil into the required vitamin. Evaluation of the benefits of the one-step process shows a reduction of CO₂ emissions of 30%.  

Industrial biotechnology made it possible to replace the purely chemical production process of cephalosporin, a commonly prescribed antibiotic, by an enzyme-catalysed manufacturing process. Biotechnological production of 7-aminodeacetoxycephalosporanic acid, a key intermediate for the synthesis of cephalosporin, resulted in 37% less electricity use and CO₂ reductions of 75%.  

Food

Enzymes have been used in food manufacturing for hundreds of years, mainly based on fermentation by micro-organisms. The last ten years in particular have seen an increase in new enzyme applications in food. Before that, the dominant new enzyme innovations were aimed at the production of high fructose syrups from corn starch. Today, novel enzyme applications are also being implemented in baking, fruit and vegetable processing, brewing, wine-making, processing of vegetable oils, cheese manufacturing, and meat- and fish-processing. Many enzymes applications in the food industry are advantageous due to their impact on processing conditions in food manufacturing plants, where enzyme use may result in savings of energy and chemicals.

Recently a special amylase has been commercialised that diminishes the crystallisation of starch, reducing waste of bread by allowing bread to stay fresh and moist longer. This effect has provided industrial bakeries with new opportunities for changing their production and delivery setup in order to produce at larger, centralised bakeries and make fewer deliveries to retailers. The industry can save both money and energy, while less waste bread also means more efficient use of agricultural raw materials. There are significant environmental gains due to better utilisation of agricultural raw materials. A reduction of GHG emissions of up to 54 t per million loaves of bread sold can be obtained. The major contribution to the reduction of CO₂ emissions is also, in this case, the agricultural load. Some 65% of the reduction stems from savings in the production of wheat, including agricultural emissions, production of fertiliser and traction. Some 15% of the reduction comes from savings in energy consumption during milling and baking and 15% comes from reduced transportation.
**Malting barley** for use in brewing is an energy and water intensive process. The barley has to be soaked in water to allow it to germinate and then has to be heated for drying. Brewers and biotechnologists developed a process removing this entire step with the use of an enzyme. By removing the malting process, the application of this enzyme to brewing is estimated to save 350 000 tons of CO₂ for every 10% of global beer production that is converted to un-malted barley—a CO₂ savings equivalent to the emissions of 85 000 cars.  

**Tanning and leather**

Enzymes have been used in the tanning industry for centuries because they are efficient in degrading protein and fat. In early times, the enzymes were derived from animal excrement and later on from the pancreas of cattle. Today, the enzymes are almost entirely produced by microbial fermentation. Soaking enzymes reduces the required soaking time, leading to electricity savings in turning the drum where the hides rest. Enzymes that remove hair during the tanning process reduce the sulfide requirements for the process. The environmental impacts of producing and delivering the enzymes to the tannery on the one hand and the savings in chemicals and electricity on the other have been evaluated via a LCA study. This comparison of conventional and enzyme-assisted bovine soaking and de-hairing/liming processes indicates that the application of enzymes in the tanning industry is justified by considerable energy savings and considerable reductions in the contribution of the processes to global warming. Assuming that the environmental improvements by switching from conventional to enzyme-assisted soaking and de-hairing/liming are applicable worldwide, the global saving potential is in the order of 8 million GJ of energy and 0.7 million tonnes of CO₂ per year.

**Dyes**

Bioprocesses to produce biobased colourants have recently been developed as an alternative to traditional chemical synthesis. While the creation of chemical-based dyes requires temperatures of up to 70-90 °C in harsh conditions, the enzymatic synthesis of these colourants can be obtained at ambient temperature, under mild conditions. LCAs have illustrated that on an industrial scale, enzymatic processes could help to reduce CO₂ emissions and toxicity towards the environment.
Enzymatic treatment of coloured wastewater cannot only cut human toxicity in half, but a LCA study\textsuperscript{45} showed that, as compared to classical chemical sludge, enzymes can reduce by 10 times the impact on global warming (Figure A2), reduce by a factor of two the impact on the ozone layer, reduce by a factor of three the impact on abiotic (non-living) components in the environment and decrease by a factor of three the impact on marine toxicity.

\textit{Figure A2. Climate change impacts of enzymatic versus traditional treatment of coloured wastewater}

\textit{Source:} EuropaBio (2008), How industrial biotechnology can tackle climate change.
Biofuels

To ameliorate GHG emissions in the transport sector, there are no short to medium term alternatives but to combine further leaps forward in automobile fuel efficiency with biofuels. While first-generation corn-to-ethanol plants reduce GHG emissions by as much as 52% over petroleum-based fuels, ethanol made from cellulosic feedstocks, agricultural residues, or wood forest residues has the potential to reduce GHG emissions by as much as 129%, compared to gasoline. The CO₂ savings (Figure A3) depend very much on the feedstock and conversion process.

**Figure A3. Costs and CO₂ profile of various biofuels compared to the fossil fuel counterpart**

<table>
<thead>
<tr>
<th>Biofuels</th>
<th>Feedstocks examples</th>
<th>Production cost €/MWh</th>
<th>CO₂ profile**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bioethanol</strong></td>
<td>Corn (US)</td>
<td>46</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Wheat (EU)</td>
<td>63</td>
<td>60-105</td>
</tr>
<tr>
<td></td>
<td>Sugar beets (EU)</td>
<td>69</td>
<td>30-70</td>
</tr>
<tr>
<td></td>
<td>Sugarcane (Brazil)</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Wood*</td>
<td>47</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Other lignocellulosic feedstock*</td>
<td>41</td>
<td>12</td>
</tr>
<tr>
<td><strong>Biodiesel</strong></td>
<td>Rapeseed (EU)</td>
<td>64</td>
<td>40-80</td>
</tr>
<tr>
<td></td>
<td>Soy bean (US)</td>
<td>59</td>
<td>25-60</td>
</tr>
<tr>
<td></td>
<td>Syndiesel BTL* (direct-foil)</td>
<td>42</td>
<td>15</td>
</tr>
</tbody>
</table>

*Expected cost in 2020 **Percentage of CO₂ release for the corresponding fossil fuel (well to wheel)

Source: EuropaBio (2008), How industrial biotechnology can tackle climate change.
Notes

1. UNEP (2010), Environmental Impacts of Consumption and Production.
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