WWF for a living planet®

novozymes®
Rethink Tomorrow

GHG Emission Reductions With Industrial Biotechnology:

Assessing the Opportunities

Marco Buttazzoni
Sustainability 3.0 LLC
1180 8th Avenue West #316
Palmetto FL 34221-3810
United States

MButtazzoni@sustainability30.org

The opinions and assumptions presented in this report are not necessarily those of WWF or Novozymes. If nothing is otherwise stated they can only be assigned to the Author(s). This report is based on calculations and analysis made through contribution of sector experts and peer reviewed LCAs from a.o. Novozymes. The report can be downloaded at www.wwf.dk

Content

1. Introduction

INDUSTRIAL BIOTECHNOLOGY, cleverly working with nature to meet human needs, can potentially play a significant part in the effort to reduce human impact on the environment.

In particular, industrial biotechnologies deployed to pursue sustainability goals can potentially enable a transition from the energy-, resource- and waste-intensive processes that currently dominate many industrial production processes, and human activities in general. They are one of the enablers for a shift to economic paradigms that are based on biological processes and, like natural ecosystems, use natural inputs, expend minimum amounts of energy and do not produce any waste, as all 'discarded' materials are reused in the ecosystem.

WWF and Novozymes have decided to work together to better understand these opportunities to speed up the deployment of biotechnology solutions with the potential to reduce greenhouse gas (GHG) emissions.)

This report is one of the initial products of this collaboration and focuses on undertaking a first estimate of the GHG emission reductions that could be achieved, on a global scale, if the potential of sustainable biotechnologies is fully harvested. The report builds on input from Novozymes and other companies and experts from a variety of sectors and disciplines, which have been involved in the work, as well as WWF. (see Appendices 1 and 2).

The first part of the report (section 2) provides background on the report discussing the vision behind it and its goals.

Section 3 discusses the activities undertaken during the making of this report, describing data collection approaches, analytical framework and stakeholder involvement activities.

The approach followed is aimed at providing insight into the opportunities to reduce GHG emissions with a strategic deployment of industrial biotechnology. The results of this analysis are reported in Section 4, where also the key factors that affect the achievement of such opportunities are discussed.

Identifying the potential to reduce GHG emission does not equate to achieving such emission reductions. Several factors need to be in place in order to fully harvest the opportunities offered by industrial biotechnology. Leveraging the insights offered by sections 2 and 4, section 5 discusses the strategies that policy makers and corporations can implement (jointly) to maximize the GHG benefits that can be achieved by industrial biotechnology.

The final section of the report, section 6, summarizes the results of the analysis and highlights a set of activities that, if undertaken, would enable a faster and more effective development of biotechnology solutions with positive climate impacts.

2. Project Vision and Goals

Industrial biotechnology is the application of biotechnology for industrial purposes, including manufacturing, alternative energy (or "bioenergy"), and biomaterials. It includes the practice of using cells or components of cells like enzymes to generate industrially useful products (Europabio)[1]

THE HYPOTHESIS AND VISION underpinning this project is that sustainable biotechnology solutions, applied in the industrial sector, can provide a critical contribution in the transition from current, unsustainable, economic practices to more sustainable economic systems, which are able to meet human needs without destroying the natural ecosystems that support life (including human life) on our planet.

To achieve such a transition several critical changes are required both in mindset and practice, as illustrated by table 1. [2]

Key dimensions	Unsustainable	Sustainable
Societal/Policy goals	Economic growth	Growth in well being
Approach to nature	Control over nature	Work with nature
Predominant work mode	'Big is better'	'Smart is better'
Focus of business activities	Goods	Services /needs
Energy sources	Fossil fuels	Renewable energy (including biofuels)
Iconic Materials	Iron, steel and cement	Bio-based materials and digitalization/ dematerialization
Predominant chemistry	Energy intensive	Low energy – Biomimicry
Waste production	High waste	No waste

Table 1: Unsustainable vs. Sustainable mindsets and practices

Industrial biotechnology solutions are among the enablers of the transition towards sustainable socio-economic systems, as they:

- Aim at identifying, selecting and using biological processes that satisfy human needs and
- Are based on renewable biological inputs, as opposed to the non-renewable resources currently used in agricultural, industrial and consumer processes alike.
- As they are based on biological processes, they also tend to be highly energy efficient and to use renewable bio-based energy.
- Finally, different biotechnology solutions can potentially be combined to create 'ecosystems' in which materials discarded by one process are inputs for another process, and do not produce any waste.

Industrial biotechnology can enable a shift to a bio-based economy i.e. an economy based on production paradigms that rely on biological processes and, as natural ecosystems, use natural inputs, expend minimum amounts of energy and do not produce any waste, as the materials discarded by one process are inputs for another and are reused in the ecosystem.

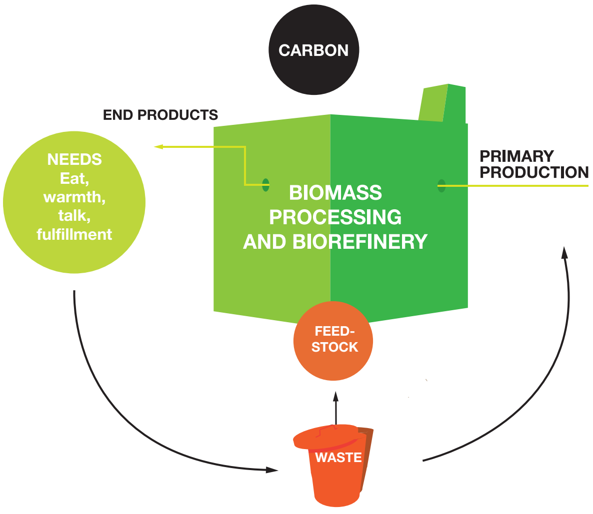


Figure 1: The Biobased economy[3]

As with most technologies, the potential to achieve sustainability goals does not automatically result in such goals being realized. The net impact of biotechnologies on sustainability and on GHG emissions will depend on the context in which the technologies are applied. Whereas biotechnology solutions typically increase process efficiency and reduce emissions in the short term, the broader socio-economic environment in which such solutions are applied,

---

[1] Industrial bio technology includes only the use of GMOs in contained environments. Source: Europabio - white biotechnology gateway for a more sustainable future.

[2] The table was elaborated by WWF and discussed during the expert workshops undertaken during the project. The table cannot be taken to represent the vision of the corporations and industry experts who contributed to the expert workshops

[3] Source: Sustainable 3.0 elaboration

and the policy context affecting them, may generate dynamics that lead to even deeper emission reductions over time (low carbon feedbacks) or to situations where short term benefits vanish and are overwhelmed by rebound effects and perverse incentives that lead to higher long term emissions (high carbon feedbacks)[4]. Figure 2 provides an illustration of these alternative paths.

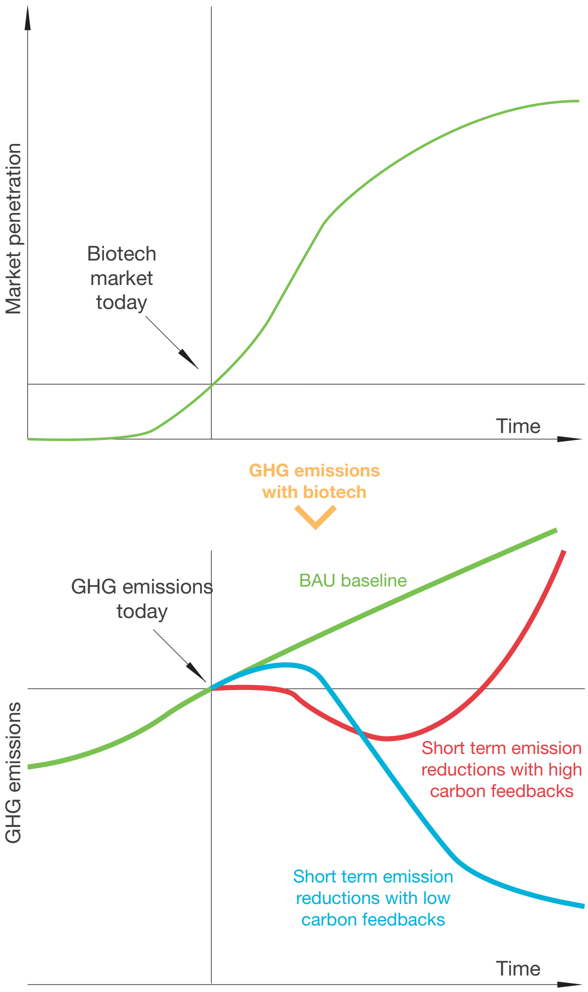


Figure 2: GHG emissions with biotechnology, the impact of high and low carbon feedbacks

As the GHG emissions path is not determined by technology alone, harvesting the opportunities to create socio-economic systems that meet sustainability needs will require insight and a proactive effort from both industry and policy makers.

This report aims at contributing to this effort by focusing on understanding the deployments of industrial biotechnology solutions in ways that deliver reductions in GHG emissions in the short term, while also enabling deeper reduction over time, identifying policies and strategies that enhance positive impacts over time, while reducing the risks of negative rebound effects.

Whereas biotechnologies entail a wide range of applications and procedures that use biological organisms to satisfy human needs (see box below), this project focuses on a subset of biotechnology solutions.

Definition of biotechnology
“Any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use”.[5]
Biotechnology branches[6, 7]
Green biotechnology is biotechnology applied to agricultural processes. Green biotechnology may include:

• Selective breeding and hybridization undertaken using traditional techniques
• Marker-Assisted Selection (MAS) a process whereby a marker (morphological, biochemical or one based on DNA/RNA variation) is used for indirect selection of a genetic determinant or determinants of a trait of interest (i.e. productivity, disease resistance, abiotic stress tolerance, and/or quality).
• Genetic modification of plants or animals i.e. the creation of organisms whose genetic material have been altered using recombinant DNA technology. Such organism can be:
  • Cisgenic if they contain no DNA from other species
  • Trangenic if they have inserted DNA that originated in a different species.

Red biotechnology is applied to medical processes. Some examples are the designing of organisms to produce antibiotics, and the engineering of genetic cures through genomic manipulation.
Industrial biotechnology, also known as white biotechnology, is biotechnology applied to industrial processes. An example is the designing of an organism to produce a useful chemical. Another example is the using of enzymes as industrial catalysts to either produce valuable chemicals or destroy hazardous/polluting chemicals. White biotechnology tends to consume less in resources than traditional processes used to produce industrial goods.
Scientific and technical domains
Modern biotechnology is a high-tech sector, which builds on several scientific disciplines, including genetics, molecular biology, biochemistry, embryology and cell biology,

Table 2: Biotechnology: definition and characteristics

In particular the report focus on identifying and analyzing biotechnology solutions that are applied to industrial processes and meet the following climate change and sustainability criteria (table 3):

---

[4] See for example Buttazzoni et al. 2009 ‘From Workplace to Anyplace – Assessing the global opportunities to reduce GHG emissions with virtual meetings and telecommuting’ for an analysis of how both technology and policy, taken together, affect GHG emissions

[5] See UN Convention on biological diversity Article 2: use of terms http://www.cbd.int/convention/articles.shtml?a=cbd-02 accessed march 2009

[6] Source: Wikipedia http://en.wikipedia.org/wiki/Biotechnology#cite_note-Springham_biotechnology-2 accessed March 2009

[7] Additional terms sometimes associated to the biotechnology field include: Bioinformatics: an interdisciplinary field, which addresses biological problems using computational techniques, and makes the rapid organization and analysis of biological data possible. And Blue biotechnology, a term used to describe the marine and aquatic applications of biotechnology

Climate Change benefit
• Users of biotechnology solutions achieve GHG emission reductions (estimated on a LCA basis) • A biotechnology solution provides building blocks for additional biotechnology solutions that enable further reduction in GHG emissions • The adoption of a biotechnology solution, and systems of biotechnology solutions, boost the development and deployment of technologies that are instrumental to further reducing GHG emissions over time • The adoption of biotechnology solutions, and systems of biotechnology solutions, are conducive to socio-economic changes and changes in behavior that lead to further reductions of GHG emissions over time
Sustainability benefits and constraints
• The deployment of biotechnology solutions does not represent a dangerous threat for human health • The deployment of biotechnology is not associated with unacceptable risks of alien species invading natural ecosystems • The deployment of biotechnology solutions does not lead to changes in land use that damage sensitive natural ecosystem • The deployment of biotechnology solutions does not lead to changes in land use that crowd out food production and result in endangering the subsistence of human communities

Table 3: Climate change and sustainability requirements

Meeting these requirements would lead to identifying a subset of biotechnology solutions, and complementary policies and business strategies, which can be implemented so that a path of progressively lower GHG emissions is achieved.

3. Activities and methodology to assess potential benefits

THE ANALYSES IN THIS REPORT are the result of a 5-month workstream that took place between February and June 2009 as a part of the Biosolutions initiative, a joint project between WWF and Novozymes, which aims at exploring and establishing biotechnology solutions for both climate and industrial policies.

The workstream aimed at reviewing existing and market-ready biotech solutions in different sectors and to estimate their greenhouse gas reduction potential, in order to identify the first strategic billion tonnes of GHG reductions.

The first part of the project focused on identifying biotechnology applications with GHG impacts. Sector experts from industry, academia and relevant organizations were identified and contacted between February 2009 and May 2009. Input was gathered via email and telephone conferences.

An expert meeting took place on April 17th in Copenhagen.[8] Representatives from academia, industry and relevant organizations met to discuss key definitions, validate classification schemes and methodological framework devised to analyse Biotech solutions with GHG emission reduction potential.

The second part of the project focused on analyzing and assessing the potential GHG impact of different biotech solutions and on identifying policies and strategies that could maximize GHG benefit. The work entailed an initial collection of existing literature, and LCA studies, on individual biotechnology applications. In parallel, macro level data was also collected on relevant markets and sectors and associated GHG emission. Inputs from both bottom up and top down analyses where used to model the potential impact of biotechnology and select appropriate parameters and assumptions.

Biotechnology and GHG accounting experts were consulted in June 2009, to assess and validate the approaches and assumptions used in the calculations. An expert meeting[9] was organized in Bonn on June 10th to discuss and assess the results emerging from the application of methodologies, including dynamic effects. The expert meeting was also designed to obtain a better understanding of the barriers hindering the development and dissemination of biotech solutions with positive GHG impacts.

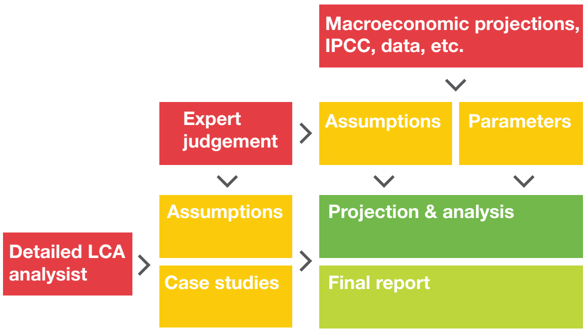


Figure 3: Top down and bottom up inputs to analysis

---

[8] See Expert Meeting agenda and list of participants in Apendix 1

[9] See Expert Meeting agenda and list of participants in Apendix 2

4. Assessing the opportunities

THE ANALYSIS OF current technological and market developments within the biotechnology sector, indicates that path-dependencies and technological learning, occurring within the industrial biotechnology sector, may be leveraged to pursue a path of lower GHG emissions over time, as illustrated in figure 4.

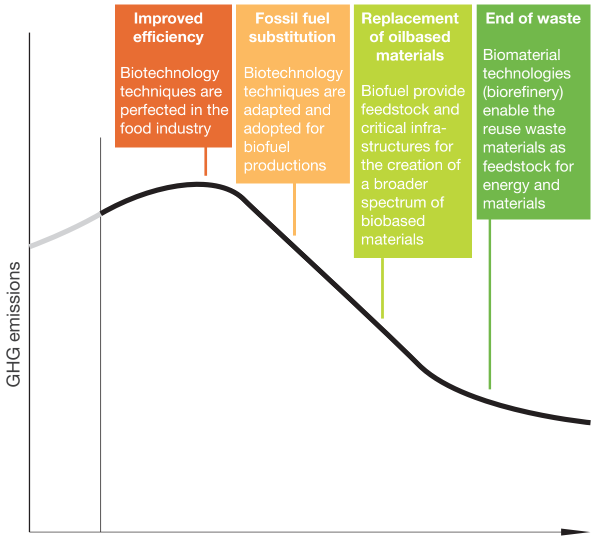


Figure 4: Industrial biotechnology's path to a low carbon economy

The sections that follow will better assess these dynamics, assessing the GHG emission reductions that can be achieved if the path described above is followed, analyzing the contribution of different clusters of biotechnology solutions and the linkages that can be created to generate low carbon feedbacks.

4.1 Biotechnologies to improve efficiency

Biotechnology techniques are currently used in a number of processes within traditional industries. The food industry was the first industry in which biological organisms were used in production processes and remains one of the major fields of biotechnology deployment. For this reason it will be discussed separately in section 4.1.1 below. The application of efficiency-enhancing biotechnology solutions in other traditional industries will be discussed in section 4.1.2

4.1.1 Biotechnologies to improve efficiency in the food industry

Food processing techniques, based on enzymes and yeasts, were discovered early in human history. Cultures such as those in Mesopotamia, Egypt, and India developed the brewing beer process, using malted grains (containing enzymes) to convert starch from grain into sugar before adding specific yeasts to produce beer. More recent cultures used the process of lactic acid fermentation, which allowed the fermentation and preservation of food. Fermentation was also used to produce leavened bread[10].

By and large the basic processes discovered by early civilizations are still the basis of modern biotechnology application in the food industry: enzymes and yeasts are deployed for food processing following the identification and selection of organisms that best perform a desired function.

Biotechnology provides enzymes and yeasts that are widely deployed in food production processes. Many everyday food items can be produced thanks to the deployment of naturally occurring organisms and the services they provide in various stages of production.

Modern biotechnology applications in the food industry typically focus on increasing the quality of foods or the

---

[10] Wikipedia: Biotechnology http://en.wikipedia.org/wiki/Biotechnology#History accessed April 2009

efficiency of food production. The use of enzymes and yeasts in food production can therefore result in a more efficient use of natural resources and a reduced use of energy, either during the production stage, where the enzymes or yeast are usually deployed or, indirectly, in connected steps up and down the value chain. These improvements generally result in reductions in GHG emissions and a broad benefit for the environment.

Food product or process	Description of biotech solution	Main environmental and GHG benefits
Baking	Enzymes added during the baking process maintain the freshness of breads and other baked products for longer, reducing waste	Reduced waste, Reduced upstream emissions from farming and grain/flower transportation, More efficient production processes enabled
Cheese production	Enzymes can: increase curd coagulation, enabling a higher production of cheese with the same quantity of milk, reduce ripening time, increase products shelf life	Lower number of milk producing animals needed to satisfy the same human need, enabling a reduction of associated GHG emissions and a lower pressure on land, Reduced production related emissions, Reduced waste
Wine and fruit juice production	Enzymes can be added to: increase yields during juice extraction phase, enabling a higher production of wine or juices with the same quantity of grapes or fruits and reduce waste	Lower volume of grapes/fruits required to satisfy the same human needs, enabling a reduction in associated GHG emissions
Brewing and distilling	Enzymes can be used to: Supplement (or substitute) enzymes naturally present in malt, increase the release of fermentable sugars, increase filtration	Elimination of the GHG emissions associated to processes that are eliminated (e.g. malting in some cases), Reduction of GHG emissions associated to processes that are improved (e.g. filtration)
Oils and fats	Enzymes can be deployed in the refining processes (e.g. degumming) of vegetable oils and fats as an alternative to chemical processes	Elimination of the GHG emissions associated to the chemical processes substituted by enzymes
Meat and fish processing	Enzymes are used to enable a more efficient and complete extraction of food (proteins)	Reduced food waste, Lower number of animals needed to satisfy the same human need, enabling a reduction in associated GHG emissions and a reducing the pressure on land and fisheries
Swine and poultry raising	Enzymes are added to the feeds to improve their digestibility enabling animals to eat less without compromising their growth	Reduced need to produce feeds, leading to a reduction in associated GHG emissions and a lower pressure on land use

Table 4: Biotechnology applications in the food supply chain[11]

4.1.1.1 GHG emission reductions from industrial biotechnology in the food industry

A number of yeast- and enzyme-based applications have shown benefits in terms of increased efficiency and reduced environmental and GHG impact, as highlighted below.

Biotech solutions typically affect GHG emissions at various stages of a supply chain by replacing a single process (e.g. a chemical process), which consequently changes the associated upstream and downstream processes.

Life cycle techniques provide valuable tools for the assessment of the short-term impacts of biotechnology solutions, as they analyze and estimate the various relevant impacts occurring throughout supply chains as a consequence of the deployment of a biotechnology solution. The box below, for example, illustrates the life cycle impacts of enzymes used in baking, in particular focusing on the production of bread with extended shelf life, leading to reduced bread waste and bread production.

Process	GHG emission sources without enzyme use (larger bread production)	GHG emission sources with enzyme uses (smaller bread production)
Wheat farming	Production of additional wheat needed for bread making	Production of sugars for enzyme manufacturing
Milling	Production of energy needed for milling the additional wheat	Production of energy needed for enzyme production
Transport	Fuel needed to transport additional flower needed for bread making	Fuel needed to transport the enzymes used in bread making (added)
Baking	Energy used to bake additional bread	
Packaging	Production of packaging (e.g. polyethylene) needed for the additional bread produced	
Waste		Production of additional animal feed needed to replace the wasted bread that would otherwise be used
LCA impact	Estimated reduction in GHG emissions with the use of enzymes: • 54 t per million breads sold if the wasted bread is not used as animal feed, • 29 t per million breads sold if the wasted bread is used as animal feed	

Table 5: Life cycle impacts of enzyme use in baking – extended shelf life of bread – source Oxenbøll and Ernst (2007)

A number of LCA screenings have been undertaken to assess the GHG impact of a variety of enzymes currently on the market.

The table below summarizes some of the results of such analyses. Additional information, including bibliographic references can be found in the LCA screens provided in appendix 3.

---

[11] Table constructed with inputs from Novozymes and other industry executives who participated to the expert workshops organized during the project, coupled with analysis of web sides of Novozymes, DSM, CHR Hansen, Genencor/Danisco

Benefit of biotech solution	GHG emissions from enzyme production, transportation and use	GHG emissions from alternative to enzyme	GHG benefit per unit of output
Longer shelf life for bread			29 – 54 t CO_2 per million ton of bread
Increasing yield in mozzarella production			230 kg CO_2 per ton production
Improving extraction of grape juice for red wine production	0.06 kg CO_2e per ton of wine	120 kg CO_2e per ton of wine	120 kg CO_2e per ton of wine
Malt substitution in brewing	9.1 kg CO_2e per 100 l of beer	12.5 kg CO_2e per 100 l of beer	3.4 kg CO_2e per 100 l of beer.
Degumming in soy bean production			45 kgCO_2e per ton of soy oil
Improved meat processing	About 6.3 kg CO_2e per ton of living animal	About 260 kg CO_2e per ton of living animal	About 250 kg CO_2e per ton of living animal
Improved fish processing	100 kg CO_2e per ton of fish	180 kg CO_2e per ton of fish	80 kg CO_2e per ton of fish
Improved swine feed			20 kg CO_2 per ton of feed
Improved chicken feed			20 kg CO_2 per ton of feed

Table 6: Biotechnology applications in the food supply chain and GHG emissions

4.1.1.2 GHG emission reduction potential of industrial biotechnology applications in the food industry

The target market of different efficiency-enhancing industrial biotechnology solutions in the food industry varies significantly, as highlighted by the table below.The market penetration of efficiency-enhancing industrial biotechnology solutions in the food industry vary by type of application, reflecting different degrees of market maturity. In many markets, however, biotechnology applications cover a limited share of the potential market[9]. Opportunities for further growth in biotechnology use appear significant and such growth would be accompanied by a correspondent increase in the GHG emission reductions enabled by industrial biotechnology applications, as highlighted by figure 5.

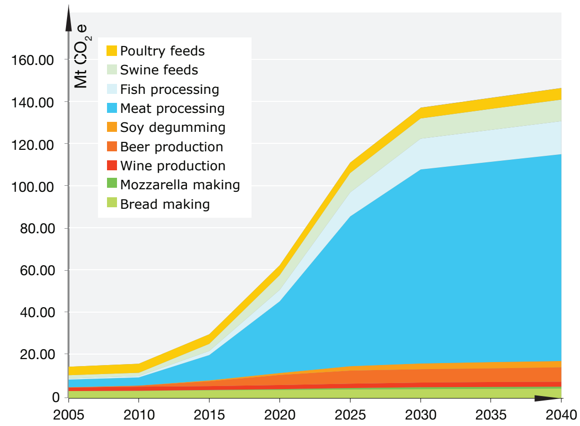


Figure 5: GHG emission reductions food industry.

Biotech solution	Key market driver	Estimated production worldwide 2010	Sources
Longer shelf life for bread	Bread production	498 Mln tons	Sustainability 3.0 LLC estimate, assuming 0.2 kg of average bread consumption per capita. Data on bread consumption derived from Aykut Gül et al.[12] Population data based on data from Population Division of the Department of Economic and Social Affairs of the United Nations
Increasing yield in mozzarella production	Mozzarella production	3 Mln tons	Unpublished market survey by Chr. Hansen A/S
Improving extraction of grape juice for red wine production	Red wine production	13.5 Bln liters	Murray Silverman et al. Competition in the Global Wine Industry: A U.S. Perspective available at http://online.sfsu.edu/~castaldi/bie/globcase.htm#table1 (May 2009)
Malt substitution in brewing	Beer production	164 bln liters	Joh. Barth & Sohn The Barth Report 2005/2006
Degumming in soy bean production	Vegetable oil production	52 Mln tons	FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org/site/636/DesktopDefault.aspx?PageID=636#ancor
Improved meat processing	Meat production	307 Mln tons	FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org (April 2009
Improved fish processing	Fish production	153 Mln tons	FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org (April 2009)
Improved swine feed	Number of swine grown	1.5 Bln	FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (April 2009)
Improved chicken feed	Number of chicken grown	53 Bln	FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (April 2009

Table 7: Biotech applications – food industry

The analysis assumes that industrial biotechnology applications in the food industry reach a 100% market penetration during the 2010 – 2030 period while key market drivers (bread production, mozzarella production, wine production, etc.) grow at a rate equivalent to the population growth rate. A growth rate for key market drivers that matches the population growth rate may be considered conservative, as it assumes no changes in consumptions patterns taking place as population, and income grow. On the other hand a 100% market penetration assumption may be optimistic as it implies advanced biotech solutions to be viable worldwide, even where traditional societies and economic systems are prevalent. Table 8 investigates the sensitivity to these two

---

12 Aykut Gül, Hilal Isik, Tufan Bal, Sertac Ozer BREAD CONSUMPTION AND WASTE OF HOUSEHOLDS IN URBAN AREA OF ADANA PROVINCE who, quoting Spencer B. 1974. Br. Baker 176 (44) 19-20, point out that bread consumption is between 41-303 kg/year per capita in the world.

13 Personal conversation with industry executives

variables by showing the total GHG emission reductions that would be achieved with more or less aggressive assumptions on growth rate and penetration.

		Growth rate of key drivers is equal to:	
		Population growth rate[14]	Population growth rate * 2
Biotech Penetration	50%	74 MtCO$_2$	94 MtCO$_2$
	100%	138 MtCO$_2$	173 MtCO$_2$

Table 8: Total 2030 GHG emission reductions in food industry – sensitivity analysis

From the analysis above it can be concluded that novel biotechnology solutions, based on natural processes, can improve several steps in the value chain by reducing food waste, increasing the efficiency in food processing, reduced emissions from farming and husbandry, reducing the need of natural resources to satisfy the same human needs.

Biotechnology is providing various solutions to the food industry to improve efficiency and reduce environmental and GHG impacts. Typically these solutions typically enable marginal improvements of existing processes

The products currently on the market reflect existing demands, market conditions and overarching policies. They therefore reflect the fact that the food industry has operated in a socio-economic environment that has not demanded strong reductions in GHG emissions. A stronger focus on identifying areas where biotechnology solutions could deliver greater GHG emission reductions may uncover significant opportunities. Table 9 illustrates some of the concepts the biotechnology industry could explore.

High GHG activity	Possible opportunity for biotech
Food waste by end consumers – e.g. estimated to reach 28% of purchases in some developed countries[15]	Biotech solutions to extend food durability or measure and communicate food quality so that food is not thrown away unnecessarily
High volume and/or Energy intensive processes in the food industry – e.g. corn milling uses 15% of the total energy used by the US food industry [16]	Biotech solutions that eliminate energy intensive processes or reduce the energy required
Methane emissions deriving from entheric fermentation by ruminants	Biobased feed additives that reduce or eliminate methane emissions
Methane emissions from manure, generating over 420 MtCO$_2$e per annum[17]	Biotech solutions to improve the effectiveness of biological digesters and increase their economic viability and use

Table 9: Examples of opportunity-areas for industrial biotechnology solutions in the food value chain

The concepts listed above are to be considered examples of possible opportunities for industrial biotechnology rather than an exhaustive or priority list. They serve, however, to illustrate a broad set of benefits that biotechnology use in the food industry could bring. If stronger incentives to achieve GHG emission reductions in the food sector were introduced, it is likely that the biotechnology industry would identify a variety of production processes with significant GHG footprints, where biotechnology applications could yield high GHG benefits.

4.1.2 Biotechnology in traditional industries

The experiences developed in the food industry for enzymatic and fermentation processes have found application in a number of traditional industries, typically with processes involving raw materials derived from living organism – e.g. pulp and paper, leather, textiles.

Enzymes and other biological organisms can perform, in few steps, using limited energy, and with little waste products, 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.

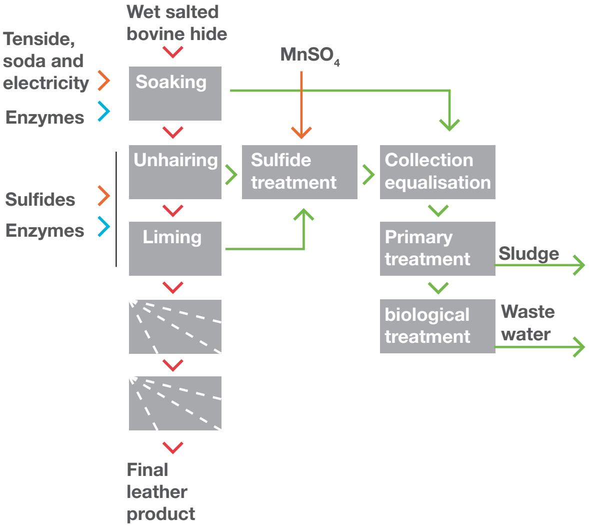


Figure 6: Efficiency enhancing Biotechnology/enzyme solution in the leather (tanning) industry – source Nielsen 2006

Red arrows indicate the movement of the hides through the tannery. Orange arrows indicate additional inputs when enzyme-assisted technology replaces conventional technology. Blue arrows indicate saved materials and energy and green arrows indicate changed material streams.

4.1.2.1 GHG emission reductions from efficiency gains enabled by industrial biotechnology in traditional industries

When used with these processes, biotechnology solutions deliver productivity improvements and help reduce the impact and GHG emissions associated with a (typically pre-existing) production process. Various applications are already in use, as described on next page.

With these applications, such as in the food industry, biotech can provide marginal improvements of existing processes within longer process flows. Although significant, therefore, opportunities to reduce GHG emissions are not dramatic.

When deployed downstream in value chains, efficiency gains can reverberate upstream with positive impact in term of resources use, GHG emission and pollution.

A number of LCA studies have been performed on biotechnology use in traditional sectors, as highlighted by table 12. Additional information can be found in LCA screens provided in appendix 3.

---

[14] Population growth rates derives from data from the Population Division of the Department of Economic and Social Affairs of the United Nations
[15] WRAP, 2008: The Food we Waste http://www.wrap.org.uk/retail/case_studies_research/report_the_food_we.html (May 2009)
[16] See http://www.aceee.org/pubs/ie981.htm (May 2009)
[17] IPCC 2007, Climate change 2007: Forth Assessment Report

Area of application	Description of biotech solution	Main GHG benefit
Pulp and paper industry	Lignin removal from pulp	Reduced use of bleaching chemical and associated emissions
Pulp and paper industry	Wood chip softening to facilitate refining during mechanical pulping	Reduced use of electricity for pulping
Textiles industry	Enzymatic removal of starches during desizing process	Elimination of chemical such as acids bases and oxidizing agents used to remove the starches Lower temperatures processes
Textiles industry	Enzymatic bleach clean up enables washes at lower temperatures using less water and chemicals	Reduced emissions from energy used to source and heat water
Leather production	Leather softening and unhairing	Elimination of chemicals such as sulfites, lime and surfactants
Laundry and dish washing	Enzymes added to detergents substitute surfactants and enable washing at lower temperatures	Reduced need for surfactants Reduced emissions form electricity (to heat water for washing) Reduced packaging

Table 10: Efficiency enhancing biotechnology applications in traditional industries

Benefit of biotech solution	GHG emissions from enzyme production	GHG emissions from alternative to enzyme	GHG benefit per unit of output
Bleaching of Pulp	40 kgCO$_2$ per kg pulp production	3 kgCO$_2$ per kg pulp production	37 kgCO$_2$ per kg kraft pulp production
Wood chip softening for mechanical pulping	negligible	150 kgCO$_2$ per kg ton pulp (varies significantly by country)	150 kgCO$_2$ per ton pulp
Desizing of textiles	45 kgCO$_2$ per ton fabric	910 kgCO$_2$ per ton fabric	870 kgCO$_2$ per ton fabric
Enzymatic bleach clean up			400 kg CO2 per ton fabric or yarn
Leather conditioning (softening and unhairing)	5 kgCO$_2$ per ton hide or skin	133 kgCO$_2$ per ton hide or skin from goat 194 kgCO2 per ton hide or skin from cattle	128 kgCO$_2$ per ton hide or skin from goat 189 kgCO$_2$ per ton hide or skin from cattle
Detergents	12 kg per ton of laundry	Per ton laundry: 55 kgCO$_2$ per for surfactant replacement 49 and 36 KgCO$_2$ from reduced electricity use in Europe and US respectively 1.4 kgCO$_2$ from packaging reduction	Per ton of laundry 93 kgCO$_2$ in Europe 80 kgCO$_2$ in USA 44 kgCO$_2$ in ROW
Dishwashers	5 g CO$_2$e per wash cycle	85 g CO$_2$e per wash cycle	80 g CO$_2$ per wash cycle

Table 11: Biotechnology applications in traditional industries and GHG emissions

4.1.2.2 GHG emission reduction potential from the industrial biotechnology applications in traditional industries

Like for the food industry the target market of efficiency-enhancing industrial biotechnology solutions vary significantly by type of application (see table 11).

Biotech solutions	Key marked driver	Estimated production worldwide 2010	Sources
Bleaching of Pulp	Pulp production	117 Mln tons	Fischer (2007): Fischer database. Fisher International Inc. www.fisheri.com
Wood chip softening for mechanical pulping	Thermo-mechanical pulp production	23 Mln tons	Fischer (2007): Fischer database. Fisher International Inc. www.fisheri.com
Desizing of textiles	Fabrics market	23 Mln tons	Market assessment from Novozymes
Enzymatic bleach clean up	Textiles subject to bleach clean up	7 Mln tons	Market assessment from Novozymes
Leather conditioning (softening and unhairing)	Production of goat and cattle skin	7 Mln tons	FAOSTAT (2009): FAOSTAT database http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (April 2009) [18]
Detergents	Laundry washed	234 Mln tons laundry	Sustainability 3.0 LLC estimate
Dishwashers	Dish washing	75 Mln wash cycles	Sustainability 3.0 LLC estimate

Table 12: Biotech applications – other industries

Market penetration of efficiency-enhancing industrial biotechnology solutions is still medium/low, presenting significant opportunities for further growth[19]. If industrial biotechnology applications in traditional industries were to reach a 100% market penetration during the 2010 – 2030 period, for example, GHG emission reductions would climb from about 15 MtCO$_2$e in 2010 to about 65 MtCO$_2$e by 2030.

---

[18] Data in FAOSTAT have been multiplied by 0.8 to convert data for 'hides' into data for 'wet salted hides'. See Nielsen 2006

[19] Source: personal conversation with industry executives

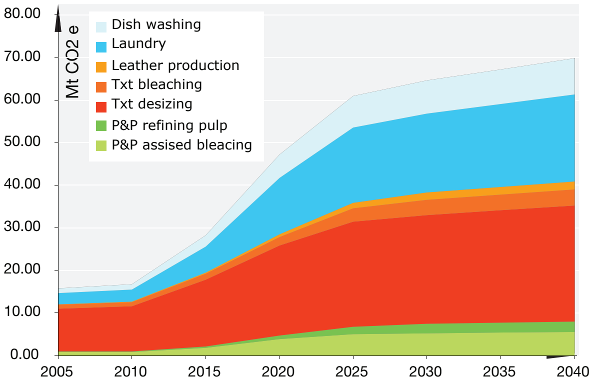


Figure 7: GHG emission reduction potential from industrial biotechnology use in traditional industries

Figure 7 assumes that key market drivers (pulp production, textile production, etc.) grow at a rate equivalent to the population growth rate[20]. Table 13 investigates the sensitivity to these two variables by showing the total GHG emission reductions that would be achieved with more or less aggressive assumptions on growth rate and penetration.

Growth rate of key drivers is equal to…			
		Population growth rate	Population growth rate * 2
Biotech Penetration	50%	32 $MtCO_2$	39 $MtCO_2$
	100%	65 $MtCO_2$	77 $MtCO_2$

Table 13: Total 2030 GHG emission reductions in traditional industries – sensitivity analysis

4.1.3 Dynamic impacts – low and high carbon feedbacks

The deployment of biotechnologies in the food and other traditional industries to improve process efficiency has a number of dynamic impacts that can lead to higher or lower GHG emissions over time, as illustrated by figure 8.

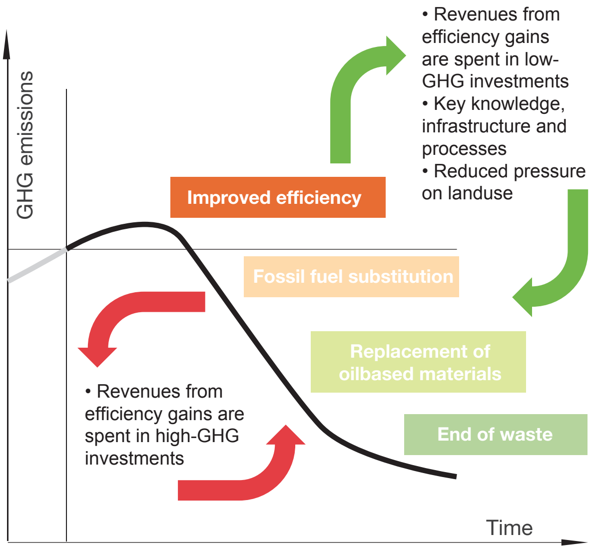


Figure 8: Dynamic impacts of biotech use as efficiency-enabler in traditional industries

A first dynamic impact derives from the increased resources (income for suppliers or consumers) that more efficient processes make available. If such resources are invested in activities that further decrease GHG emissions, low carbon feedbacks can be achieved (top right in the figure). This may for example be the case of investments in process efficiency, energy efficiency or renewable energy projects. On the other hand, if the additional resources are spent on products or activities associated with high GHG emissions, high-carbon feedbacks would be achieved (bottom left in the figure). With the increased resources made available by efficiency gains the following of a low- or a high carbon path will be largely dependent on the overall socio-economic environment in which the additional resources are deployed, including the incentives and constraint that derive from relevant public policies.

Two other dynamic impacts from the deployment of efficiency-enhancing biotechnology solutions appear to have clear positive impacts in terms of enabling low-carbon feedbacks.

The development of biotechnologies in the food industry, and in other traditional industries, has been critical, and is critical, for the development of knowledge, infrastructure and processes that can be applied in other sectors, where they can generate significant GHG emission reductions. The development of these biotech applications in the food industry, therefore, produces 'positive externalities' that can generate GHG emission reductions in broader sections of the economy.

A final, relevant, benefit is that improvements in the food industry and in other industries that use agricultural products as feedstock (e.g. pulp and paper, leather production, textiles production) enable the use of a smaller amount of land to deliver the same benefits. Thus, additional land becomes available for other bio-based applications that enable reductions in GHG emissions, such as the ones that will be discussed in the next two sections.

4.2 Biotechnology to produce biofuels and displace fossil fuels

The feedstock processing and fermentation expertise and technologies developed in traditional industries were critical components in the creation of biotechnology solutions for the transformation of agricultural feedstock (or other biological feedstock) into biofuels.

4.2.1 Biotechnologically produced biofuels

Today the main use of biotechnology in the biofuels sector is for bioethanol production. Emerging technologies, currently in R&D or demonstration phases, will enable the use of biotechnology solutions also for the production of other biofuels such as butanol and biodiesel[21].

4.2.1.1 Bioethanol

Bioethanol is produced by the fermentation of sugars from biomass. With crops with high sugar contents, such as sugar cane or sugar beet, ethanol can be produced by direct fermentation With crops that are higher in sugar-contain ing-materials such as cellulose or starch, (e.g grains of including maize or, wheat and cassava) or byproducts that contain cellulose (e.g stovers of maize), an additional step is needed to convert cellulose or starch in sugar (see figure 9)[22]

As shown in table 14 a variety of crops can potentially be used as feedstock for ethanol production. All production facilities

---

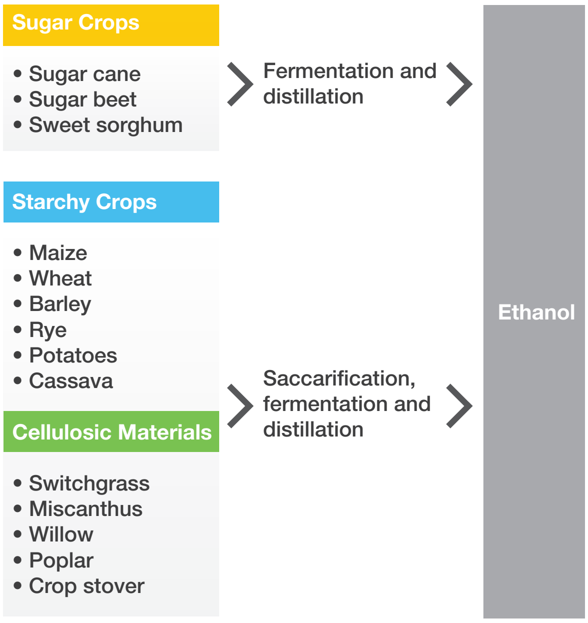
[20] For use of laundry and dish washing machines the assumption is that the growth in non-OECD countries is twice the growth rate of the population

[21] Although based on a biological feedstock, currently the production of biodiesel is not based on a biological process as it relies on esterification processes in which an alcohol reacts with the feedstock and extracts the oils that are then used for fuel

[22] This and the following paragraphs are based on FAO (2008) 'The state of food and agriculture – 2008, Biofuels: prospects risks and opportunities'

currently in commercial operation utilize sugar crops or starch crops to produce what are referred to as ‘first generation’ bio-ethanol. The largest share of ethanol production is obtained from sugar cane and maize, which are the crops most utilized by the world largest producers of ethanol: Brazil and USA.

Figure 9: Ethanol production



New technologies, currently under development and in pre-commercial trial, can extract sugars, and subsequently ethanol, from lignocellulosic biomass. As cellulosic biomass is the most abundant biological material on earth, these ‘second generation’ biofuel technologies would enable the use of a much broader volume and variety of feedstocks, largely expanding the potential for biofuel use.

Sources of cellulosic biomass
Cellulosic waste, including
waste products from agriculture (straw, stalks, leaves)
waste products from forestry
wastes generated from processing (nut shells, sugar cane bagasse, sawdust)
organic parts of municipal waste
Dedicated energy crops including
short-rotation woody crops (willow, hybrid potpalrs, eucalyptus)
grassy species (miscanthus, switchgrass, reed canary grass)

Table 14: Sources of cellulosic biomass

The production of ethanol from cellulosic feedstocks requires, as a first step, the conversion of cellulose or hemicellulose components in the biomass into sugars. Performing this step cost-effectively is a critical requirement for the commercial development of cellulosic ethanol. As cellulosic materials are more resistant than starches and therefore more difficult to break down, the development of innovative enzymatic processes has been an area of intense research for the biotechnology industry, and for the governments that have pursued biofuel opportunities more aggressively (e.g. the USA). The intense effort that took place between 2000 and 2009 has enabled significant process improvements enabling a dramatic reduction in the cost of enzymes per unit of fuel (see figures 10 and 11).

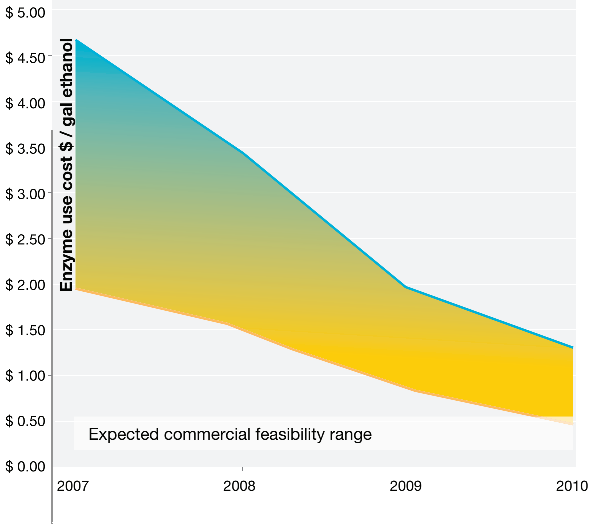


Figure 10: Enzymes for cellulose conversion – enzyme costs per gallon ethanol[23]

As a result of these improvements the total production cost of cellulosic ethanol has decreased significantly and has now reached levels that near market readiness.

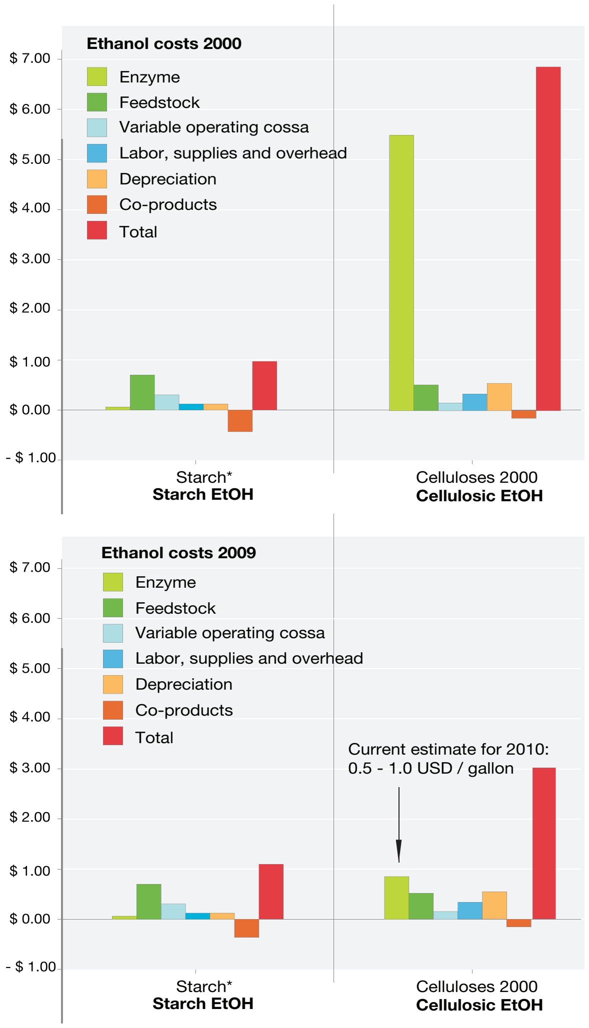


Figure 11: Cost comparison of starch and cellulosic ethanol 2000 vs. 2009[24]

---

[23] Source Karen Oxenbøll, Novozymes, ”The GHG abatement potential for biofuels” slide presentation presented during the first expert meeting, April 2009

[24] Source Karen Oxenbøll, Novozymes, ”The GHG abatement potential for biofuels” slide presentation presented during the first expert meeting, April 2009 analysis based on data from “Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks”, NREL/TP-580-28893 joint USDA, NREL study released in October 2000.

4.2.1.2 Biobutanol

Biobutanol can be produced by the fermentation of biomass, utilizing the same feedstock used for ethanol production: sugar beets, sugar cane, corn grain, wheat and cassava as well as agricultural byproducts, such as straw and corn stalks. The process uses the bacterium Clostridium acetobutylicum, also known as the Weizmann organism, first used in 1916 for the production of acetone[25] from starch[26 27].

The technology and market developments taking place in the ethanol industry, and the perceived pent up demand for biofuels, have brought increasing attention to biobutanol production, aided by the considerations that existing bioethanol plants can cost-effectively be retrofitted for biobutanol production, since the difference from ethanol production is primarily in the fermentation of the feedstock and minor changes in distillation[28].

Although butanol produced from biological feedstock is not yet competitive in the market, current technological and market developments may add this fuel to the portfolio of biotechnologically produced biofuels available to reduce GHG emissions.

4.2.1.3 Biodiesel

Although based on a biological feedstock, currently the production of biodiesel is not based on a biological process as it relies on extraction and esterification processes in which an alcohol reacts with the feedstock and extracts the oils that are then used for fuel[29]. Typical feedstock for biodiesel production includes oil-rich plants (see figure 12). Biodiesel can also be produced from waste vegetable oil, animal fat and algae.

Figure 12: Biodiesel crops and production[30]

The current worldwide production of biodiesel is about a quarter of the worldwide ethanol production (see table 15) and both are growing rapidly, in response of aggressive public policies promoting biofuels (see section 4.2.2 below).

Country/ Country grouping	Ethanol (Million litres) / (Mtoe)	Biodiesel (Million litres) / (Mtoe)	Total (Million litres) / (Mtoe)
Brazil	19 000 /10.44	227/0.17	19 277/10.60
Canada	1000/ 0.55	97/0.07	1097/0.62
China	1 840 /1.01	114/0.08	1 954/1.09
India	400/0.22	45/0.03	445/0.25
Indonesia	0/0.00	409/0.30	409/0.30
Malaysia	0/0.00	330/0.24	330/0.24
United States of America	26 500/14.55	1 688/1.25	28 188/15.80
European Union	2 253/1.24	6109/4.52	8 361/5.76
Others	1 017/0.56	1 186/0.88	2 203/1.44
World	52 009/28.57	10 204/7.56	62 213/36.12

Table 15: Biofuel production by country, 2007[31]

Biotechnological techniques for producing biodiesel are currently not economically viable but are being actively researched.

4.2.2 GHG benefits per unit of production

The transportation sector is far the largest user of biofuels. The analysis undertaken in this section will therefore focus on the potential GHG impacts of biofuels in this sector.

Using biofuels in the transportation sector to substitute traditional fossil fuels, such as petrol, can typically reduce GHG emissions per km travelled. The total level of benefit achieved, on a life cycle basis, depends on a number of factors including: type of feedstock used, land productivity, farming practices (more or less intensive in terms of fertilizer use or mechanization), distance travelled by feedstock or fuel, emissions associated with the energy utilized in the transformation processes, production of co-products and their use. Figure 13, based on ethanol production, illustrates the differences that may occur when different feedstock or production processes are used. Ethanol today shows the GHG emissions associated with a typical ethanol production process using corn as feedstock and the average amount of energy (MJ inputs per MJ fuel) for traction, fertilizers, transportation and processing of corn. Overall this process emits 81 GHG equivalents in the atmosphere, 13 fewer than the generation of an equivalent amount energy with gasoline. If the production of ethanol is CO_2 intensive, however, with corn being transported over long distances and being manufactured in biorefineries using coal derived energy, then the life cycle emissions associated with ethanol production could exceed the emissions produced by the production of an equivalent amount of energy from gasoline. Finally, if cellulosic ethanol were produced, with processes that utilize a larger share of plant biomass as feedstock, then the GHG emission, as compared with gasoline related emissions, would be significantly lower, 11 vs. 94 GHG equivalents per MJ of energy[32].

---

[25] The main use of acetone was in the production of Cordite, a gunpowder replacement
[26] Butanol was a by-product of this fermentation (twice as much butanol was produced), along with recoverable amounts of H2, acetic, lactic and propionic
[27] Source: Wikipedia accessed June 2009
[28] Source: BP/Dupont FactSheet on biobutanol
[29] Source: Wikipedia, accessed June 2009
[30] Source FAO 2008,
[31] Source FAO 2008, based on F.O. Licht, 2007 and data from the OECD-FAO AfLink-Cosimo database
[32] Source: Farrell et al 2006

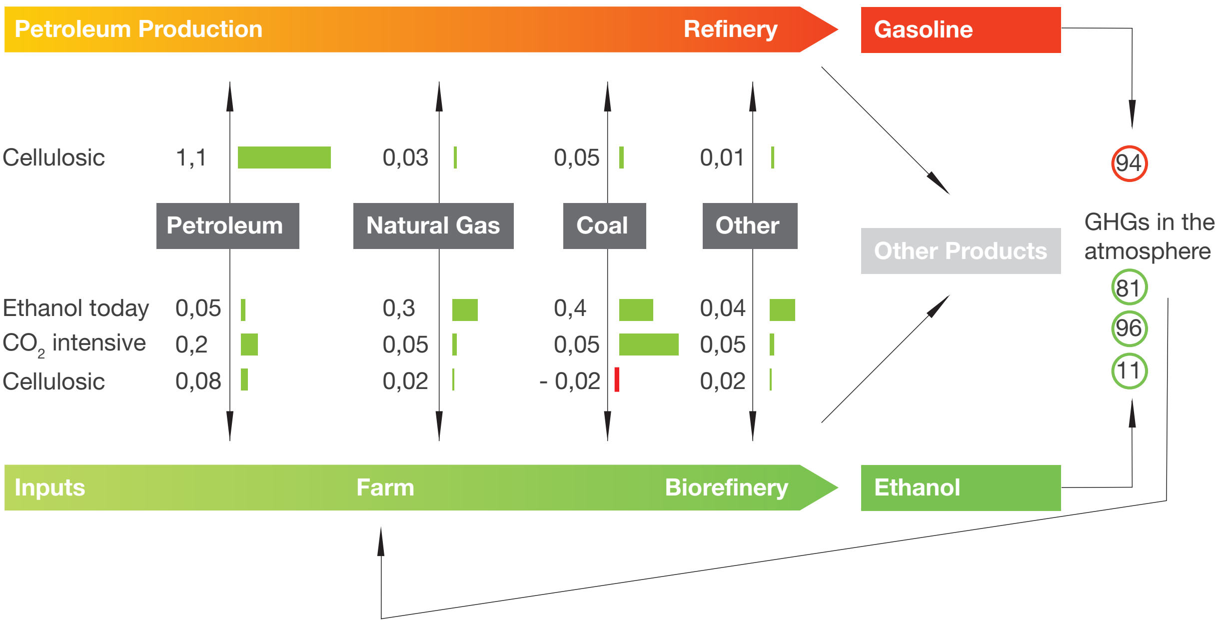


Figure 13: Life cycle GHG emissions of ethanol production[33]

Improvements in existing technologies also affect the GHG emissions of biofuels. The above mentioned study by Farrell, for example, builds on US data from 2001-03. However, the majority of current bioethanol capacity in US was build after 2003, typically deploying more energy efficient technologies than the ones assessed by Farrell. Thus a more recent review[34] estimated that the GHG emission from 1 MJ of bioethanol amounts to 40-50 GHG equivalents as opposed to 81 reported by Farrell.

Significant variability affects all the factors driving the overall GHG impact of ethanol production processes. Moreover, when life cycle analyses are performed in practice, data availability and data uncertainty further compound the variance. Consequently, the various analyses that have assessed the GHG impacts and benefits of biofuels have produced a broad range of estimates. The figure below shows the average emission reductions estimated for various biofuels, highlighting the degree of variability in the estimates. Whereas for some biofuels, e.g. ethanol from sugar cane, the degree of variability is low and the GHG impact is clearly positive, for other biofuels, namely ethanol from grain, the degree of variability in the estimates is high and the estimated GHG impact, although generally positive, at times can be negative (as was also highlighted by Figure 114). Finally, with emerging technologies, such as ethanol from cellulosic feedstock, the GHG benefits are clearly positive, but the degree of variability in the estimates is high, reflecting the lower maturity in the technologies involved and the various feedstock pathways that are still being experimented. This variability points to the need to carry out assessments on specific processes and specific data. It also illustrates the potential for improvement of old as well as new processes. The estimates provided below do not take into full account the potential direct and indirect impact of biofuel production on land use. As changes in land use can a significant impact on GHG emissions, land related issues will be discussed separately in this chapter and in the chapters that follow.

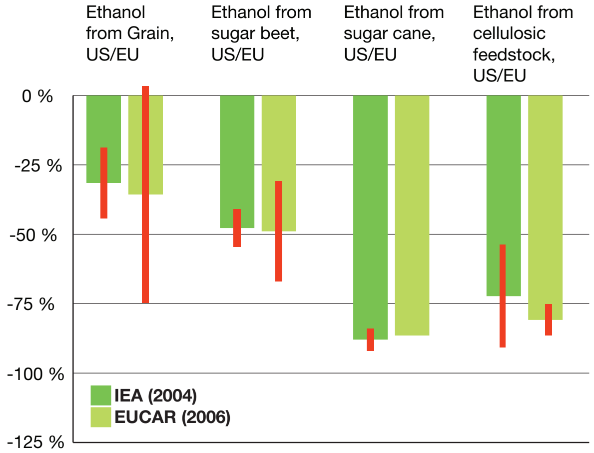


Figure 14: Reduction in GHG emissions of selected biofuels relative to fossil fuels average estimated (bars) and variances (red lines)[35]

---

[33] Source: Farrell et al 2006

[34] Source: Liska A. (2008) Improvement in Life Cycle Energy Efficicency and Greenhouse Gas Emissions of corn ethanol, Journal of Industrial Ecology

[35] Source: IPCC 2007, Climate change 2007: Forth Assessment Report, working group 3, chapter 5

4.2.3 GHG emission reductions from biofuels

Over the last decades, GHG emissions from transportation have been steadily increasing, in both developed and developing countries, and are projected to further increase in the future. IEA and WBCSD, for example, project that worldwide transportation emissions will climb to 8 $GtCO_2e$ by 2030 and over 12 $GtCO_2e$ by 2050 (see figure 15).

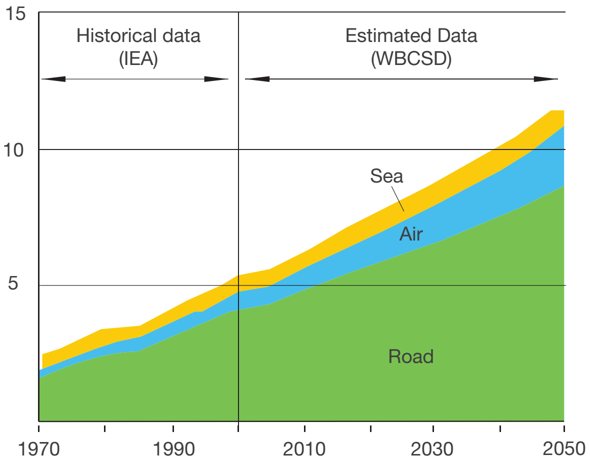


Figure 15: Historical and projected GHG emissions from the transportation sector[36]

As bioethanol, and other biofuels, can reduce the amount of GHGs emitted per km travelled they could provide a useful instrument to mitigate such increase.

The market penetration of biofuels in the transportation sector depends on a variety of factors, including price of feedstock, price of petrol, technological development and public policies providing incentives (or disincentives) for biofuel utilization.

Public policies have played a critical role in the recent growth in the biofuel markets. Much of the biofuel growth in the market is driven by supporting policies and measures, which often involve the establishment of some targets for biofuel use, typically in terms of percent of biofuel use compared with total fuel consumption (See table 16)[37].

Country / Country grouping	Targets
Brazil	Mandatory blend of 20-25 percent anhydrous ethanol with petrol; minimum blending of 3 percent (B5) by end of 2010
Canada	5 percent renewable content in petrol by 2010 and 2 percent renewable content in diesel fuel by 2012
China	15 percent of transport energy needs through use of biofuels by 2020
France	5.75 by 2008, 7 percent by 2010, 10 percent by 2015 (V), 10 percent by 2020 (M= EU target)
Germany	6.75 percent by 2010, set to rise to 8 percent by 2015, 10 percent by 2020 (M= EU target)
India	Proposed blending mandates of 5-10 percent for ethanol and 20 percent for biodiesel
Italy	5.75 percent by 2010 (M) 10 percent by 2020 (M= EU target)
Japan	500 000 kilolitres, as converted to crudeoil, by 2010 (V)
Mexico	Targets under consideration
Russian Federation	No targets
South Africa	Up to 8 percent by 2006 (V) (10 percent target under consideration)
United Kingdom	5 percent biofuels by 2010 (M), 10 percent by 2020 (M= EU target)
United States of America	9 billion gallons by 2008, rising to 36 billion by 2022 (M). Of the 36 billion gallons, 21 billions to be from advanced biofuels (of which 16 billion from cellulosic biofuels)
European Union	10 percent by 2020 (M proposed by EU Commission in January 2008)

Table 16: Examples of Biofuel targets by country[38]
(M) = Mandatory. V= Volontary

Existing policies have resulted in significant incentives, on a per liter basis, for biofuel production and utilization (see table below).

OECD economy	Ethanol	Biodiesel
	Average (US$/litre) (1) / Variable (US$/litre) (1)	Average (US$/litre) (1) / Variable (US$/litre) (1)
United States of America (2)	0,28 / Federal: 0.15 States: 0.00-0.26	0,55 / Federal: 0.26 States: 0.00-0.26
European Union (3)	1,00 / 0.00-0.90	0,70 / 0.00-0.50
Canada (4)	0,40 / Federal: up to 0.10 Provinces: 0.00-0.20	0,20 / Federal: up to 0.20 Provinces: 0.00-0.14
Australia (5)	0,36 / 0.32	0,35 / 0.32
Switzerland (6)	0,60 / 0.62	1,00 / 0.60-2.00

Table 17: Example of biofuel support – approximate average and variable rates of support per liter of biofuel in selected OECD countries[339]
Notes:
1. Values (exept in the case of United States of America and Australia) are rounded to the nearest US$0.10
2. Lower bound of reported range. Some payments are budget-limited.
3. Refers to support provided by Member States
4. Provisional estimates includes incentives introduced on April 8 2008.
5.Data refer to the fiscal year being 1 July 2006. Payments are not budget-limited.
6. Range for biodiesel depends on source and type of feedstock. Some numbers are limited to a fixed number of litres.

As a result of the public policies currently in place, biofuels have been gaining market share also when market prices for petrol and feedstock would have impeded their profitable commercialization. An example of these dynamics is illustrated by figure 16, which compares breakeven points for corn-based ethanol, with and without subsidies, in the US. The figure highlights that, thanks to the incentives, bioethanol production was profitable for most of the 2003-2008 period, whereas, without incentives, profitability would have been achieved only in March 2006 and October 2007.

---

36 Source IEA 2006 World Energy Outlook also discussed in WBCSD 2004 Mobility 2030 meeting the challenge to sustainability
37 For a description of various policies affecting the biofules value chain see appendix 4
38 Source: GBEP, 2007, updated with information from the United States Department of Agriculture (USDA, 2008a), the Renewable Fuels Association (RFA, 2008) and written communication from the EU Commission and Professor Ricardo Abramovay, University of São Paulo, Brazil, cited by FAO 2008
39 Source Steenblik, 2007 "Biofules – at what cost? Government support for ethanol and biodiesel in selected OECD countries p 39, cited by FAO 2008

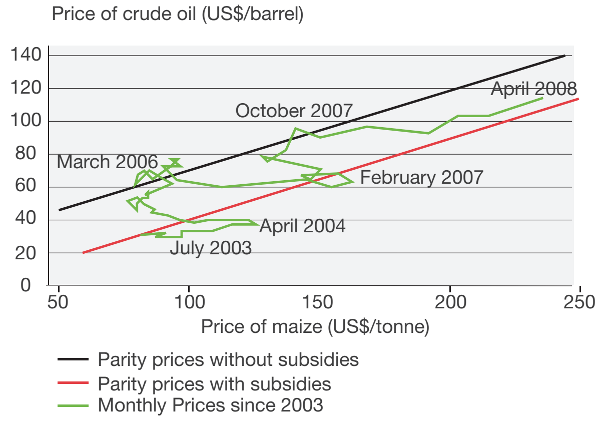


Figure 16: Maiz and crude oil breakeven prices and observed prices, 2003 – 2008

As the cost structures of different feedstocks vary, due to the different productivity of geographic regions, the breakeven of biofuels produced with different feedstocks in terms of prices for crude oil also varies (see figure 17).

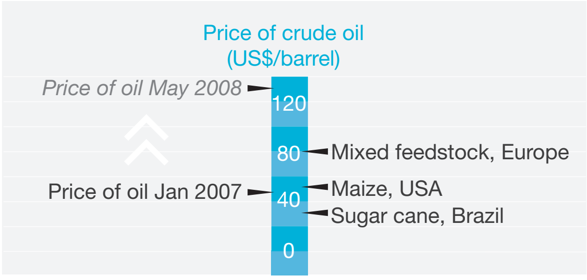


Figure 17: Breakeven prices for crude oil and selected feedstocks in 2005[40]

The variables affecting the take up of biofuels , and their impact in terms of GHG emissions, are interlinked and may produce competing effects that may vary significantly over time. For example an increasing use of biofuels enables economies of scale, learning by doing and technological development, which decrease production costs. On the other hand it also increases demand for feedstock, which may lead to cost increases and, if high volumes are achieved, may cause a reduction in petrol prices, which may reduce the relative advantage of biofuels over petrol. Public policies can dramatically change the economics of biofuels, driving demand up. However, aggressive policies could also lead to a backlash if their costs are perceived to be too high or if unintended and undesired impacts are caused, such as an increase in food prices.

Several different scenarios could therefore unfold for biotechnologically produced biofuels. As part of this project the following scenarios were estimated.

Scenario name	Description
Targe 5, fast tech	1. Oil prices remain low compared to feedstock prices 2. Public policies supporting biofuels are not aggressive – 5% target in OECD countries 3. Development and dissemination of second generation biofuels is fast
Target 20, slow tech	4.Oil prices are high compared to feedstock prices 5. (if 4 does not hold) Public policies supporting biofuels are more aggressive – 20% target in OECD countries 6. Development and dissemination of second generation biofuels is slow
Target 20, fast tech	7.Oil prices are high compared to feedstock prices 8. (if 7 does not hold) Public policies supporting biofuels are aggressive – 20% target in OECD countries 9. Development and dissemination of second generation biofuels is fast

Table 18: Biofuels – scenarios analysed

The analysis was undertaken using as a basis for calculations the transportation model developed by WBCSD-IEA/SMP[41], which includes projections for car ownership rates, vehicle kilometers, vehicle efficiency, fuel mix and GHG emission factors. The WBCSD-IEA/SMP model and assumptions were used as baseline for the analysis and to estimate the potential impact of biofuels on the emissions associated with road transportation. Some of the key scenarios assumptions are summarize in Appendix 5.

Figure 18 shows the GHG emission reductions projected in each of the scenarios analysed, as compared to the GHG emissions that would occur in a situation in which no biofuels were used.

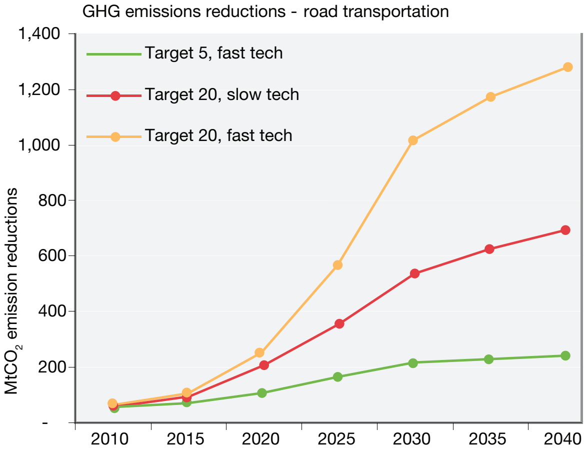


Figure 18: GHG emission reduction potential of biofuels in alternative scenarios

The analysis highlights that whereas biofuel use (as a preportion of total fuels) exercises the greater drive on emission reductions, a faster development of second generation biofuels can also play a significant role, almost doubling the emission reductions that can be achieved, given a similar market penetration for biofuels.

Given the WBCSD-IEA/SMP baseline, the substitution of about 20% of fuels with biofuels has the potential to deliver about 1 billion tons of emission reductions by 2030, if second generation biofuels were rapidly adopted. Without a rapid

---

[40] FAO 2008 The state of food and agriculture Biofuels: prospects, risks and opportunities
[41] IEA/SMP transportation model http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc

introduction of second generation biofuels, on the other hand, the emission reductions potential would be almost 50% lower, at 530 $MtCO_2e$.

This result should be considered in the context of the projected growth of GHG emissions from transportation. Figre 19 compares business as usual emissions with the emissions that would be achieved in each of the scenarios analysed in this section.

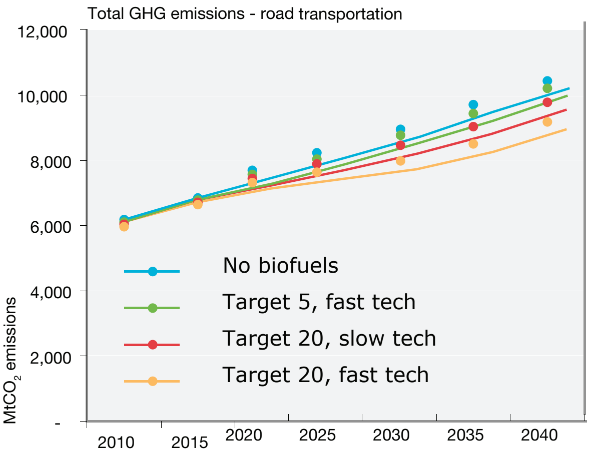


Figure 19: Total GHG emission from road transportation with alternative biofuel scenarios

As highlighted by the figure above, the GHG benefits potentially deriving from biofuels in the three scenarios analysed in this section would be more than compensated by the overall growth in traffic volumes, and the associated GHG emissions. Biofuels appear therefore to provide a useful tool that can be part of the portfolio of instruments available to slow the growth of emissions from the transportation sector. Such tool, however, should be integrated by policies and strategies that address the fundamental issues associated to transportation related emissions, for example by promoting:

- Technologies and behaviors that enable dematerialization processes (moving bits instead of people and goods)
- More advanced and efficient systems of public transportation
- Smart urban planning
- Addition transportation technologies that increase efficiency and reduce GHG emissions

In principle, aggressive public policies could pursue market penetration rates for biofuels that are higher than the ones assumed in the three scenarios discussed in this section. Such goals, however, would have to consider the possible limitations deriving from land availability, and from the potential impacts that biofuel production could have on the production (and prices) of food crops. These issues will be discussed in more detail in the following section and in section 4.5.

4.2.4 Land use impacts

The land needed to produce different biofuels can vary substantially depending on the feedstock used and the geographic area where the feedstock is produced, reflecting variations in land productivity, climate and farming technologies. Table 19 summarizes some of the literature on crop and biofuel yields for different feedstocks and geographic areas.

Crop	Global / National estimates	Biofuel	Crop yield (tonnes/ ha)	Convrsion efficiency (litres/ tonne)	Biofuel yield (litres/ ha)
Sugar beet	Global	Ethanol	46.0	110	5060
Sugar cane	Global	Ethanol	65.0	70	4550
Cassava	Global	Ethanol	12.0	180	2070
Maize	Global	Ethanol	4.9	400	1960
Rice	Global	Ethanol	4.2	430	1806
Wheat	Global	Ethanol	2.8	340	952
Sorghum	Global	Ethanol	1.3	380	494
Sugar cane	Brazil	Ethanol	73.5	74,5	5476
Sugar cane	India	Ethanol	60.7	74,5	4522
Oil Palm	Malaysia	Biodiesel	20.6	230	4736
Oil Palm	Indonesia	Biodiesel	17.8	230	4092
Maize	United States of America	Ethanol	9.4	399	3751
Maize	China	Ethanol	5.0	399	1995
Cassava	Brazil	Ethanol	13.6	137	1863
Cassava	Nigeria	Ethanol	10.8	137	1480
Soybean	United States of America	Biodiesel	2.7	205	552
Soybean	Brazil	Biodiesel	2.4	205	491

Table 19: Biofuel yields for different feedstocks and countries[42]

On the basis of these analyses the following assumptions were made on feedstock production per hectare of land.

	2010	2015	2020	2025	2030	2035	2045
Starch based ethanol	1960	1960	1960	1960	1960	1960	1960
Sugar cane ethanol	4550	4550	4550	4550	4550	4550	4550
Lignocellulosic ethanol	4550	4550	4550	4550	4550	4550	4550
FAME biodiesel	1960	1960	1960	1960	1960	1960	1960
Biotech biodiesel	1960	1960	1960	1960	1960	1960	1960

Table 20: Biofuels production per ha of land (liters per ha)

Figure 20 illustrates the land that would be required, give the assumptions of Table 20, to deliver the production levels, and

---

[42] Source Rajagopal et al 2007 Review of environmental, economic and policy aspects or biofuels World Bank Policy Research Working Paper N 44 cited by FAO 2008

GHG emission reductions, projected for different scenarios.

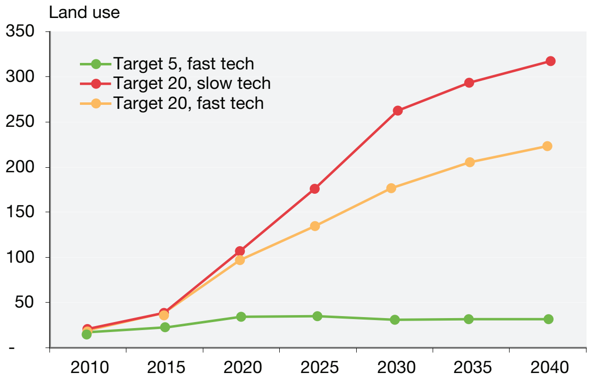


Figure 20: Land uses for biofuels in different scenarios

The analysis highlights the important land use benefits associated with the adoption of second generation biofuels. With the deployment of second generation biofuels the supply of about 5% of the global road-transport fuels would be possible with about 34 million hectares. With a 20% rate of biofuels utilization second generation biofuels would save about 83 million hectares by 2030 and 97 million hectares by 2040 as compared to a scenario where a larger share of first generation biofuels are used. Figure 21 illustrates the land required in year 2030 to produce biofuels under different scenarios. For comparison, the figure estimating the land requirement for the production of 100% of road fuels is also included.

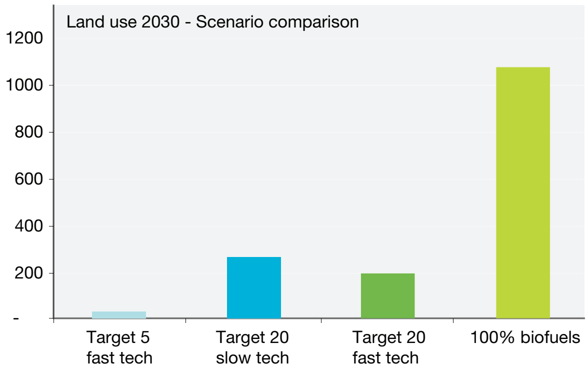


Figure 21: Land use in 2030 different biofuel scenarios

These variables will be further discussed in section 4.5, where a more comprehensive discussion of the linkages between biotechnologies and land use is undertaken.

4.2.5 Dynamic impacts – low and high carbon feedbacks

In addition to the more direct impacts on GHG emissions such as the ones highlighted above, the development of innovative biotechnologies for biofuel production, and fossil fuel substitution, may generate a number of additional dynamic impacts, as highlighted by figure 22.

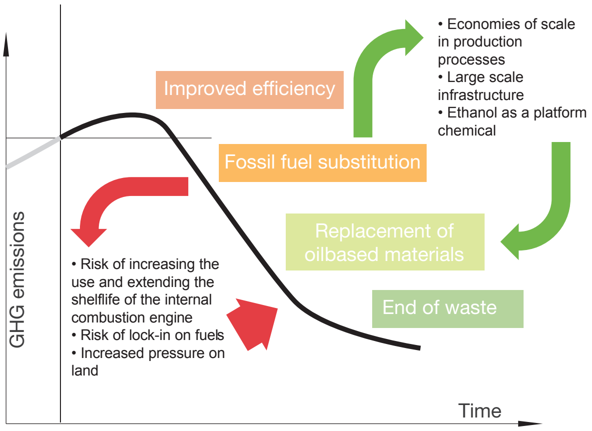


Figure 22: Dynamic impact of biotechnology use in biofuel production

The biotechnology-enabled production of biofuels in large volumes may play a critical role in unlocking economies of scale in the industrial biotechnology field while also driving the creation of the critical logistical infrastructures needed to collect the feedstock, distribute the biofuels, or any other end-product, and handle secondary products generated from biofuel production.

These factors are enablers for a wider use of biotechnologies in the creation of a variety of different biobased, low-GHG-emission compounds, which can replace petrochemical products[43].

Furthermore, ethanol production enables a biobased sugar platform chemical, which can be used as feedstock for the production a variety of other compounds. The ability to produce large volumes of bioethanol efficiently is therefore an additional enabler for the production of biotechnologically produced biobased material[44].

The achievement of low-carbon feedbacks with biofuels may be undermined, at least partially, by countervailing dynamic impacts that may lead to slower reductions of GHG over time. An initial risk is that the switch from fossil fuels to biofuels with privately owned vehicles, powered by internal combustion engines, may generate a feeling that progress is made. This may lead to complacency and to a slower dissemination of the more radical innovations, which are needed in order to dramatically reduce the GHG emissions associated with transportation. A second risk is that the strong focus on biofuels, typical of current policies, may lead to the creation of highly specialized biotechnology solutions (in terms of feedstocks used, enzymes, fermentation processes, separation processes, etc.) that are not applicable in the production of other biobased materials, thus reducing or delaying their take up. Moreover, as investment resources are finite, strong investment in biofuels may crowd out investments in broad-spectrum-biorefinery projects, which would be critical for the production of a large variety of the low-GHG biobased materials discussed in the following section.

Finally, the increased demand for biofuels will lead to increased demand for feedstock, as discussed in section 4.2.4. This will generate incentives to devote more land to feedstock production, with the risk of releasing in the atmosphere significant amounts of carbon stored in vegetation and soils.

---

[43] The role and potential for biobased materials will be further discussed in section 4.3
[44] Personal conversation with industry association representatives and other industry experts

Overall biofuels can play a critical role at mitigating emissions growth in the short term while helping developing the technologies and infrastructures that can support the establishment of a stronger market for biobased materials. For the long term, however, biobased materials have a greater promise to deliver GHG emission reductions and low carbon feedback, as it will discussed in the next two sections.

4.3 Biotechnology to replace crude oil in the production of everyday materials and products

As discussed in section 4.2, increasing investments in the biofuel sector, responding to existing incentives, facilitate the construction of the physical infrastructure, and associated technologies, needed for the cost-effective collection and utilization of natural feedstock and for their processing, which could be used for the production of a great variety of biobased materials.

Moreover, advancements in industrial biotechnology, such as increased productivity and yields of fermentation processes, are creating broader opportunities for the production of materials from natural feedstock[45].

More specifically, industrial biotechnology, taking advantage of biological processes and using biological materials, can produce a variety of molecules that are currently produced using hydrocarbons as feedstock or that have chemical/physical properties that make them market substitutes for petro-chemical materials. This provides a significant opportunity to substitute petrochemical products with biobased products that are produced biotechnologically.

Biotechnology processes are particularly suited for the transformation of natural feedstock into the necessary sugars and building blocks for the production of secondary chemicals and end-products, as highlighted by the two figures below. The figures show a flow chart with an example of petro-chemical-based processes to produce many of the end-products of everyday use (Figure 23) and alternative processes (flow chart) with bio-based feedstock and biotechnology processes (Figure 24).

Upstream processes, such as the ones targeted by industrial biotechnology, can be energy intensive and use large volumes of oil feedstock. The substitution of petro-chemical processes with biobased-biotechnology processes can therefore produce significant benefits in terms of GHG emission reductions. The EU-funded BREW project[46], on the basis of independent analysis and expert input from industry representatives, identified a number of biobased materials, produced biotechnologically, which offer considerable opportunities to achieve significant emission reductions, due to their large production volumes and GHG benefit per ton of production. Table 21, which is based on the work undertaken in the BREW project, provides a list of such biobased chemicals, their petrochemical counterpart and includes examples of product use. The potential offered by these biobased materials will be further analysed in this section.

---

[45] Herman B. G. et al. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change

[46] Patel et. al. (2006) The BREW Project: Medium and long term opportunities and risks of biological production of bulk chemicals from renewable resources – the potential for white biotechnology

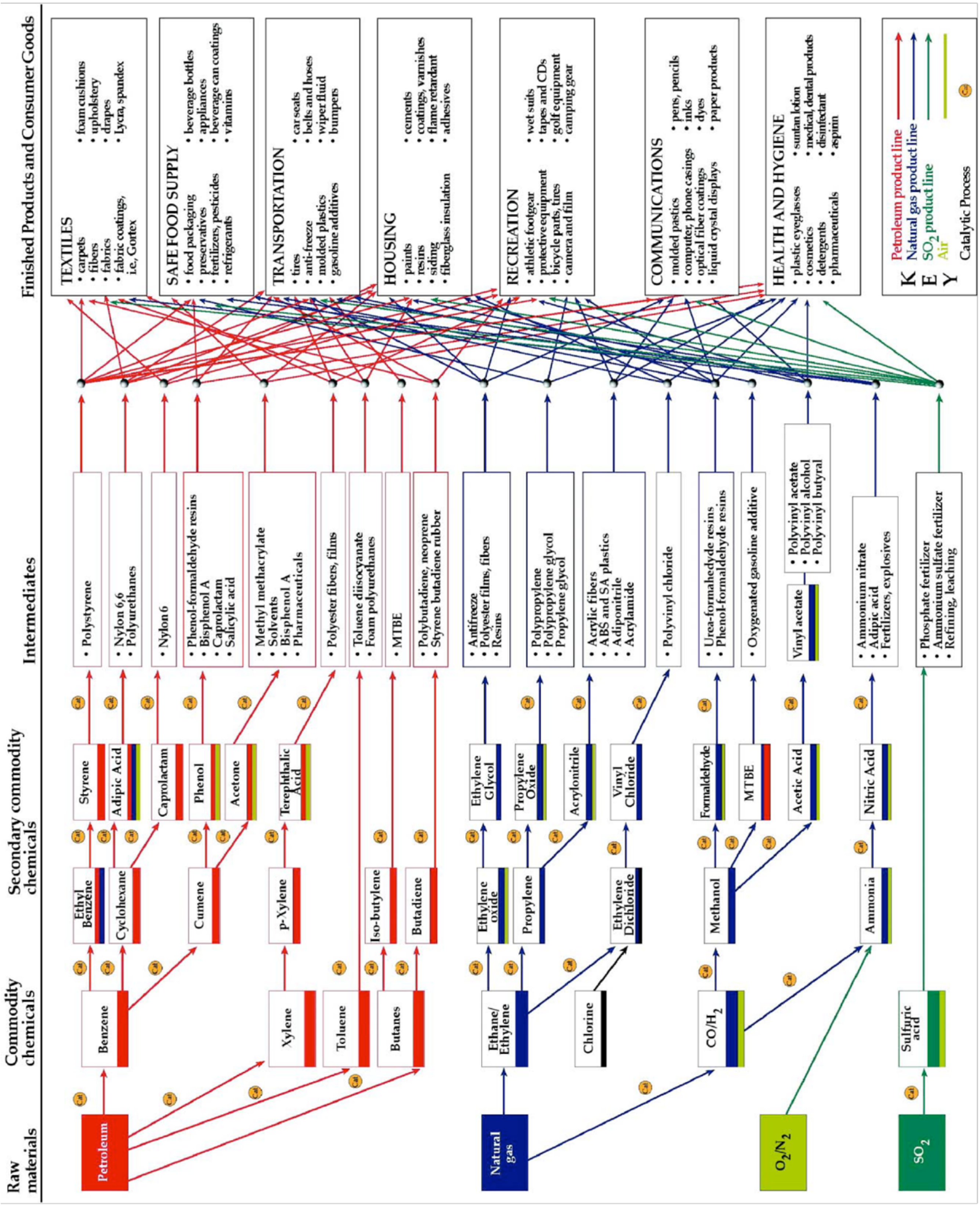


Figure 23: An example of a flow-chart for products from oil-based feedstock[47]

[47] Source NREL 2004 The value added chemicals from biomass volume 1: Results of screening for potential candidates from sugars and synthesis gas

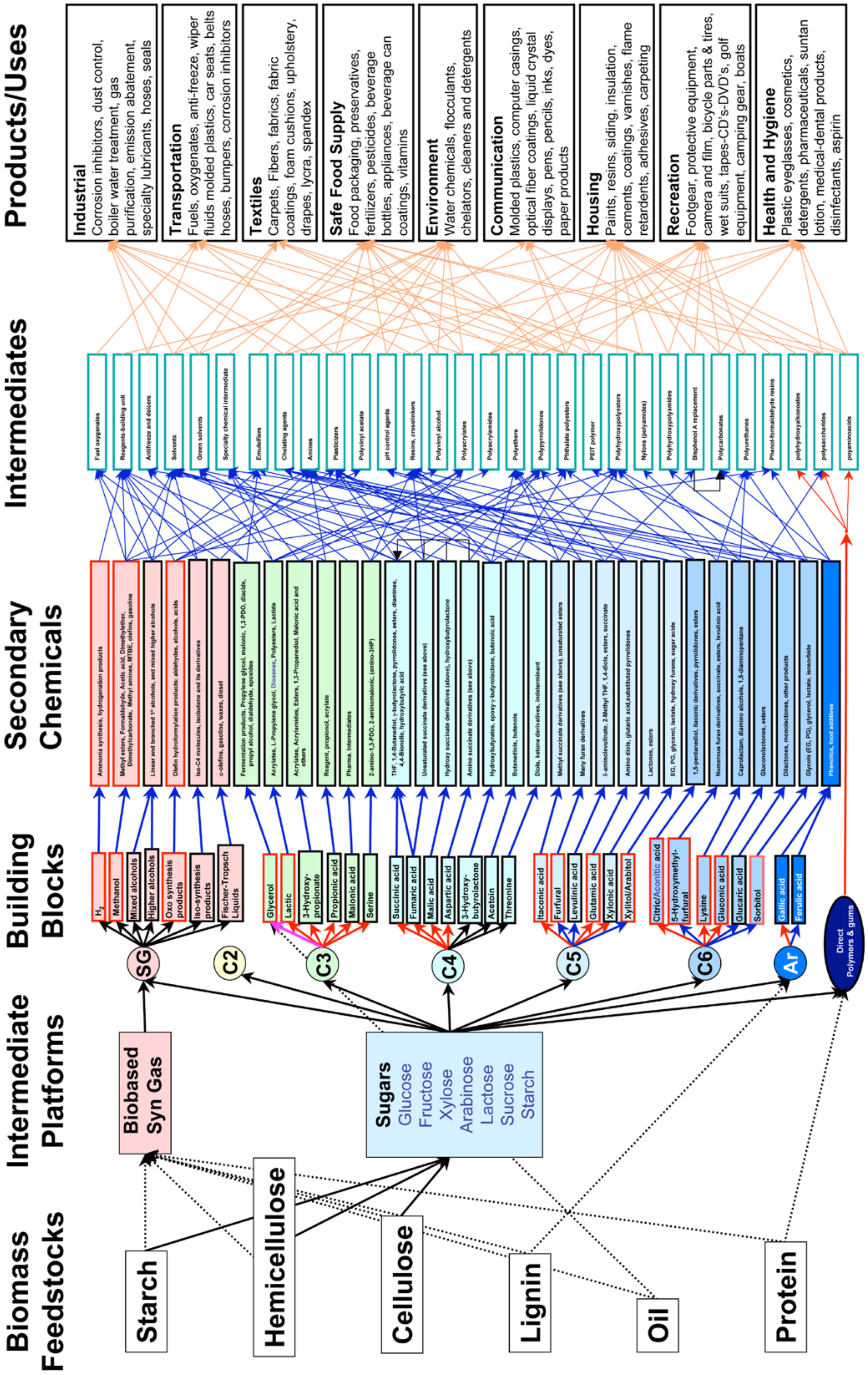


Figure 26: Analogous Model of a biobased product flow-chart for biomass feedstocks[48]

[48] Source NREL 2004 The value added chemicals from biomass volume 1: Results of screening for potential candidates from sugars and synthesis gas

Biobased Chemical	Reference Petrochemical	Application examples of the reference petrochemical
PHA (plyhydroxyalkaonates)	HDPE (high density poly-ethylene) [49]	• Containers: laundry detergent bottles, milk jugs, fuel tanks for vehicles, refillable bottles • Plastic lumber, folding tables and folding chairs • Plastic bags • Chemical resistant piping systems and containers • Piping systems for geothermal heat transfer, natural gas distribution, water distribution • Corrosion protection for steel pipelines • Caox cables inner insulators • Cell liners in sanitary landfills
PTT (poly-trimethylene terephtalate) From 1,3 propanediol	PTT, Nylon 6	• Carpet fibers • Bristles for toothbrushes, sutures for surgery, etc. • Hosiery, knitted garments, etc. • Threads, ropes, filaments, nets, tire cords, etc. • Classical guitar strings
PLA (poly lactic acid)	PET (polyethylene terephtalate) PS (polystyrene)	• Synthetic fibers (polyester) • Bottles, plastic cutlery, food containers (frozen dinners) • Carrier for magnetic tapes • CD cases, smoke detectors, license plates • Building insulation (Polystyrene foams) • Packaging peanuts
Ethyl lactate	Ethyl lactate	• Pharmaceutical preparations, and fragrances • Food additives • Solvent for nitrocellulose, cellulose acetate and cellulose ether
Ethylene	Ethylene	• Raw material for the production of: Polyethylene: film applications for packaging carrier bags, trash liners Ethylene oxide: key raw material for the production of surfactants and detergents Ethylene dichloride: used to produce vinyl chloride monomer (VCM, chloroethene), the major precursor for PVC production Anesthetic agent (in an 85% ethylene/15% O2 ratio) • Fruit ripening agent
Succinic acid	Maleic anhydride	• Flavoring agent for food and beverages • Inermediate for dyes, perfumes, lacquers, photographic chemicals, alkyd resins, plasticizer, letal treatment chemical, vehicle water cooling systems, coatings • Drugs – sedatives, antispasmer, antiplegm, antiphogistic, contraception and cancer-curing
Adipic acid	Adipic acid	• Precursor for the production of nylon • Monomer for production of Polyurethane • Its esters are plasticizers, especially in PVC. • Small but significant amounts of adipic acid are used as a food ingredient as a flavorant and gelling aid
Acetic acid	Acetic acid	Chemical reagent for the production of: •Vinyl acetate monomer - polymerized to: polyvinyl acetate, used in adhesives (wood glue, paper production, bookbinding, handcrafted works) other polymers, applied in paints and adhesive • Acetic anhydride • Ester production
n-butanol	n-butanol	• Fuels • Solvents (paint thinner) • Hydraulic and brake fluids • Perfumes

Table 21: Biobased chemicals and their petrochemical reference[50]

4.3.1 GHG emission reduction enabled by biobased material produced biotechnologically

As highlighted by the figures and tables above, materials produced utilizing biological processes can potentially substitute high GHG petrochemicals used in a variety of everyday products.

Life cycle analyses of biobased materials produced with industrial biotechnology highlight that significant reductions of both energy use and GHG emissions are possible in most cases with current technologies. The environmental impact of the processes typically depends on yield productivity and concentrations achieved in the fermentation stage[51].

With emerging technologies and the ability to utilize a broader set of feedstock the GHG emission reductions achievable can further increase, as highlighted by the figure below, which compares the average GHG savings of industrial biotechnology products with their petrochemical equivalents (see figure 25).

---

[49] Either the polyethylene can be replaced by the biobased polymer PHA or the ethylene needed for polyethylene production can be produced from biobased ethanol

[50] Sources Dornburg et. Al (2007) and Wikipedia entries on the chemicals listed in the table

[51] See Herman et. Al. (2007) Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change

[52] Source Herman et al. (2007)

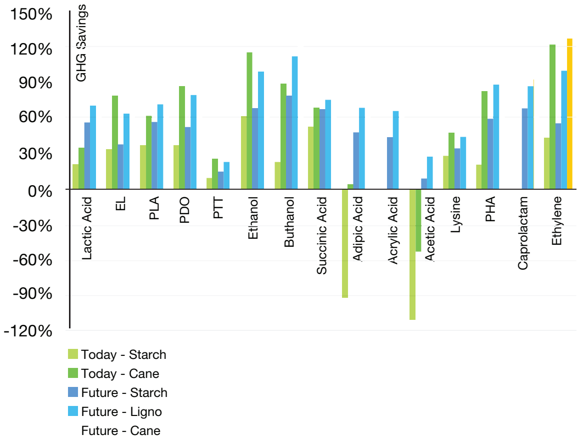


Figure 25: GHG emission savings of biotechnology based products vs. petrochemical equivalent- – Bars represent the arithmetic mean across several industrial biotechnology production routes for the same chemical[52]

Herman et al (2007) estimated that if chemicals produced by industrial biotechnology were to fully replace their petrochemical counterparts the GHG emission reductions achieved would top 500 MtCO$_2$e, based on 1999/2000 production levels. The future savings potential would be even higher if lignocellulosic or sugar cane were used as feedstock, with total savings of 820 MtCO$_2$e and 1,030 MtCO$_2$e respectively.

Currently, however, the market share of biotechnology-produced biobased chemicals is relatively small. Biobased polymers, for example, account for less then 0.1% of polymer production[53]. Accurate data for bulk chemicals is not available, but the current market share of biotechnologically produced biobased compounds is also estimated to be below 1%[54].

Several factors drive the market penetration of biobased materials produced biotechnologically, including:

- The substitution potential for biobased materials versus their petro-chemical counter part
- The status of technological development of different production processes
- The relative prices of feedstock and crude oil
- Relevant policies and measures, which can affect all the factors above

The potential market penetration of biobased materials depends on the substitution potential that biobased materials have compared with their petrochemical counterpart. Some biotechnology processes create the same molecules that are produced petro-chemically. In these instances the substitution could, in principle, be complete. Other biotechnological processes lead to the creation of different compounds that have similar functionalities than to petro-chemical products (e.g. PLA is functionally similar to PET). In this case the biotechnology-derived molecules may not be suitable for a complete substitution of their petro-chemical counterpart. The table below, based on an analysis by the BREW team, illustrates the biobased material substitution potential, as identified in Table 21.

Biobased material	Reference petrochemical	Max technical substitution of petrochemical
Acetic acid	Acetic acid	100%
Acrylic acid	Acrylic acid	100%
Adipic acid	Adipic acid	100%
Butanol	Butanol	100%
Caprolactam	Caprolactam	100%
Ethyl lactate	Ethyl lactate	100%
Ethylene	Ethylene	100%
Lysine	Lysine	100%
Succininc acid	Maleic Anhydride	85%
1,3-propanediol (PDO, PTT precursor)	1,3-propanediol	100%
Polyhydroxyalkanoates (PHA)	PE	25%
Polylactic acid (PLA)	PET	90%

Table 22: Technical substitution of petrochemicals with biobased materials

A second factor affecting the penetration of biobased materials is the level of technological development for the associated production processes. Whereas for some of the biobased material production facilities have been created for market production, other production technologies are at a trial phase or undergoing R&D. Performances and cost levels associated to the latter would have to be reduced before market entry and before market share can be gained.

A final factor driving the take up of biobased materials produced biotechnologically is the relative price of feedstocks compared to the price of crude oil. As with ethanol and other biofuels (see section 4.2.3), many biobased materials would struggle to compete in the market with low oil prices and high feedstock prices, even if production technologies are already established. Conversely, high oil prices, or high GHG emission prices, would make a larger number of biobased materials market-competitive. For example, the table below, from the BREW report, estimates which biobased materials are commercially viable at different sugar prices, assuming a oil price of $ 25 per barrel[55].

Sugar price level	Economically viable products	
	Today	Future
70 Euro/t	Ethanol, Pdo, Succinic acid (possibly), PTT	Ethanol, PDO, PTT, Butanol (ABE), Acetic acid (possibly), Acrylic acid, Succinic acid, Adipic acid, Caprolactam, PHA (possibly), Ethylene (possibly), Ethyl acetate (possibly), PLA (possibly), PTT
135 Euro/t	Ethanol (possibly), PDO, PTT	Ethanol, PDO, PTT, Butanol (ABE), Acrylic acid, Succinic acid, Adipic acid (possibly), Caprolactam (possibly), PTT
200 Euro/t	Ethanol (possibly, PDO, PTT (possibly)	Ethanol (possibly), PDO, Butanol (ABE, possibly), Succinic acid, Adipic acid (possibly), Caprolactam (possibly), PTT
400 Euro/t		PDO, Succinic acid (possibly), PTT (possibly)

Table 23: Economic viability of biobased products[56]

---

[53] European data. Source European Commission JRC, ETSO, IPTS, Techno-economic feasibility of Large-scale Production of Bio-based Polymers in Europe EUR 22103 EN

[54] Source: private conversations with industry experts

[55] See BREW report section 3.4.4 for further details on these dynamics

[56] Source: BREW report - the analysis assumes oil prices of US$ 25 per barrel

The market penetration of biobased materials with high potential for GHG emission reductions, and the GHG impact achieved, may therefore vary substantially depending on market developments and technology dynamics in the industrial biotechnology and petro-chemical fields, which may be significantly affected by public sector policies and business strategies.

In evaluating the potential for GHG emission reductions deriving from biotechnologically produced biobased materials the following scenarios were analysed.

Scenario	Description
Slow growth	• Relatively low growth in the reference petro-chemical markets • Relatively high oil prices and low feedstock prices - Biobased materials produced biotechnologically enter the market rapidly • Relatively quick migration to (second generation) technologies that increase GHG benefits
Slow take up	• Higher growth in the reference petrochemicals markets • Relatively low oil prices and high feedstock prices - Biobased materials produced biotechnologically enter the market slowly • Relatively slow migration to (second generation) technologies that increase GHG benefits
Fast growth and take up	• Higher growth in the reference petrochemicals markets • Relatively higher oil prices and lower feedstock prices - Biobased materials produced biotechnologically enter the market rapidly • Relatively quick migration to (second generation) technologies that increase GHG benefits

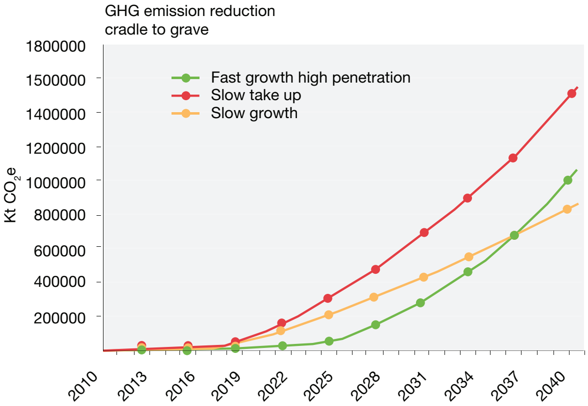
Table 24: Biobased materials produced biotechnologically - scenarios

Some of the key input variables used in the analyses are summarized below:

	slow growth	slow take up	fast growth and take up
Growth rate petro-chemical per annum	1.5%	3.0%	3.0%
Year market entry late entrants biomaterials	2018	2025	2018
Year market entry medium entrants biomaterials	2015	2020	2015
Year market entry early entrants biomaterials	2012	2015	2012
Better starch based technologies, market entry year	2010	2010	2010
Year required for full migration to better starch based technologies	10	10	10
Years to reach max substitution	30	30	30
Lignocellulose technologies market entry year	2012	2020	2012
Max lignocellulose penetration	90.0%	90.0%	90.0%
Years to reach max for lignocellulose penetration	15	20	15

Table 25: Key assumptions used in the projections of GHG emission reductions deriving from the biotechnological production of biobased materials

The following graphs compare the projected impact of the three scenarios under consideration. Figure 26, below, shows the GHG emission reductions occurring in each scenario in comparison with the emissions that would have occurred if all production would have continued using petrochemical feedstocks.



GHG emission reductions $MtCO_2$			
	2020	2030	2040
fast growth and take up	116	668	1,552
slow take up	16	282	1,058
slow growth	87	430	863

Figure 26: GHG emission reductions achievable in different scenarios

The analysis highlights that significant benefits in terms of GHG emissions can be achieved by utilizing industrial biotechnologies in the production of biobased materials. Both the growth of the reference market and the speed of introduction of second generation technologies (able to use lignocellulosic feedstocks) play a significant role in affecting the emission reductions achieved. Figure 27, below, shows the different projected emission paths as they compare to the baseline petrochemical path. The comparison shows that a slow uptake of more efficient technologies, coupled with growing markets for reference petrochemicals, results in a path of increasing GHG emissions that only peaks after 2030 (top right). Conversely a faster introduction of more GHG efficient technologies would lead to a substantial flattening of GHG emissions between years 2020 and 2030, followed by an absolute decline in emission (top and bottom left). A slow growth in reference petrochemical markets, coupled with a fast take up of new technologies, would on the other hand lead to 2040 emissions that are about 26% below 2010 values (bottom right).

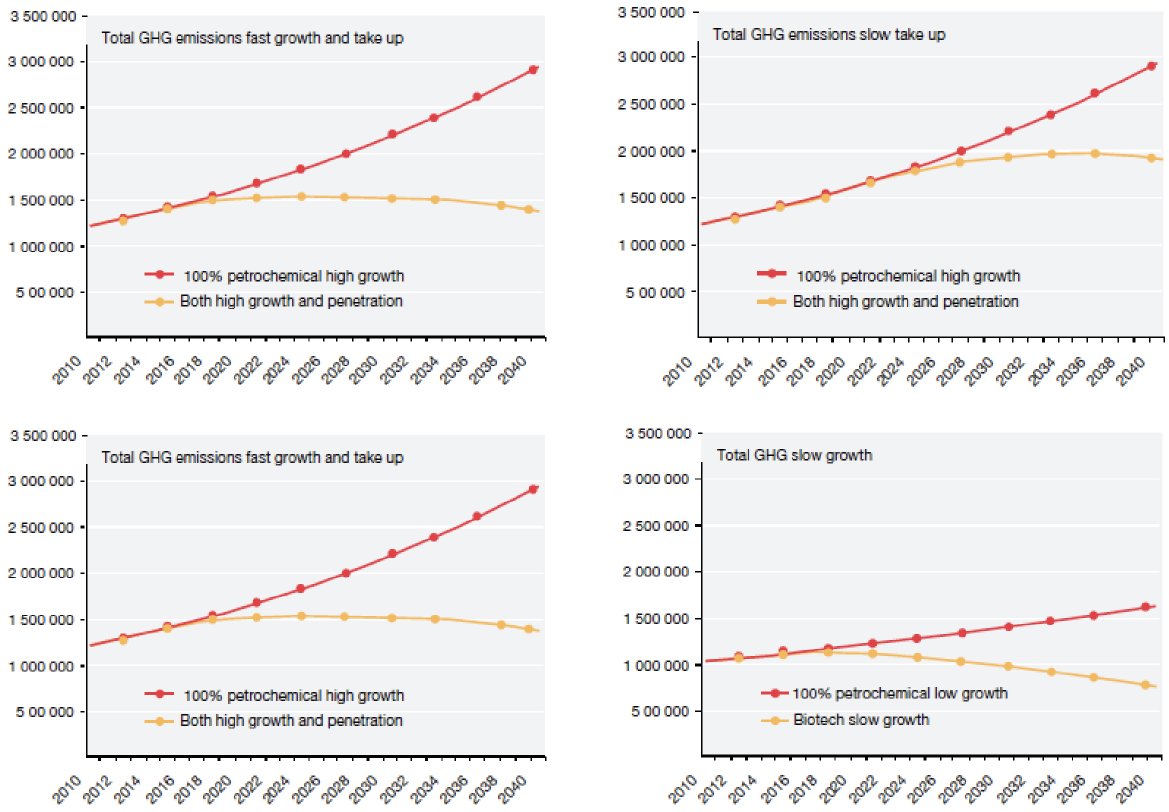


Figure 27: Comparison of baseline GHG emissions and actual emissions achieved under different scenarios – cradle to grave

The analysis undertaken highlights that there are significant opportunities to reduce GHG emissions by using industrial biotechnology solutions in the production of products that now rely on petrochemicals.

The benefits achieved are sensitive to several variables, including the speed of growth of the reference market, the competitiveness of the biobased products (which is dependent upon technological development and relative prices of sugars and petrol) and the speed of introduction of (lignocellulosic) technologies that are more beneficial from a GHG perspective.

Finally, the analyses above are based on cradle to grave emission factors based on the conservative assumption that, when they reach their end of life, products are incinerated with no energy recovery. The GHG emission reductions achieved would therefore be different if alternative solutions are utilized to handle products at the end of their life cycle. This will be discussed in further detail in section 4.4.

4.3.2 Land use impacts

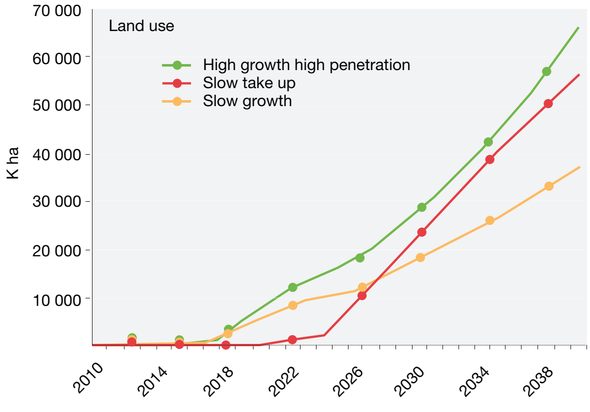
Estimates of the land potentially required to produce biobased materials biotechnologically are still subject to a significant uncertainty, due to the constant development of new technologies, the broad variety of feedstock, available farming technologies, and differences in land productivity and climate between geographic regions.

Despite these uncertainties, some estimates have been made, such as the ones reported in table 26, which provide a useful reference.

	Land required depending on feedstock used		
	Maize starch long term	Lignocellulosic	Sugar cane
	ha/t	ha/t	ha/t
Acetic acid	0.14	0.06	0.15
Acrylic acid	0.18	0.07	0.18
Adipic acid	0.27	0.11	0.28
Caprolactam	0.33	0.13	0.34
Ethyl lactate	0.16	0.08	0.16
Ethylene	0.45	0.18	0.46
Lysine	0.36	0.15	0.37
Succininc acid	0.13	0.07	0.14
1,3-propanediol	0.22	0.09	0.22
Polyhydroxyalkanoates	0.39	0.16	0.4
Polylactic acid	0.18	0.07	0.18

Table 26: Land needed for the biotechnological production of biobased materials – Source Patel et al 2006

Based on the market and technology projections illustrated in section 4.3.1 figure 28 provides an estimate of the potential impact on land use.



Land use (million hectares)

	2020	2030	2040
Fast growth and take up	7.7	28.2	66
Slow take up	0.8	23	56
Slow growth	4.2	18	37

Figure 28: Land used biotech for biobased materials

4.3.3 Dynamic impacts – high and low carbon feedbacks

The creation and dissemination of industrial biotechnology plants creates the conditions to achieve economies of scale and scope, which can improve learning and the perfection of relevant biotechnological techniques. When critical mass is achieved, network economies are also possible, as the use of a broad variety of natural feedstocks by a significant number of production facilities, removes cultural barriers and provides incentives to feedstock suppliers and infrastructure providers to supply their goods and services to industrial biotechnology facilities, while enticing a larger number of end-users to source biobased materials.

The use of biotechnology in the production of biobased materials can lead to the establishment of a significant number of biorefineries, able to produce a large portfolio of end products. If such biorefineries are built to be versatile and able to process a large variety of feedstock, they can be a critical building block for the creation of production systems that dramatically reduce waste, as all materials produced, used and disposed of can re-enter the production cycle through biorefineries. Such closed loop systems can deliver significant benefits in terms of GHG emission reductions (see section 4.4, below for a further discussion of this topic) and biorefineries can therefore be an enabler for low carbon feedbacks.

However, the construction of versatile biorefineries, able to transform waste into valuable raw materials, is not a necessary outcome of the biotechnological production of biobased materials. Specialized biorefineries, processing purely agricultural feedstrock, could also be an outcome, if the broader market and policy environment was to steer industrial biotechnology investments towards such a solution. This may limit the GHG benefits achieved with industrial biotechnology and increase the demand to use more land for feedstock production, with the risk of releasing the carbon currently sequestered in natural ecosystems into the atmosphere (see figure 29).

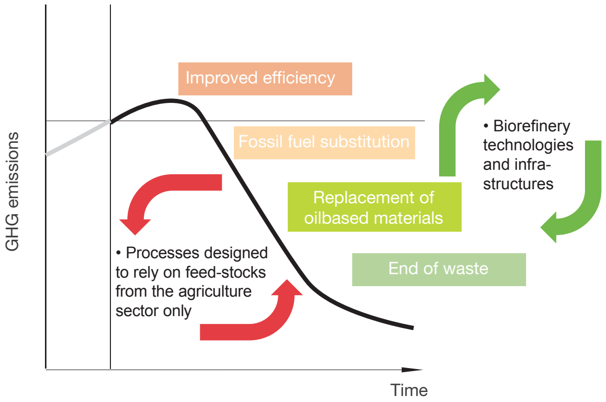


Figure 29: Dynamic impact of biotechnologically produced bio-based materials

4.4.Closing the loop

Significant amounts or carbon are disposed every day via solid waste and wastewater. IPCC estimates that in year 2002 about 900 Mt of waste were produced worldwide, whereas over 33 tons BOD/day were present in industrial wastewaters alone[57].

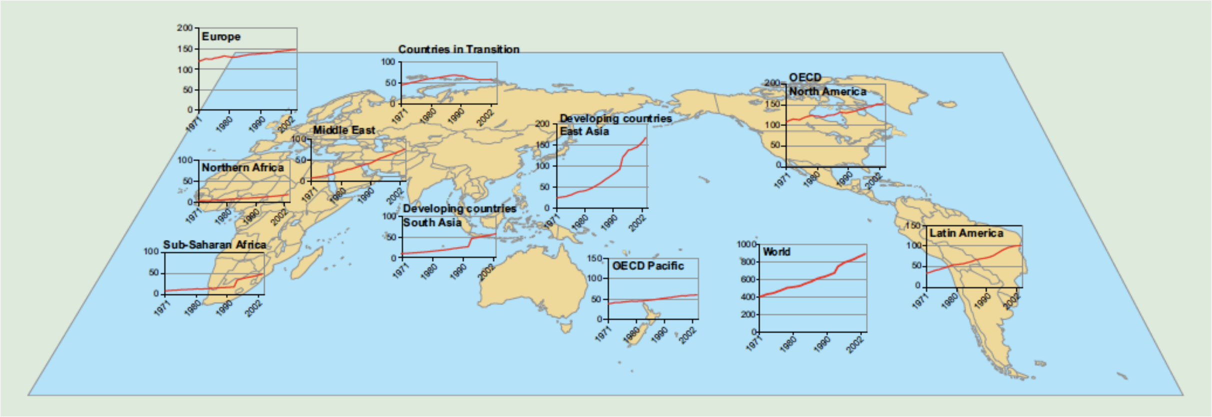


Figure 30: Annual rates of post-consumer waste generation 1971 – 2002 (Tg) using energy consumption surrogate – source IPCC Forth assessment report

---

[57] IPCC Fourth assessment report Working Group 3 Chapter 10 waste management

Regions	Kg BOD/ day	Total, Rounded (1000s)	Primary metals (%)	Paper and pulp (%)	Chemicals (%)	Food and beverages (%)	Textiles (%)
Year	1990	2001	2001	2001	2001	2001	2001
1. OECD North America	3100	2600	9	15	11	44	7
2. OECD Pacific	2200	1700	8	20	6	46	7
3. Europe	5200	4800	9	22	9	40	7
4. Countries in transition	3400	2400	13	8	6	50	14
5. Sub-Saharan Africa	590	510	3	12	6	60	13
6. North Africa	410	390	10	4	6	50	25
7. Middle East	260	300	9	12	10	52	11
8. Caribbean, Central and South America	1500	1300	5	11	8	61	11
9. Developing countries, East Asia	8300	7700	11	14	10	36	15
10. Developing countries, South Asia	1700	2000	5	7	6	42	35
Total for 1-4 (developed)	13900	11500					
Total for 5-10 (developed)	12800	12200					

Table 27: Regional and global 1990 and 2001 generation of high BOD industrial wastewaters often treated by municipal wastewater systems – source IPCC Forth Assessment report – based on world bank's world development indicators 2005

The carbon present in waste streams presents a valuable resource that sometimes on exploited for energy production (e.g. through incineration or biogas extraction from landfills) and other times is not used.

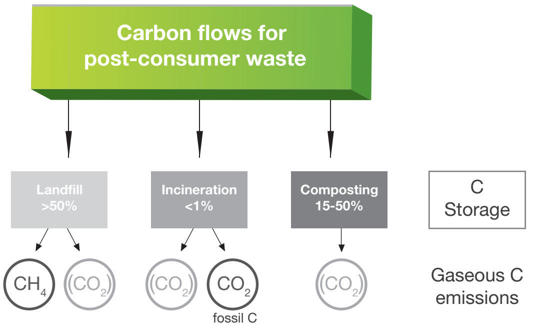


Figure 31: Carbon flows through major waste management systems including C storage and gaseous C emissions. The CO_2 from biomass is not included in GHG inventories for waste – Source IPCC Forth assessment report.

When carbon is disposed in anaerobic environments, methane may be generated, which, if released in the atmosphere, contributes to the global warming problem[58] (see figure 32 and table 28)

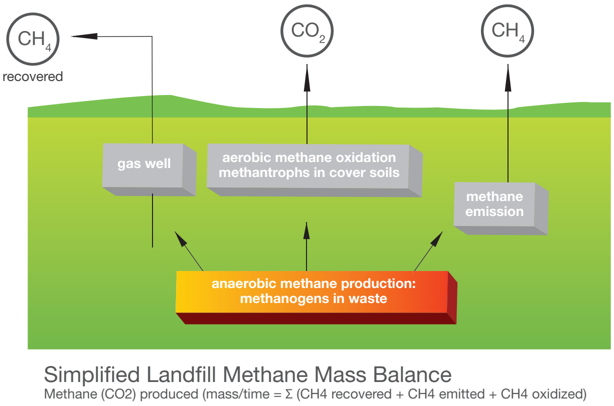


Figure 32: Simplified landfill methane mass balance[59]

Biotechnology solutions currently entering the market or being tested can increase the amount of biogas harvested from digesters and wastewater streams, for example by improving the hydrolysis and acid forming phases in methanization reactors used in wastewater treatment plants, as described by figure 33.

Source	1990	1995	2000	2005	2010	2015	2020	2030	2050
Landfill CH_4^a	760	770	730	750	760	790	820		
Landfill CH_4^b	340	400	450	520	640	800	1000	1500	2900
Landfill CH4 (average of ^{a} and ^{b})	550	585	590	635	700	795	910		
Wastewater CH_4^a	450	490	520	590	600	630	670		
Wastewater N_2O^a	80	90	90	100	100	100	100		
Incineration CO_2^b	40	40	50	50	60	60	60	70	80
Total GHG emissions	1120	1205	1250	1345	1460	1585	1740		

Table 28: Trends for GHG emissions from waste using (a) 1996 and (b) 2006 IPCC inventory guidelines, extrapolations, and projections (MtCO2-eq, rounded) – Source IPCC Forth assessment report

Notes: Emissions estimates and projections as follows: a Based on reported emissions from national inventories and national comunications, and (for non-reporting countries) on 1996 inventory guidelines and extrapolations (US EPA, 2006). b Based on 2006 Inventory guidelines and BAU projection (Monni et al., 2006). Total includes landfill CH_4 (average), wastewater CH_4, Wastewater N_2O and incineration CO_2

---

[58] The 100 year global warming potential of methane is estimated to be 23 – 25 times larger CO2's – see http://en.wikipedia.org/wiki/Global_warming_potential (July 2009)

[59] Source: IPCC Forth Assessment Report, Working Group 3

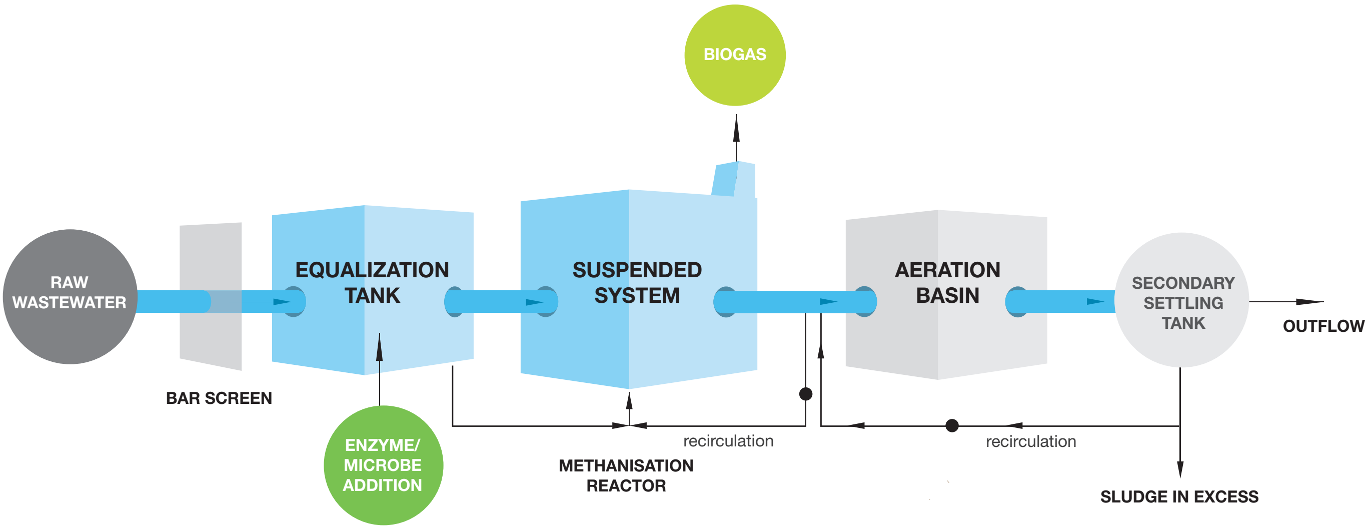


Figure 33: Use of enzymes in wastewater treatment plants for biogas extraction improvement

Field tests indicate that bioaugmentation of methanization processes can increase biogas harvesting by as much as 33-50%.[60]

From the climate perspective, increasing the amount of biogas harvested offers the following two benefits:

- The biogas (a renewable source of energy) can be used to replace fossil fuels used for electricity generation, industrial processes or building heating systems
- The increased harvesting improves the business case for systems that capture biogas, thus increasing their adoption and reducing the volume of methane released in the atmosphere

A broad adoption of biotechnology solutions could have a significant impact in terms of GHG emissions. For example if the improved business case for methane capture in wastewater treatment system was to generate a 5% reduction in methane emissions from wastewater, this would deliver a GHG emission reduction of about 33.5 $MtCO_2e$ 2020.

Whereas the exploitation of biotechnology to produce biogas provides a useful solution, which can improve the performance of (or reduce the damages caused by) existing waste management systems, this solution still leads to GHG emissions in the atmosphere and to plants (and land use) to 'close the circle' and recycle the natural carbon as feedstock. Biotechnology solutions can, however, serve a more ambitious goal. The establishment of a significant number of biorefineries, able to produce a large portfolio of end products, utilizing a large variety of feedstock, provides the opportunity to directly transform any biobased material into a valuable feedstock for the production of other biobased materials (and biofuels). In principle, therefore, biorefineries can 'close the loop' between waste and production, without requiring the use of extensive volumes of land to close the circle, enabling the creation of socio-economic systems that dramatically reduce waste, as the organic materials produced, used and disposed of re-enter the production and consumption cycles through biorefineries.

Although a number of biotechnology solutions currently in use will likely be part of the suite of technologies a biorefinery will rely upon, several additional solutions will be needed to support the creation of closed loop systems that minimize waste. Moreover, a number of logistical challenges will need to be addressed in order to create appropriate systems to channel the waste/feedstock streams into the biorefineries.

Given the relatively early stage of technological development, and the limitations of the data that can be currently collected, the sections below will focus on highlighting and analysing the key variables, and thus policy levers, that drive potential reductions in GHG emissions though versatile biorefineries that process large varieties of waste streams.

The sections specifically build on the results of section 4.3 and analyse the GHG impacts of different methods of handling biomaterials that reach the end of their life cycle.

4.4.1 GHG benefits from closing the loop

The GHG emission reductions estimates from section 4.3 were based on emissions parameters per unit of ton production based on the conservative assumption that, at the end of their life-cycle, products are incinerated and no energy recovery takes place.

The figures below compare this situation with scenarios in which closed loop systems are created, where biorefineries utilize products at the end of their use-cycle to create new biobased materials.

Three different scenarios are analyzed and compared with the

---

[60] Source: Private conversation with industry executives and confidential documentation of field test analysis

base-case situation in which products are incinerated and no energy is recovered.

The key assumptions used in the scenarios are summarized below.

	Open system (base case)	High yield loop	Low yield loop	Selective loop
Average lifetime of biobased products (years)	5	5	5	5
% products incinerated without energy recovery	100%	20%	20%	50%
% products reused as feedstock in biorefineries	0%	80%	80%	50%
Yield of biorefineries tons product/tons feedstock	0	0.8	0.5	0.8
Net GHG emissions to close the loop tCO_2e/ton feedstock	0	0.2	0.6	0

Table 29: Closing the loop scenarios for analysis

Each of the scenarios not only results in different emission profiles, but also in different amounts of renewable biobased carbon embedded in new and existing products in the market, as highlighted by the figure 34.

The establishment of closed loop systems lead to the creation of an increasing pool of biobased/renewable carbon that is stored in end-products and is continuously reused in production processes. As additional biobased carbon, derived from farming activities, is continuously added to this pool, a growing volume of carbon is ultimately stored in end products (see the figure 35).

Compared to open or less efficient systems, a high yield loop could lead to higher volumes of biological carbon being stored in everyday products. With the scenarios analysed in this report a high yield loop, for example, would sequester almost 3 billion tons of additional carbon in products than the base case (open system) and almost 1.5 billion tons more than low yield or loose loop systems.

Although the data underlying these analyses is not grounded on real-cases of biorefinery-enabled-closed-loop-systems, the simulations undertaken above indicate that closed loop systems could contribute significantly to the GHG emission reduction potential of industrial biotechnologies. A more accurate and detailed understanding of these dynamics is clearly needed, and proactive policies may be targeted to support both further analyses and the real life implementation of closed loop systems.

4.4.2 Land use impacts

Closed loop systems in which waste products become feedstock for the creation of new products are beneficial in terms of land use impacts, as they create a parallel pool of feedstock that does not need to be produced through farming.

Therefore, closed loop systems allow a larger volume of biobased products to be produced with a smaller amount of land.

Figure 36, for example, estimates the amount of land that would be needed to produce the volume of products equivalent to closed loop production, given the scenarios

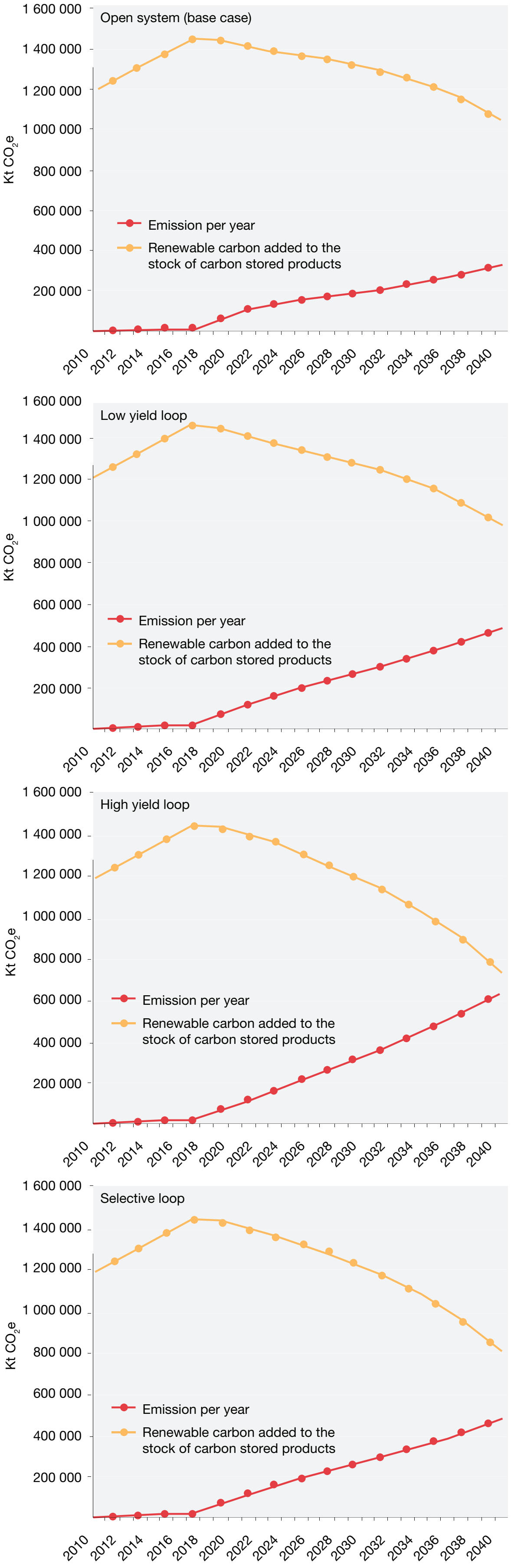


Figure 34: Closing the loop – impacts on GHG emissions and renewable carbon stored in products

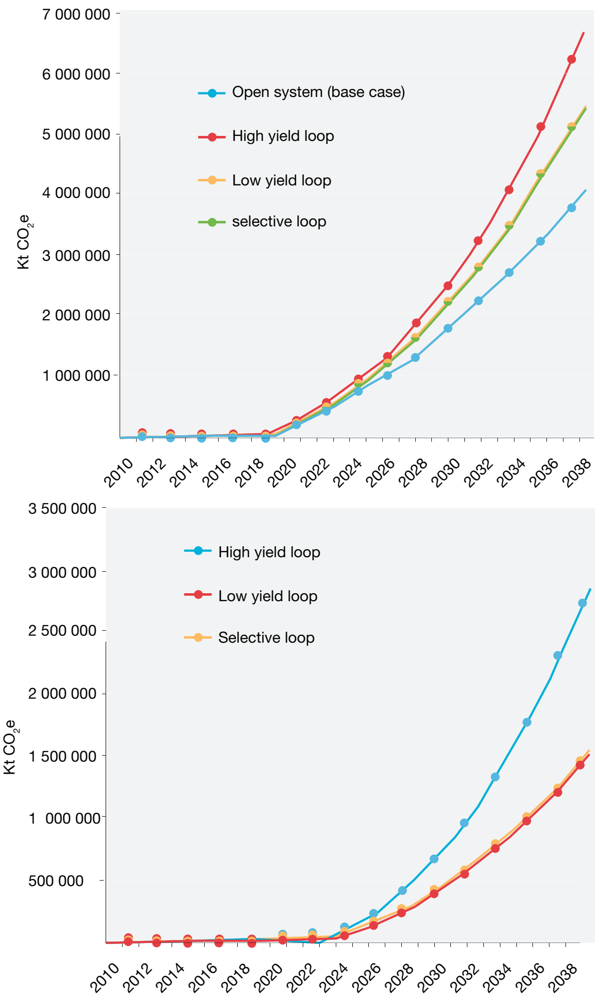
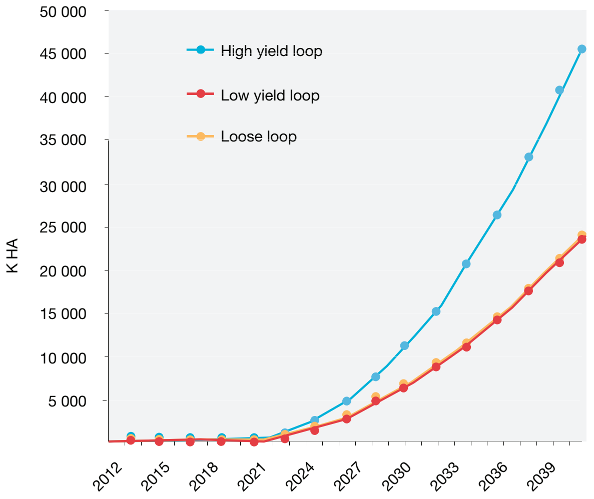


Figure 35: Renewable carbon stored in products in use. Comparison between different scenarios



already discussed in the sections above.

	Land saved million hectares		
	2020	2030	2040
High yeld loop	0.4	12	46
Low yeld loop	0.3	7	23
Selective loop	0.3	7	23

Figure 36: Volume of land that would be required to produce the products in biorefineries utilizing closed-loop feedstock

Versatile biorefineries, able to support efficient closed loop systems are therefore to be considered a key tool in coping with land use constraints that may otherwise limit the applicability and use of biotechnologies and biobased materials.

4.4.3 Dynamic impacts

As highlighted in the section above, closed loop systems reduce pressure on land use and therefore enable a larger utilization of biotechnology produced biobased materials.

Perhaps most importantly, the ability to create effective closed loop systems is an enabler for the supply of new solutions in which the services/benefits delivered by a product, rather than the product itself, are sold to end users. This critical contribution for the migration towards a service-based economy may therefore be considered to be the most important low carbon feedback obtainable by closed loop systems enabled by biotechnology.

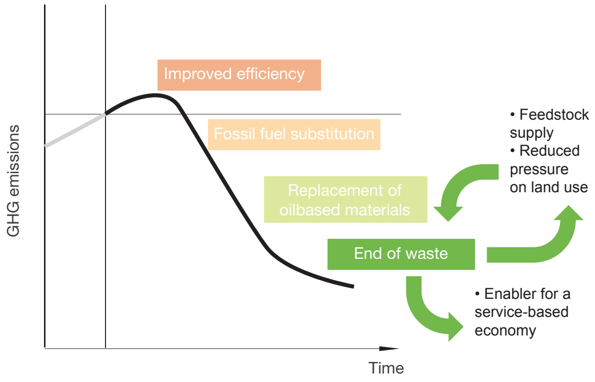


Figure 37: Dynamic impacts from the use of biotechnologies (in biorefineries) to close the waste loop

4.5 Land use considerations

The industrial biotechnology solutions discussed in section 4 generate various impacts on land use, as summarized in table 30.

Industrial biotech application	Description of impact on land use	Estimated impact in 2030
Efficiency enhancing applications	Food industry • (small) increase land use to produce efficiency enhancing enzymes • decrease in land use enabled by efficiency gains in various steps of the value chain Other industries • (small) increase land use to produce efficiency enhancing enzymes	Decreased pressure on land use (not quantified)

Fuel switching applications (biofuels)	• Significant impact on land use due to the potentially high production volumes • Decreased impact enabled by second generation biofuels	Land required: Target 5, fast tech: 30 million Ha Target 20, low tech: 262 million Ha Target 20, high tech: 179 million Ha If 100% of fuels used by road vehicles are biofuels: 1,085 million Ha
Biotechnologically produced biobased materials	• Significant impact on land use due to the potentially high production volumes • Decreased impact with second generation technologies • Possibility to use biobased materials in closed loop systems (see next raw)	Land required: Slow growth: 18 million Ha Slow take up: 23 million Ha Fast growth and take up: 28.2
Closing the loop	• Decrease impact on land use as biobased materials are continuously reused and create a separate pool of feedstock	Land saved, assuming fast growth and take up in biobased materials: High yield loop: 12 million Ha Low yield loop: 7 million Ha Selective loop: 7 million Ha

Table 30: Land use impacts of different industrial biotech applications and scenarios

The total impact on land use of the various industrial biotechnology applications analyzed in this report may therefore vary from 227 million hectares to 43 million hectares, and would require about 195 million hectares in the most favorable scenario in terms of emission reductions achieved at lower ‘land use cost’. Land requirements for biofuel production appear particularly high in both absolute and relative terms[61].

The extreme situation in which all road vehicle fuels are substituted by biofuels would require a land area of about 1,100 million hectares. This can be compared to the total worldwide cropland area of about 1,600 million hectares.

If natural ecosystems were converted into cropland to meet this demand, carbon currently stored in vegetation and soils could be released into the atmosphere.

Figure 38 illustrates the GHG emissions generated by the conversion of different ecosystems into cropland and indicates the length of time that would be required for the application of biotechnology (in this case different type of biofuels) to pay back the initial carbon debt.

It is clear that the conversion to cropland of many natural ecosystems would release significant amounts of carbon into the atmosphere (e.g. over 700 and up to 3400 tCO_2 for tropical rainforests), which could not be ‘paid back’ the biotechnology crops that replace the natural ecosystem within a reasonable length of time.

Potential limitations in terms of land availability, or negative impacts due to the conversion of vast areas of land to produce

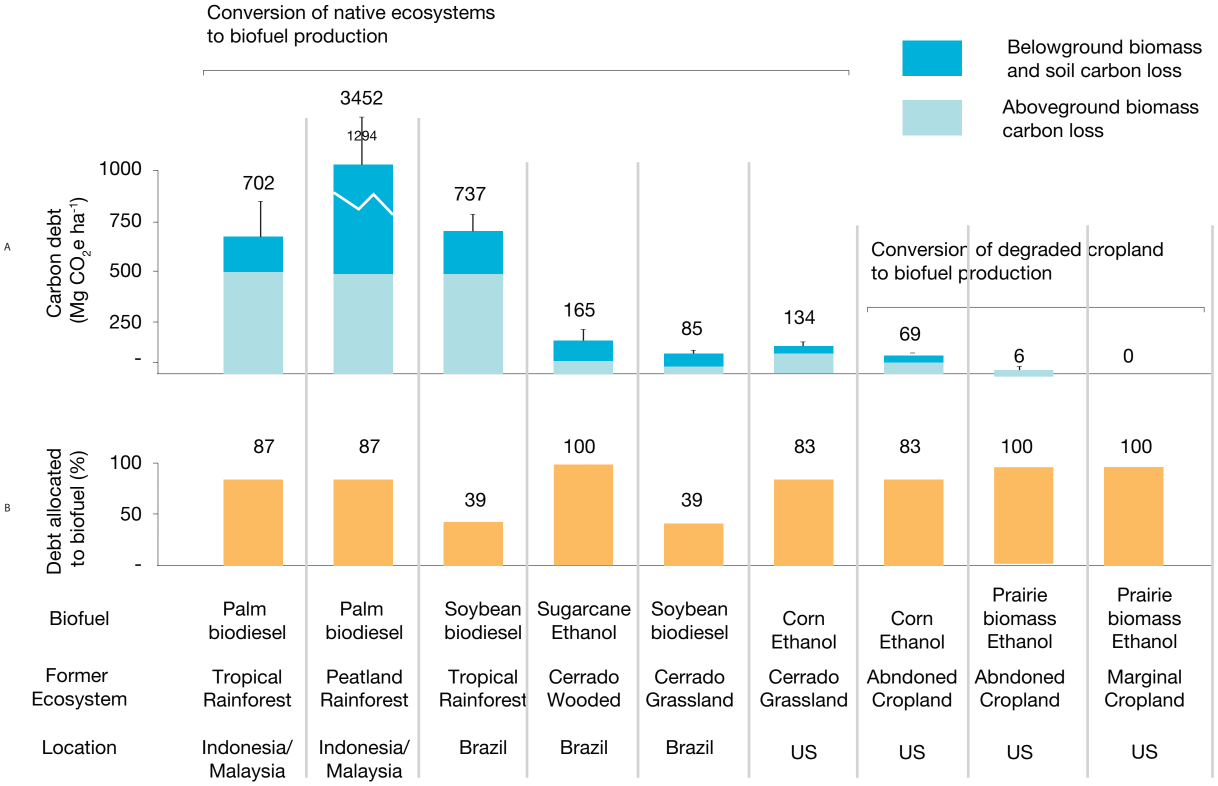


Figure 38: Carbon debt resulting from land use change – Source: Frangione et al, 2008[62]

---

[61] This may be partially due the different sources that had to be used for the analysis and to the high degree of uncertainty persisting in literature on land

[62] Means and SDs are from Monte Carlo analyses of literature-based estimates
of carbon pools and fluxes (5). (A) Carbon debt, including CO2 emissions from soils, and aboveground and belowground biomass resulting from habitat conversion. (B) Proportion of total

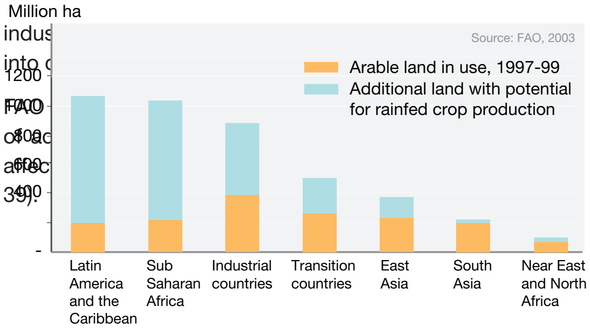


Figure 39: Potential for cropland expansion

However, these optimistic estimates should be taken with caution. The authors of the FAO study warn that these estimates should be treated with considerable caution[63].

Even if additional land is, in principle, available, a rapid growth in the demand of feedstock for industrial biotechnology applications can have a dramatic impact on food markets, farming communities, and natural ecosystems. Increased demand could lead to price increases in food commodities, which would damage low income households[53], displace local farming communities (or competition for limited land) or lead to the conversion of sensitive areas to industrial biotechnology crops, with significant damage to local ecosystems and biodiversity[54], or with significant losses of carbon stored in vegetation and soil.

The creation of strong and effective systems to ensure that land use constraints are adequately taken into consideration is therefore a necessary precondition for the development of an industrial biotechnology sector that can truly contribute towards GHG emission reduction and broader sustainability goals.

4.6 Emission reductions potential: summary

The analysis undertaken in this section has highlighted that there is significant potential to achieve GHG emission reductions with an intelligent use of industrial biotechnologies. Whereas several industrial biotechnology solutions can deliver significant GHG emission reductions today, greater potential can become available if the synergies between different industrial biotechnology solutions are pursued, and if low carbon feedbacks are consequently achieved.

Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030	Low-carbon feedback potential
Efficiency enabling in food and traditional industries	Food industry: up to 139 $MtCO_2e$ Other traditional industries Up to 65 $MtCO_2e$	• Efficiency gains invested in way that further reduce GHG emissions • Key knowledge, infrastructure and processes • Reduced pressure on land use
Biofuels[66]	207 to 1,024 $MtCO_2e$	• Economies of scale in production processes • Large scale infrastructure • Ethanol as a platform chemical
Biobased material production	282 to 668 $MtCO_2e$	• Fully developed and versatile biorefineries
Closing the loop	376 to 633 $MtCO_2e$ or renewable carbon stored in materials	• Feedstock supply for material's production • Reduced pressure on land use • Enabler for the creation of a service-based economy
Total	1,066 to 2,528 $MtCO_2e$	

Table 31: GHG emission reduction potential - summary

The estimates reported in table 31 are subject to a high degree of uncertainty, due the uncertainties and variability of key underlying variables such as the degree of technological development, the price of feedstock and oil and the presence or absence (and characteristics) of supporting policies.

Despite these limitations the analysis provides a useful indication of the scale of benefit that can be achieved and of the key interdependencies between different types of industrial biotechnology solutions.

As discussed in section 4.5, one critical physical constraint can strongly affect the GHG emission reduction potential achieved through industrial biotechnologies: namely land availability.

The amount of land available for the sustainable production of industrial biotechnology feedstock, and the resulting GHG benefit delivered by industrial biotechnology, will be strongly influenced by international and national policies and by their ability to bring to production marginal (low carbon) land, while eliminating the risk of bringing to production lands in which a significant amount of biological carbon is currently stored (which would be released in the atmosphere following the conversion of the land to feedstock production).

Given the land constraints, public policy and the industrial biotechnology sector strategies can play a critical role in determining the growth rate of the industrial biotechnology industry, of different clusters of solutions within the industry (e.g. biofuels vs. biobased materials if land use or other constraints create interconnectedness between these two clusters of solutions) and the GHG emission reductions achieved from individual clusters of solutions and overall. Key market players and policy makers have different tools to shape the future of the industrial biotechnology sector and these tools will be further discussed in the next section.

---

63 FAO State of food and agriculture 2008, page 60

64 See FAO State of food and agriculture 2008, section 6

65 See for example Madoffe (2009) Africa: Biofuels and neocolonialism http://allafrica.com/stories/200906040880.html accessed June 2009

66 The maximum biofuel market penetration is assumed to be 20% of the total biofuels used for road transport

5. Policies and strategies to achieve the potential of industrial biotechnologies

Section 4 analysed a number of GHG emission reduction opportunities potentially achievable with industrial biotechnology solutions, discussing key drivers for dissemination and for the achievement of environmental benefits.

As pointed out in section 2 the net GHG impact of industrial biotechnologies will be strongly influenced be the overall socio-economic environment and the policy landscape surrounding the dissemination of these technologies.

For industrial biotechnologies to deliver their full GHG emission reduction potential it is therefore paramount that strong public policies and private sector strategies are in place to channel the sector's growth towards low carbon paths, while averting the risks of high-carbon lock-ins (perhaps enticing because of their ability to deliver GHG emission reductions in the short term).

The goals of such policies and strategies should be to:

- Support existing and new efficiency-enabling solutions to fully harvest their short term potential
- Anticipate and nurture the progression towards large scale bio materials and closed loops systems
- Ensure that the supply of industrial biotechnology feedstock land is used according to principles of sustainability
- The industrial biotechnology sector can pursue the achievement of such goals with strategies such as:
- Scoping existing markets to identify areas where higher GHG emission reductions can be achieved with existing or emerging industrial biotechnology applications
- Developing standards and tools to be deployed systematically across the industry and to document the GHG impacts of specific industrial biotechnology solutions
- Work with customers and suppliers to develop funding instruments for low carbon solutions
- Pursue R&D and market investment in biobased materials following 'Designed for the Environment' approaches (thus including solutions to 'close the loop')
- Work with policy makers to develop policies that support the progression towards large scale biobased materials and closed loops systems
- Support the development and implementation of public policies that address the risk of unsustainable land use practices being associated with the production of industrial biotechnology feedstock

Policy makers could complement and stimulate private sector activities with specific public policies such as the ones highlighted in table 32:

The GHG emission reductions achieved with industrial biotechnology will largely depend on the strength and the success of policies and strategies such as the ones highlighted above. In many instances current policies and private sector strategies fall short of the potential and effectiveness required to fully develop and harvest the GHG emission 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.

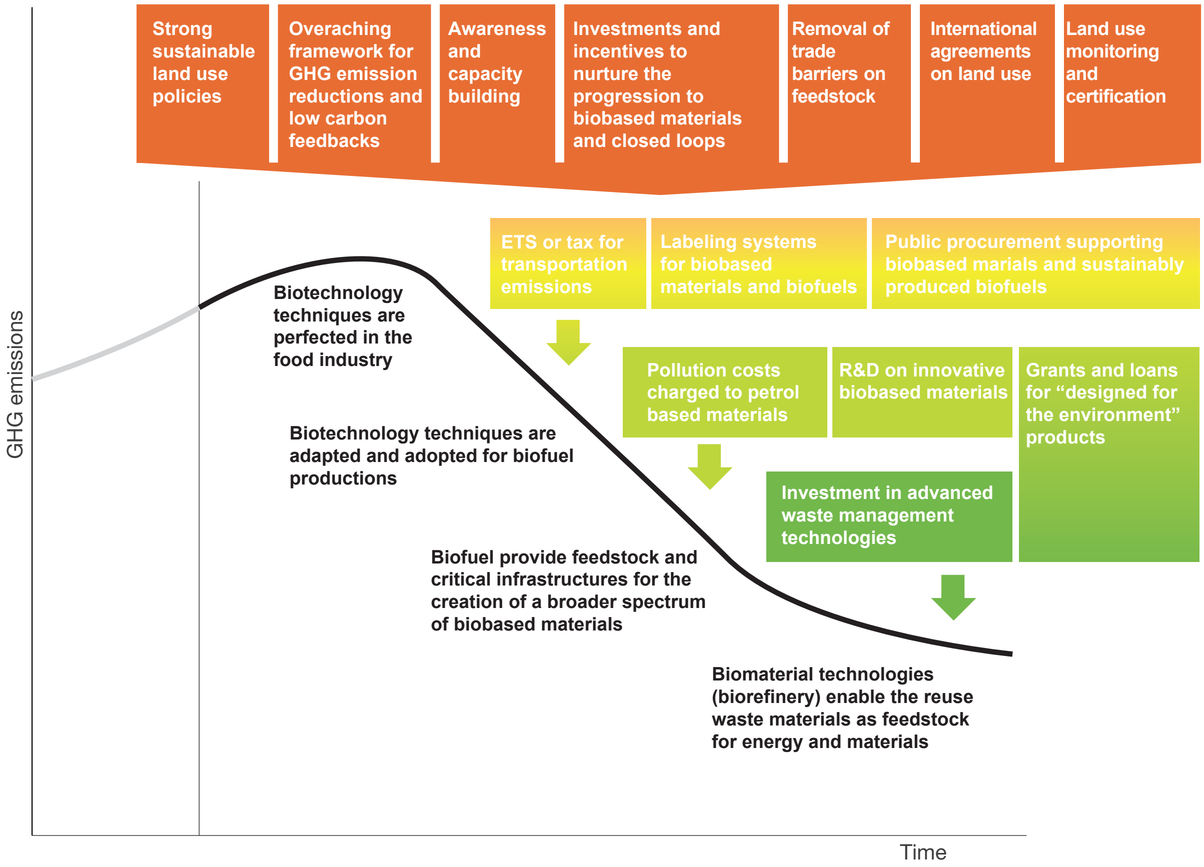


Figure 40: Policies for a low GHG path

Policy clusters	Examples of specific policies
Strong sustainable land use policies	• Solid international agreements on land use as part of climate change negotiations • Implementation of monitoring and certification systems at national level • Capacity building with the farm community
Overarching framework in which incentives are provided for the achievement of GHG emission reductions and low carbon feedbacks by the industrial biotechnology sector	• GHG emission trading systems that includes emissions from oil based chemicals, land use and land use change or rewards emission reductions in such areas • Introduction of appropriate charges/taxes to compensate for the environmental cost derived from oil based products • Removal of barriers to the international trade of industrial biotechnology feedstock (providing environmental costs, e.g. associated to transportation, are fully accounted for)
Awareness and capacity building for the dissemination of critical knowledge and information among consumers and users, and throughout the various branches and levels of government	• Labeling system for biobased materials • Support training and formal education on biomaterials and closed loop systems • Public procurement to prioritize biobased materials and closed loop systems
Investments and incentives that nurture the progression towards large scale biobased materials and closed loops systems	• Establishment of revolving funds that support efficiency projects and promote the investment of additional incomes generated in low-carbon projects • Grants and loans for the development of versatile biorefineries • Grants and loans for the development of products designed according to 'Designed for the Environment' principles •Funding for basic research on new biobased materials with high GHG emission reduction potential • Research and investments in advanced waste management technologies

Table 32: Examples of policies for a low GHG path

6. Conclusions

This report focused on estimating and discussing the potential GHG emission reductions that can be achieved, on a global scale, with a deployment of industrial biotechnologies that focused on achieving sustainability goals.

Current technological and market developments within the biotechnology sector indicates that path-dependencies and technological learning, occurring within the industrial biotechnology sector, may be leveraged to pursue a path of lower GHG emissions over time, as illustrated in figure 41.

The analysis of existing and potential GHG emission reductions indicates that:

- From the food industry and from traditional industries that use biological inputs, several efficiency improvements can be achieved with industrial biotechnologies. Whereas individual improvements tend to be marginal, taken together, they can have a significant impact on GHG emissions. Moroever the knowledge and technology developed in these sectors has been instrumental for a further development of industrial biotechnology solutions. Finally the efficiency improvements tend to result in a decreased use of land, which benefit other industrial biotechnology solutions.
- Leveraging the technologies developed by the food industry, biofuel technologies are driving the development of critical infrastructures and additional technologies that can enable a broad use of biological feedstrocks for the production of fuels and other chemicals. Given the large volume of GHG emissions deriving from the transportation sector, a substitution of fossil fuels with biofuels can deliver significant GHG emission reductions (estimated to be between 207 and 1024 $MtCO_2$ by 2030, depending on scenarios). This provide an important tool to help reduce the impact of fossil fuels in the short and medium term. However, biofules alone cannot solve the issues associated with the transportation sector and additional strategies will be necessary. Investment in biofuels is likely to be most effective if it also nurtures the development of a biomaterials industry
- If versatile biorefinery technologies are built, a critical number of petrochemical materials could be substituted by biobased materials, achieving GHG emission reductions ranging between 282 and 668 $MtCO_2$ by year 2030 and further increasing thereafer. Critical factors such as the capabilities of the technologies and the prices of crude oil and sugars/feedstock, play a key role in determining the speed of development in this sector
- Finally a growing adoption of biobased materials and the presence of versatile biorefineries could be leveraged to build systems that are able to reuse materials the use the end of their use cycle as feedstock for the production of other biobased materials. The technologies and systems (including logistical systems) to achieve this goal are at a relatively early stage of development. A successful development of closed loops could however would create a separate pool of organic feedstocks that does not need to be produced by land. Large volumes of biological carbon would be sequestered in products used in the economy and lower pressure on land would be achieved.

Table 33 summarizes the potential benefits that have been estimated

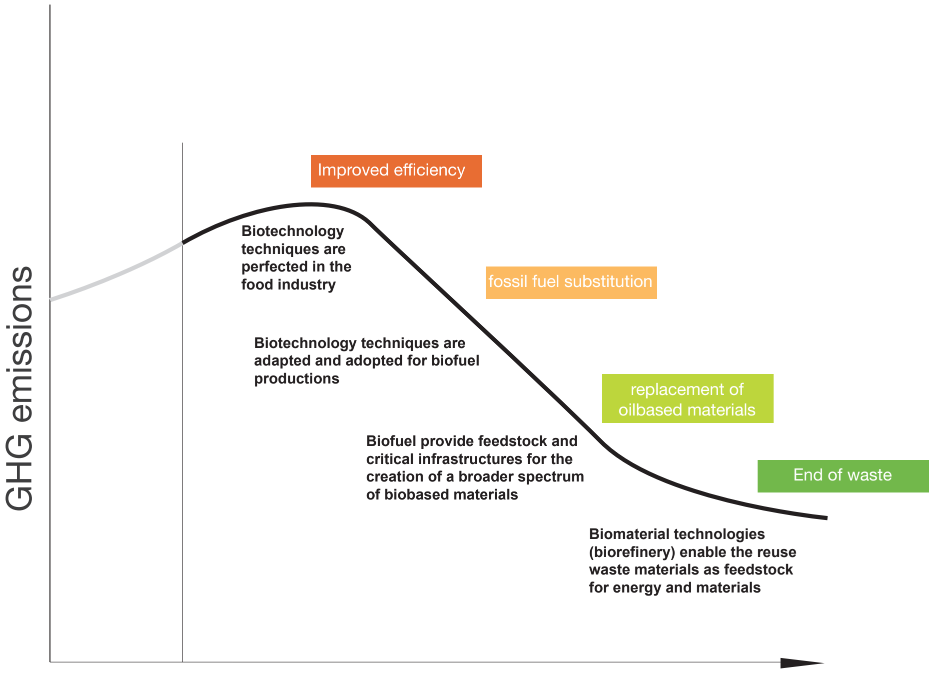


Figure 41: Industrial biotechnology's path to a low carbon economy

Type of industrial biotechnology solution	Estimated GHG emission reductions vs. baseline 2030	Low-carbon feedback potential
Efficiency enabling in food and traditional industries	Food industry: up to 139 $MtCO_2e$ Other traditional industries Up to 65 MtCO2e	• Efficiency gains invested in way that further reduce GHG emissions • Key knowledge, infrastructure and processes • Reduced pressure on land use
Biofuels	207 to 1,024 $MtCO_2e$	• Economies of scale in production processes • Large scale infrastructure • Ethanol as platform chemical
Biobased materials' production	282 to 668 $MtCO_2e$	• Fully developed and versatile biorefineries
Closing the loop	376 to 633 $MtCO_2e$ or renewable carbon stored in materials	• Feedstock supply for material's production • Reduced pressure on land use • Enabler for the creation of a service-based economy
Total	1,066 to 2,528 $MtCO_2e$	

Table 33: GHG emission reduction potential - summary

The uncertainty associated to the estimates above should be considered high due to various limitations in the analysis including:

- A limited range of available sources and data for some of the biotechnology solutions analyzed (e.g. for biobased materials and 'closing the loop)
- Uncertainty about key drivers such as technology performance and price of critical feedstock
- Uncertainty about the market share that biotechnology solutions can actually gain in more established markets such as food or textile production

Despite these limitation the analysis provides useful indication of the scale of emission reductions that biotechnology solutions can potentially achieve, compared to a scenario where not biotechnologies are deployed. The analysis alos highlights the links between different biotechnology solutions and the path that can be followed to grow the GHG benefit of industrial biotechnologies over time.

As agriculture is a main provider of the feedstock used by the solutions discussed above, a sustainable development of the industrial biotechnology sector must take into consideration possible constraints deriving by land availability. Current analysis by FAO seem to indicate that, in principle, sufficient land is available to increase the production of feedstock, without hindering sensitive natural ecosystem or damaging human communities. Achieving this goal, however is only possible if adequate policies are in place so that actual practice on the ground is in keeping with land availability constraints. This issue requires further analysis and more accurate assessments.

The actual impact of industrial biotechnologies on GHG emissions will largely depend on the overall socio-economic environment and the policy landscape surrounding the dissemination of these technologies. For industrial biotechnologies to deliver their full GHG emission reduction potential it is therefore paramount that strong public policies and private sector strategies are in place to channel the sector's growth towards low carbon paths, while averting the risks of high-carbon lock-ins (perhaps enticing because of their ability to deliver GHG emission reductions in the short term). Some of the key policies and strategies are summarized in 42.

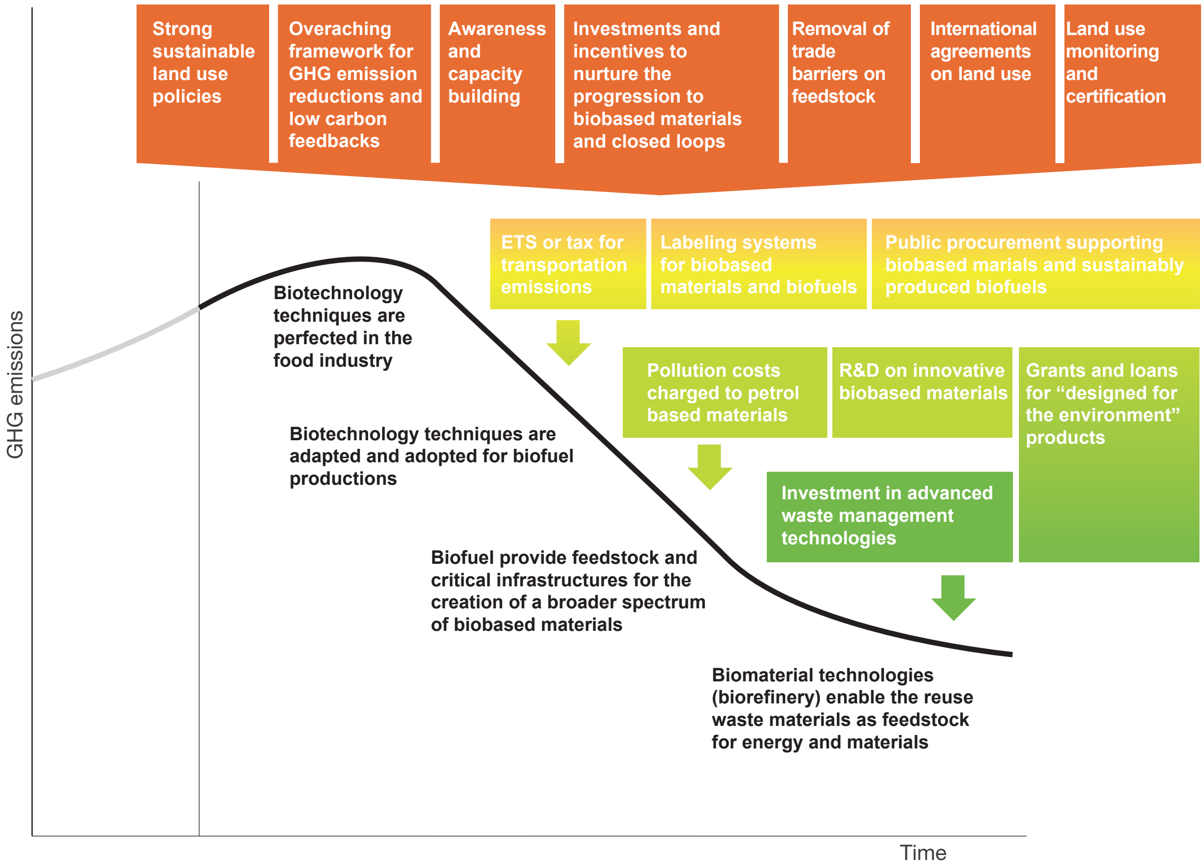


Figure 42: Policies for a low GHG path

This report showed that industrial biotechnology can deliver significant GHG emission reductions, if focused on achieving sustainability goals. The report also illustrated the path that can be followed to harvest such GHG benefits, providing an estimate of the scale of GHG emission reductions achievable. The understanding of these dynamics and benefits can be further improved with more systematic data collection and monitoring of technology and market developments in the industrial biotechnology sector. Further analysis on the impacts, or potential impacts, on land use is necessary to avoid risks of unintended environmental and social damages. The construction of more detailed analytical tools, able to model key technologies, drivers and constraints, and their interaction, at industry and economy level, could provide further insight on the potential of industrial biotechnology and on the key levers (policies and strategies) that industry and policy makers can deploy to fully achieve GHG emissions and broader sustainability goals.

7. References

Aykut Gül, Hilal Isik, Tufan Bal, Sertac Ozer BREAD CONSUMPTION AND WASTE OF HOUSEHOLDS IN URBAN AREA OF ADANA PROVINCE

Berlin J (2002) Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. Int Dairy J 12:939–953

Biotimes (2006): Unlocking the magic of barley brewing. http://www.novozymes.com/NR/rdonlyres/ED3736E8-7325-4FC6-AA99-9AE0182C522A/0/GB_Unlocking.pdf

Biotimes (2008): Vinozym® Process – We make the wine. November 27, pp. 3-4. http://www.novozymes.com/NR/rdonlyres/FBB7ACD6-9D52-4855-B3F4-3FC9079C4411/0/GB_wine.pdf

Buttazzoni et al. 2009 'From Workplace to Anyplace – Assessing the global opportunities to reduce GHG emissions with virtual meetings and telecommuting'

Cowan D, Oxenbøll KM and Holm HC (2008): Enzymatic bioprocessing of oils and fats. Inform April 210-212. http://www.novozymes.com/NR/rdonlyres/60336379-3DAB-41A9-A409-F67A2383C1C8/0/April08inform210212.pdf

DMG (2005): Green account 2004, Danish Malting Group A/S, 4760 Vordingborg, Denmark.

Dornburg V., Hermann B., Patel M. (2008) Scenario projections for future market potentials of biobased bulk chemicals Environmental Science and Technology 2008, 42, 2261-2267

Ecoinvent (2007): Ecoinvent (2007): The Ecoinvent Data Base v2.0 www.ecoinvent.com

Euromonitor (2009): Euromonitor International. www.euromonitor.com

FAO 2008 The state of food and agriculture Biofuels: prospects, risks and opportunities

FAOSTAT (2009): FAOSTAT database http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (April 2009).

FAOSTAT (2009): FAOSTAT database. http://faostat.fao.org (April 2009).

Farrel A.E. Plevin R., Turner B. T., Jones A. D., O'Hare M., Kammern D. M. (2006) Ethanol can contribute to energy and environmental goals Science 311, 506

Fischer (2007): Fischer database. Fisher International Inc. www.fisheri.com

Hermann, B. G.; Blok, K.; Patel, M. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change. In Environ. Sci. Technol. 2007, 41 (22), 7915–7921.

Høier E, Lilbæk H, Broe ML, Sørensen NK (2006): Enhancing cheese yield by hospholipase treatment of cheese milk. Aust J Dairy Technol 61:179–182.

Hubbe MA (2005): Paper. KirkOthmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

IEA/SMP transportation model http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc

ICBPPI Meeting, Progress in Biotechnology, Vol. 21, pp. 281–290, Elsevier Science

IPCC, 2007, Climate change 2007: Forth Assessment Report

Joh. Barth & Sohn The Barth Report 2005/2006

Joseph Fargione, Jason Hill, David Tilman, Stephen Polasky, Peter Hawthorn (2008) Land Clearing and the Biofuel Carbon Debt Science vol 319 29 feb 2008

Kirk O , Damhus T, Borchert TV, Fuglsang CC, Olsen HS, Hansen TT, Lund H, Schiff HE, Nielsen LK (2004): Enzyme

Applications, Industrial. KirkOthmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

Kottwitz B (2007): Enzymes in automatic dishwashing. In Enzymes, 4. Non-food Application. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co.

Lenting (2007): Enzymes in Textile Production. In Enzymes, 4. Non-food Application. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co.

Liska A. (2008) Improvement in Life Cycle Energy Efficicnecy and Greenhouse Gas Emissions of corn ethanol, Journal of Industrial Ecology

Murray Silverman et al. Competition in the Global Wine Industry: A U.S. Perspective available at http://online.sfsu.edu/~castaldi/bie/globcase.htm#table1

Nielsen (2006) Environmental assessment of enzyme application in the tanning industry in Leather International August/September 2006 18-24

Nielsen PH and Høier E (2009): Environmental assessment of yield improvements obtained by the use of the enzyme phospholipase in mozzarella cheese production. Int J Life Cycle Assess (2009) 14:137–143. http://www.springerlink.com/content/n4373237257wx111/fulltext.pdf

Nielsen PH and Skagerlind P (2007): Cost-neutral replacement of surfactants with enzymes - a short-cut to environmental improvement for laundry washing. Household and Personal Care Today. No. 4. http://www.novozymes.com/NR/rdonlyres/C23C3F09-CAA4-40DC-A0A9-E8E0262ACDDC/4769/Costneutralreplacementofsurfactantswithenzymes.pdf

Nielsen PH, Dalgaard R, Korsbak A and Petterson D (2008): Environmental assessment of Ronozyme WX CT xylanase used in Danish pig production. International Journal of LCA. No. 13. http://www.novozymes.com/NR/rdonlyres/C23C3F09-CAA4-40DC-A0A9-E8E0262ACDDC/4547/Ronozyme.pdf

Nielsen PH, Kuilderd H, Zhou W and Lu X (2009): Enzyme biotechnology for sustainable textiles. In Blackburn RS: Sustainable textiles: Life cycle and environmental impact. Woodhead Textiles Series No. 98. Woodhead Publishing Limited. http://www.woodheadpublishing.com/en/book.aspx?bookID=1506

Nielsen PH, Oxenbøll and Wenzel (2006): Cradle-to-Gate Environmental Assessment of Enzyme Products produced in Denmark by Novozymes. International Journal of LCA. http://www.novozymes.com/NR/rdonlyres/398BFC2D-2017-411B-B99B-121EC6BA0BE1/0/lca2006082651.pdf

Novozymes (2006): Fish and seafood protein extracts (FPEs). Novozymes, Application sheet. www.novozymes.com. No. 2006-42579-02

Novozymes (2006): Meat protein extracts (MPEs). Novozymes, Application sheet. www.novozymes.com . no. 2006-42588-02

NREL 2004 The Value Added Chemicals from biomass Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas

Oliver Wolf (editor) 2005 Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe EU JRC IPTS EUR 22103 EN

Oxenbøll K and Ernst S (2008): Environment as a new perspective on the use of enzymes in the food industry. Food Science and Technology, 22(4). http://www.novozymes.com/NR/rdonlyres/C23C3F09-CAA4-40DC-A0A9-E8E0262ACDDC/4919/ENZYMES2.pdf

Pere J, Siika-Aho M, Viikari L (2000): Biomechanical pulping with enzymes: response of coarse mechanical pulp to enzymatic modification and secondary refining. Tappi J 83, 1–8.

Pere, J., Ellmén, J., Honkasalo, J., Taipalus, P. and Tienvieri, T. (2002). Enhancement of TMP reject refining by enzymatic modification of pulp carbohydrates - A mill study. In: Viikari, L. and Lantto, R. (Eds) Biotechnology in the Pulp and Paper Industry: 8th

Skals P, Krabek A, Nielsen PH and Wenzel (2008): Environmental Assessment of Enzyme Assisted Processing in Pulp and Paper Industry. International Journal of LCA 13:124-132. http://82.98.75.226/sj/lca/Pdf/doi/lca2007.11.366

Spencer B. 1974. Br. Baker 176 (44) 19-20,

Suh S (2004): Materials and energy flows in industry and ecosystem networks. Life Cycle Assessment, Input-Output Analysis, Material Flow Analysis, and Their Combinations for Industrial Ecology, CML Leiden

Thomas A (2002): Fats and Fatty Oils. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co.

Thorstensen TC (1995): Leather. KirkOthmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

Thrane M (2004): Environmental impacts from Danish fish products. Ph.D. dissertation. Department of Development and planning. Aalborg University, Denmark.

Vils E (2005): Ny fodermiddeltabel til svin (New feeding table for pigs). Danish Agricultural Advisory Service. www.landscentret.dk. In Danish.

Wikipedia (2009) http://en.wikipedia.org/wiki/Biotechnology, accessed April 2009

Wikipedia (2009): http://en.wikipedia.org/wiki/Brewing accessed May 2009

Wikipedia http://en.wikipedia.org/wiki/Global_warming_potential accessed July 2009

Wikipedia (2009) http://en.wikipedia.org/wiki/Industrial_biotechnology, accessed April 2009

Wikipedia (2009): http://en.wikipedia.org/wiki/Winemaking accessed May 2009

WRAP, 2008: The Food we Waste http://www.wrap.org.uk/retail/case_studies_research/report_the_food_we.html (May 2009)

Zhou Chang-Sheng (2005). Study and improvement of sodium sulphide. Chemical Engineering (China) 33 (1) 75-78. In Chinese.

Figures

Tables

WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by:

- conserving the world's biological diversity
- ensuring that the use of renewable natural resources is sustainable
- promoting the reduction of pollution and wasteful consumption

WWF Denmark

Svanevej 12
DK-2400 Copenhagen NV
Tel: +45 35 36 36 35
Fax: +45 35247868

www.wwf.dk
www.panda.org

WWF for a living planet®

WWF for a living planet®

DTU Management Engineering
Department of Management Engineering

Appendix 1

Delivering the first billion tonnes of CO_2 reductions with biotech solutions

Friday 17 April in Copenhagen, Denmark
Expert meeting arranged by WWF in cooperation with Department of Management Engineering, Technical University of Denmark

(presentations available upon request)

Participants

Morten Birkved, Post Doc, Department of Management Engineering, section for Quantitative Sustainability Assessment, Technical University of Denmark

Camille Burel, Industrial Biotech Manager, Europabio

Marco Buttazzoni, Sustainability Expert, Sustainability 3.0

Andreas Follér, Project Manager/workshop co-organizer, Biosolutions Initiative

Kirsten Halsnaes, Head of programme, Risø DTU**,** National Laboratory for Sustainable Energy, Technical University of Denmark (participates during the afternoon session)

Ivan T. Herrmann, PhD-stud. Department of Management Engineering, section for Quantitative Sustainability Assessment, Technical University of Denmark

Michael Z. Hauschild, professor, Department of Management Engineering, section for Quantitative Sustainability Assessment, Technical University of Denmark

John Kornerup Bang, Head of Globalisation Programme, WWF Denmark

Christine Molin, workshop co-organizer, Department of Management Engineering, section for Quantitative Sustainability Assessment, Technical University of Denmark

Per Henning Nielsen, Manager, Novozymes

Karen Oxenbøll, Director, Novozymes

Suzanne Påhlman, Innovation Catalyst, Biosolutions Initiative

Thomas Schäfer, Senior Director, Novozymes

Marcel Wubbolts, Dr**,** Competence Manager, DSM

Not physically attending but contributing

Uffe Jorgensen, Senior Scientist, Dept. of Agroecology and Environment, Faculty of Agricultural Sciences, University of Aarhus

Luuk A.M. van der Wielen, professor, Director of B-Basic, NWO-ACTS, Department of Biotechnology, Technical University of Delft

Meeting objective

Identify and analyse biotech solutions with GHG emission reduction potential, which could help deliver one billion tonnes of CO2 reductions.

- Revise the concepts of ‘sustainable bio-based economy’ and ‘sustainable biotechnology’ and the vision underlying the 1 bn ton project
- Create a taxonomy and maps to analyse biotech solutions with emission reduction potential.
- Identify and discuss biotech applications with GHG emission reduction potential
- Brainstorm on methodological frameworks for the quantification of the GHG benefits potentially achievable, identifying preferred approaches.

Agenda

09.30-10.00 Coffee and Sandwich available

10.00-10.15 Welcome
By the host: John Kornerup Bang, WWF

10.15-10.30 Introduction
By the host: Prof. Michael Z. Hauschild

Key definitions and scope of the analysis
Expected outcome: Creating a shared vocabulary – including gaining a common understanding of the vision, goals and boundaries.

10:30 – 11.15
Presentation and discussion of the following key questions (Marco Buttazzoni)

- Why do we think biotech is relevant for GHG emissions (and sustainability)?
- How do we define 'sustainable biotech'?
- How does a 'biobased economy' look like?

Post-it exercise

Session 1 (morning): Biotech solutions with potential to deliver GHG reductions (Case Studies)
Expected outcome: Clarify the spectrum of biotech application to consider in the work ahead and agreement on key areas of Biotech solutions to be included in the final "One billion tonnes" report.

11.15– 12.15
Presentation and discussion of case studies
Provisional list:
1. "How industrial biotechnology can tackle climate change" report (Camille Burel, Europabio)
2. Biofuels (Karen Oxenboell, Novozymes)
3. Enzymes, (Per Henning Nielsen, Novozymes)
4. *Comments by Uffe Jörgensen (University of Aarhus)*

12.15-13.30 *Lunch*

Session 1 (afternoon): continuation – case studies

13.30-15.00
Presentation and discussion
5. Other solutions than the obvious, (Luuk van der Wielen, Delft University of Technology)
6. Bio materials (Thomas Schäfer, Novozymes)

Session 2: *Quantification Approach*
Expected outcome: A shared understanding on methodologies to calculate GHG emission reductions and of the approaches that best apply to Biotech solutions

15.00 – 16.00 Presentation and discussion of the following topics (Marco Buttazzoni):

- Background on key methodological issues to consider when assessing GHG emission and emission reductions
- Options and issues for the quantification of the impact of biotech solutions on GHG emissions
- Possible methodological framework

16.00-16.30
Wrap-up, action points and next steps for the project

For further information and logistical support please contact:
Andreas Follér, Project manager: andreas@climateinnovators.net

WWF for a living planet®

Appendix 2

Low Carbon Winners

Wednesday 10 June in Bonn, Germany
Expert meeting arranged by WWF

(presentations available upon request)

Participants

John Kornerup Bang, Head of Globalisation Programme, WWF Denmark

Ana Maria Bravo, Director Communications & Public Affairs, Genencor/Danisco

Sabine Klages Buechner, Manager International Government Affairs, DuPont

Camille Burel, Industrial Biotech Manager, Europabio

Marco Buttazzoni, Sustainability Expert, Sustainability 3.0

Andreas Follér, Project Manager, Biosolutions Initiative

Jens Klabunde, Scientific Advisor, Cluster industrielle Biotechnologie CLIB2021

Per Henning Nielsen, Manager, Novozymes

Martin Patel, Department of Science, Technology and Society (STS) / Copernicus Institute, Utrecht University

Thomas Schäfer, Senior Director, Novozymes

Fokko Wientjes, Director Corporate Sustainable Development, DSM

Not participating physically but contributing:

Tom Jenkins, Renewable and Sustainable Technologies Manager, Bioscience for Business KTN, Biology Department, University of York

Stephanie Batchelor, Manager, State and International Policy, Industrial and Environmental Section, Biotechnology Industry Organization (BIO)

Objectives

- Validate the approach and methodologies devised to analyse Biotech solutions with GHG emission reduction potential,
    - Key definitions and classifications. E.g. ‘sustainable bio-based economy’, ‘sustainable biotechnology’ classifications of biotech solutions.
    - Map of biotech applications with GHG emission reduction potential
    - Methodological framework for the assessment of GHG emission reductions generated by biotech
- Discuss and assess the results emerging from the application of methodologies
    - Most direct impacts and benefits
    - Dynamic impacts and benefits
    - Map of biotech applications with GHG emission reduction potential
- Obtain a better understanding on barriers hindering the development and dissemination of biotech solutions with positive GHG impacts
    - Identify policies and strategies for the dissemination of biotech solutions with GHG emission reduction potential
    - Discuss private sector strategies and public sector policies that can help eliminate such barriers
    - Map a transition path towards a biotech-enabled low (fossil) carbon economy

Agenda

09.30–10.00 Coffee/Tea and Pastry available

10.00–10.20 Introduction
By the host: John Kornerup Bang, WWF

Session 1: Summary of the work undertaken to date
Expected outcome: Gain a common understanding of the vision, and goals of the project and of the activities undertaken to achieve those goals

10.20 – 10.40
Presentation and Q&A (Andreas Follér):

- How was the project organized?
- What activities have we done to date and what's next?

Session 2: Methodological Approach
Expected outcome: A shared understanding of the methodologies used to quantify GHG emission reductions resulting from the deployment of biotechnologies.

10.40 – 11.20
Presentation of the methodological framework adopted to assess the GHG impact of biotech solutions and presentation and discussion of the provisional results obtained.
(Marco Buttazzoni):

- Background on key methodological issues to consider when assessing GHG emission and emission reductions
- Options and issues for the quantification of the impact of biotech solutions on GHG emissions
- Methodological framework adopted
- Overview of the (families of) biotech solutions with GHG impact

Session 3: Biotech solutions with potential to deliver GHG emission reductions (MB)
Expected outcome: Presentation and discussion of the estimated impact of biotech solutions on GHG emissions. (Marco Buttazzoni):

11.20 – 12.50
Biotech to reduce GHG emissions

- Quantitative and qualitative impacts considered
- Data issues faced
- GHG emission reductions estimated
- Sensitivities and uncertainties
- Critical questions

12.50–14.00 Lunch

Session 4: Break Out Session on Policy implications
Expected outcome: Obtain a better understanding on barriers hindering the development and dissemination of biotech solutions with positive GHG impacts and on solutions to eliminate such barriers.

14.00 - 16.30
Presentation by John Kornerup Bang, WWF
Introduction on exercise to map a transition path towards a biotech-enabled low (fossil) carbon economy. (Andreas Follér):

- Identify strategies for the dissemination of biotech solutions with GHG emission reduction potential
- Brainstorm and discussion on the barriers and difficulties facing the rapid uptake of biotech solutions with positive GHG impacts.
- Discuss public sector policies that can help eliminate such barriers

Session 5: Next steps
16.00-16.30
Wrap-up, action points and next steps for the project

For further information and logistical support please contact:
Andreas Follér, Project manager: andreas@climateinnovators.net

Appendix 3

Estimation of greenhouse gas emission reductions when conventional solutions are replaced with enzymatic solutions in various industries

By Per H. Nielsen and Anne Merete Nielsen, Novozymes. July 2009

Table of content

1. Introduction

Enzymes are biological catalysts with a huge capacity for speeding up biochemical reactions. Enzymes are present in all living organisms and they are essential to any type of life on earth. Enzymes have been used by man since ancient times. Today they are produced industrially and used in a broad range of industries around the world. See Figure A1.

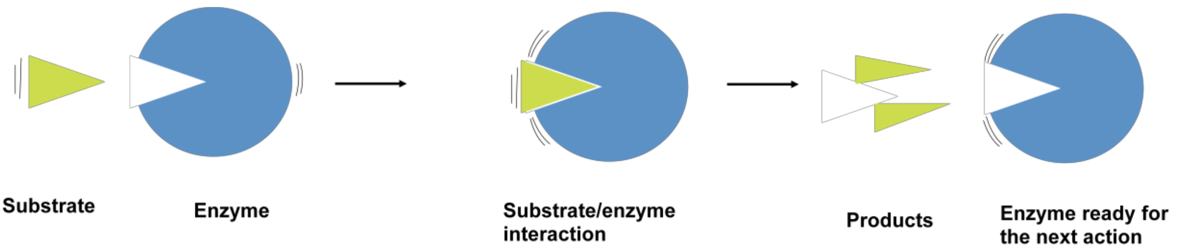


Figure A1: An enzyme catalyses the conversion of a substrate into two products.

Enzymes help industrial processes run more efficiently and small amounts of enzyme often save large amounts of raw-materials, energy, water and chemicals.

Life cycle assessment (LCA) is an environmental management tool which is used to assess environmental impacts of products and systems in all processes in the product chain, i.e. from raw material extraction through production and use to final disposal. A number of LCAs of enzyme applications in different industries have demonstrated that the production of industrial enzymes usually releases much less GHGs and other polluting substances than the amount saved when the enzymes are used in various processes[1]. Considerable GHG emissions can therefore be avoided when enzymatic processes replace conventional processes.

The purpose of the present appendix is to provide and input to an assessment of the total greenhouse gas (GHG) reduction potential of enzymatic solutions in industry in the main report.

The method is to use published data on full LCA studies whenever possible (see note 1) and supplement with LCA studies at screening level where full LCA studies are absent.

Screening LCAs are conducted in the same way as full LCAs but they are to a large extent based on readily available data an information and results are more uncertain and less well documented. Furthermore other environmental impacts categories than contribution to global warming are ignored in the present case.

---

[1] Cowan et al. (2008), Nielsen and Høier (2008), Nielsen and Skagerlind (2007), Nielsen et al. (2009), Nielsen et al. (2008), Nielsen et al. (2006), Nielsen and Wenzel (2006), Nielsen (2006), Oxenbøll and Ernst (2008), Skals et al. (2008) and Thum and Oxenbøll (2008).

Methodological details are explained in Box A1.

Box A1: Methods used in the study

The study addresses changes in greenhouse gas emissions induced by a range of technology changes and all studies cited or conducted here take a market oriented LCA approach, where the processes in the market that are actually affected by the changes are considered. See Ekvall and Weidema (2004).

The study addresses all greenhouse gasses emitted and avoided in the considered system and results are expressed in CO_2 equivalents (CO_2e) using the following formula:

$Q_{CO2e} = \Sigma(Q_i \cdot EF_i)$ See Wenzel et al. 1997

where

Q_i is the change in greenhouse gas emission, i as a result of the technology change in all processes in the considered system

EF_i is a specific equivalency factor for greenhouse gas i

Equivalency factors are derived from the 'CML 2 Baseline 2000' method and the most important factors in the present context are shown in Table A1.

Table A1: The most important equivalency factors applied in the study.

Greenhouse gas, i	Equivalency factor (EF_i)
CO_2	1
CO	1.5
CH_4	23
N_2O	296

Greenhouse gasses are emitted in numerous processes and estimation of total greenhouse gasses in the entire system is facilitated in SimaPro 7.1.8 LCA software unless otherwise noted.

Enzymatic solutions are used in many of the same production chains and use of an enzyme in for instance animal production can have an influence on the result of an assessment of enzyme use in meat processing. Such combined effects of enzymatic solutions are ignored in the study acknowledging that this may lead to slight overestimations of the total greenhouse gas reduction potential of the technology in some cases.

The study is conducted in dialogue with World Wide Fund (WWF) but no formal external review according to for instance ISO 14040 has been conducted. Furthermore no sensitivity analyses have been made and the authors acknowledge that many assumptions made in the study could have been different. The results should therefore only be seen as first attempts to provide orders of magnitudes of global greenhouse gas reduction potentials of enzymatic solutions.

2. Maintaining bread freshness

Bread becomes hard and unpleasant to eat with age not because it becomes dry as we use to say, but because the starch in the bread crystallizes. An enzyme which acts on the starch in white bread can, however, be used to diminish the crystallization, and help keeping the bread soft for longer time. Kirk et al. (2004).

This is an advantage to the retailer as well as the consumer because both need to throw less hard bread away – and to the climate because energy is saved and greenhouse gasses avoided in the entire chain from agriculture to the consumers' table.

Enzymes were introduced in bread for fresh keeping in the 90'ties and are now widely used in many places of the world.

Figure A2: Greenhouse gas emissions would be reduced if less bread was wasted because it got ´dry´.

The amount of bread which is or can be saved by extending the 'fresh-time' is difficult to estimate because it depends on many factors in the supply chain as well as the behavior of the consumers. An environmental assessment of 'Extended shelf life of bread" in the USA' reported by Oxenbøll and Ernst (2008) suggest 10% saving just in the retail and results from this study have been used to provide a conservative estimate of greenhouse gas reductions obtained by bread saving in general.

The study includes enzyme use, avoided bread production in all steps from wheat production to the gate of the bakery, reduced transportation needs and reduced packaging needs. The results show that contribution to climate change from producing the enzyme is negligible (because only a small amount of enzyme is used) and that the net avoided contribution to climate change is in the order of 110 kg CO_2e per ton bread.[2]

---

[2] 0.054 kg CO_2e per bread / 0.48 kg per bread · 1000 (see Oxenbøll and Ernst, 2008).

3. Increased yield in Mozzarella production

Cheese is produced from milk in a long series of processes. The main processes are shown in Figure A3.

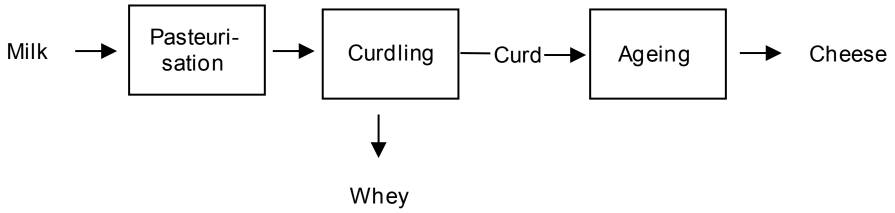


Figure A3: Main processes in cheese production.

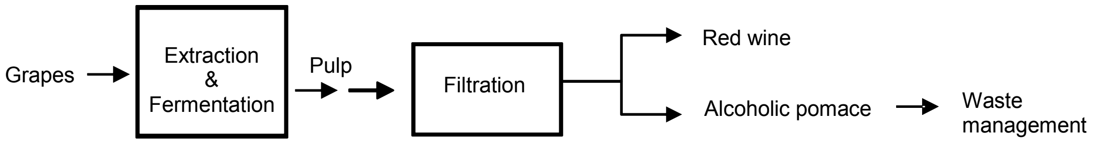
In the curdling process the pasteurized milk is mixed with enzymes and lactic acid bacteria in a tank and the mixture undergoes coagulation. During the coagulation process a watery liquid (whey) is separated until a certain consistency of the curd (a thick white substance) has been achieved. The curd is formed into blocks and left for ageing for weeks or months depending on the desired taste of the final cheese.

Yield enhancing enzymes can optimizes the coagulation process in mozzarella production giving the same amount and quality of cheese with 0.7–3.8% less milk consumption (Høier et al. 2006). Milk production is responsible for the largest greenhouse gas emission in cheese production (Berlin 2002) and reducing the amount of milk that is required to produce a certain amount of Mozzarella reduces the pressure on the climate.

The environmental advantages of using yield enhancing enzymes in Mozzarella production have been studied by Nielsen and Høier (2008). The results show that the use of enzymes saves around 230 kg CO_2e per ton Mozzarella depending on various conditions.

4. Use of enzymes in wine production

Extraction of grape juice is the first step in wine production. White wine is usually made by fermenting the juice, whereas in production of red wine, the pulp of the grapes is fermented together with the grape skins. See Figure A4.



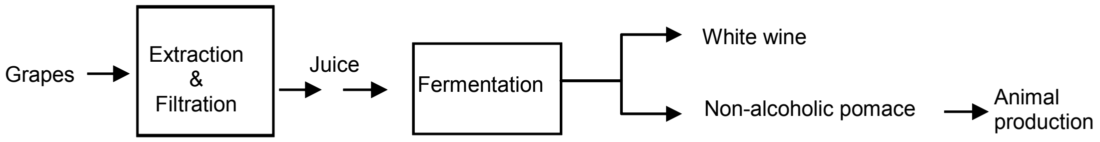


Figure A4: Main processes in production of white and red wine. Pomace is the solid remains from the grapes after the wine production.

Enzymes can be used to increase the yield during the extraction process (Biotimes 2008). As a consequence, the pomace has a lower content of water, sugar and other nutrients. This application started in the 1980-90'es, and is widely spread in Australia and South America among others. In Europe, the majority of wine is still produced without using enzymes for extraction.

As other agricultural productions, cultivation of grapes releases greenhouse gasses. Enzymatic wine extraction reduces the need for grapes and thus reduces the greenhouse gas emissions.

The amount of greenhouse gasses which could be avoided in the wine industry if enzymes were implemented globally is estimated in the following based on data and information from specialists in Novozymes unless otherwise noted.

Figure A5: Contribution to climate change is reduced when enzymes increase yield of the grapes in red wine production.

Reference situation

Juice is extracted without enzymes. The non-alcoholic pomace from white wine is often used as animal feed whereas the alcoholic pomace from red wine is often wasted.

Description of the enzymatic process

Enzymes are added directly to the grapes during the extraction process and the input of grapes is reduced by around 4% at fixed output of wine. Output of pomace is reduced accordingly. Reduced output of non-alcoholic pomace from white wine production leads to an increased consumption of alternative feed stuff (to compensate for the missing pomace) and there is no net effect on agricultural production. Reduced output of alcoholic pomace from red wine production reduces waste and there are no similar rebound effects. The following therefore addresses red wine production only.

Estimation of greenhouse gas reduction per ton red wine

Applying enzymes to wine extraction uses enzymes but saves grapes. Greenhouse gas reduction per ton wine is estimated by environmental modeling of the enzyme use and the grape saving. Modeling is based on data in Table A2.

Table A2: Uses and savings per ton red wine (from 1300 kg grapes).

	Material	Unit	Quantity	Comment	LCA data source
Used	Enzyme	g	53	3 – 5 gram per 100 kg grapes I.e. ~ 4 gram per 75 kg wine ~ 53 g per ton wine.	a)
Saved	Grapes	kg	53	4% of 1300 kg grapes	Suh (2004)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

Greenhouse gas emissions caused by the enzyme consumption is estimated at 0.06 kg CO_2e per ton wine whereas the reduced greenhouse gas emission obtained by the avoided grape production is estimated at 120 kg CO_2e per ton wine. The net greenhouse gas saving is therefore estimated to be in the order of 120 kg CO_2e per ton wine.

5. Malt substitution in production of beer

Beer is produced in a long series of processes. See Figure A6. A key process in beer production is the fermentation process where sugars are converted into alcohol. The sugars are produced from starch from various grains by allowing it to react with enzymes from germinated barley (malt) in a process called mashing. Wikipedia (2009).

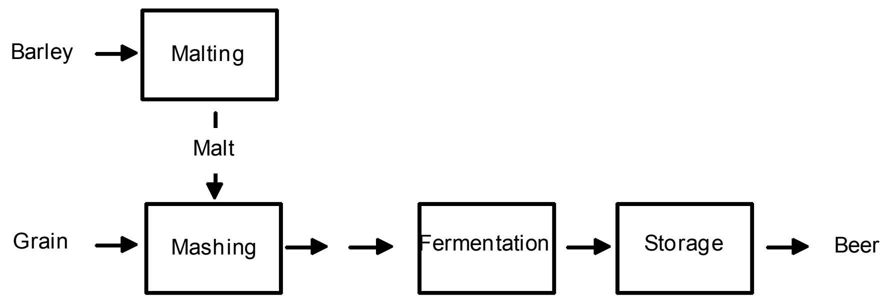


Figure A6: Main processes in production of beer.

The enzymes produced by germination of barley (malting) can, however, be substituted with enzymes produced by fermentation (commercial enzymes) and the malt replaced with barley (BioTimes 2006).

Production of malt uses energy and greenhouse gas emissions can be reduced if the malt is replaced with commercial enzymes and barley. The amount of greenhouse gasses which could be avoided if commercial enzymes and barley were implemented globally in beer production as an alternative to malt is estimated in the following. Data and process information is delivered by specialists in Novozymes unless otherwise noted. Complete substitution of malt with industrial enzymes and barley as considered here is new.

Figure A7: Greenhouse gas emissions are reduced when malt is substituted with commercial enzymes and barley in the brewing industry.

Reference situation

Malt and beer is produced in many different ways around the world and with many different grains as raw material base. It is difficult to take all this variation into account and a typical scenario has been established to serve as reference situation.

It is assumed that

- Malt substitution is zero in the reference situation
- Barley is used in malt production
- 15 kg malt is used for 100 litres of beer (one hecto litre)

Data on raw material and utility consumption in malt production is obtained from the Danish Malting Group A/S (DMG 2005). See Table A3.

Table A3: Raw material and utility consumption for producing one ton malt (DMG 2005).

	Unit	Quantity
Barley	kg	1.2
Water	l	3.1
Electricity	kWh	0.084
Natural gas	Nm^3	0.064

Description of the enzymatic process

Grinded barley and enzymes produced by fermentation are added directly in the mashing process and malt is substituted 100%. Both barley and malt needs to be grinded before the mashing process but since barley is harder to grind than malt, a bit more electricity is used in the grinding process.

Estimation of greenhouse gas reduction per 100 liter beer

Substituting malt with enzymes produced by fermentation uses enzyme, barley and electricity but saves malt. Greenhouse gas reduction per 100 liter beer is estimated by environmental modeling of the uses and the savings. Modeling is based on data in Table A4.

Table A4: Uses and savings per 100 liter beer.

	Material/utility	Unit	Quantity	LCA data source
Used	Enzyme	g	36	a)
	Barley	kg	18	EcoInvent (2007)
	Electricity	Wh	83	EcoInvent (2007)
Saved	Malt	kg	15	DMG (2005)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

Greenhouse gas emissions caused by the use of enzyme, barley and electricity consumption is estimated to be 9.1 kg CO_2e per 100 liter beer whereas greenhouse gas reduction obtained by avoiding malt production is estimated at 12.5 kg CO_2e per 100 liter beer. The net greenhouse gas saving is therefore estimated to be in the order of <u>3.4 kg CO_2e per 100 liter beer</u>.

6. Use of enzymes in degumming of vegetable oil

The vegetable oil that we are all using in cooking is produced by pressing oil rich seeds such as soy beans, sunflower seeds or rape seeds. The fresh pressed oil contains, however, a number of undesirable substances which needs to be removed in a series of refining processes before the oil is ready for sale and consumption. The first process in refining is the so called "degumming process" where phosphatides which have a negative impact on storage stability of the oil are removed. Thomas (2002).

Rather large amounts of energy, water and chemicals are traditionally used in the degumming process. However, by adding an enzyme which can degrade the phosphatides, the degumming process can be simplified and energy, water and chemical consumptions reduced (Kirk et al., 2004). Furthermore the yield of oil is increased and the same amount of oil can be produced with around 0.8% less oil seeds.

Production of oil seeds and chemicals etc. uses energy and causes greenhouse gas emissions. Contribution to climate change can therefore be reduced when enzymes are implemented in the degumming process.

Enzymes were introduced in full scale degumming in the late 1990'ties and is used in a number of innovative oil mills.

Figure A8: Greenhouse gas emissions would be reduced if more vegetable oil was degummed with the help of enzymes.

The environmental advantages of using enzymes in the degumming of soy bean oil have been studied by Novozymes. See Cowan et al. (2009). The results show that the use of enzyme in saves around <u>45 kg CO_2e per ton soy oil</u> depending on various conditions.

7. Enzymatic meat protein extraction

Meat and bone is to a large extent separated from each other by cutting at the slaughterhouse before the meat is sold to the consumers. Four to five percent of the meat remains, however, with the bones after the cutting process and is often wasted with the bones because it is difficult to remove.

The remaining meat can, however, easily be extracted from the bones with the help of enzymes and the “meat protein extracts” can be injected into meat cuts or used in processed foods such as soups and sausages as an alternative to meat or soy-protein (Novozymes 2006).

Animal production is responsible for considerable greenhouse gas emissions and using enzymes to increase the yield of protein from slaughtered animal could help reducing pressure on the climate.

Enzymatic meat protein extraction was introduced in full scale production in the 1990’ ties but spreading has so far only been limited.

The amount of greenhouse gasses which could be avoided if enzymes were implemented in meat processing to reduce waste is estimated in the following based on data and information from specialists in Novozymes unless otherwise noted.

Figure A9: Contribution to climate change would be reduces if meat on the bones was cleaned completely and all meat was used for human consumption. Photo: Danish Crown.

Reference situation

Most of the meat on bones is currently wasted with the bones and a situation where all meat remaining on the bones is wasted has been used as reference in estimating greenhouse gas savings.

The majority of bones from the slaughterhouse are converted into bone meal and incinerated. Fear of "mad cow disease" (BSE) prevents the use of the meat for feeding animals and this opportunity is not given attention as an alternative. Energy value of the meat during incineration is ignored.
Meat can also be extracted by for instance pressure cooking as in soup stocks. Extracting the remaining meat by pressure cooking is, however, negligible today and is not given attention as an alternative to the enzymatic process.

Description of the enzymatic process

Bones with small amounts of meat remaining from the cutting process are mixed with water and enzyme. Enzymes degrade the meat on the bones and all meat is extracted into the water and a soup of meat protein is created. Enzymes are deactivated by heating after the extraction process. The meat protein extract can be injected in meat cuts or used in processed foods without further treatment. Water consumption: 1 m^3/ton bone. Process temperature and time: 55°C, 1 hour. Enzyme deactivation temperature and time: 85°C, 15 min. Temperature of fresh bones: ~ 0°C. Enzyme class: Protease. Enzyme quantity: 1-2 kg/ton bone.

Assumptions

- Meat makes up 75% of a living animal and bones make up 15%.
- 50% of meat extracts replace soy bean meal (1:1 on a protein weight basis) and 50% replace meat (1:1 on a protein weight basis)
- Temperature of incoming process water: 15°C
- Specific heat capacity of bone is low and energy for heating bones is ignored.

Estimation of greenhouse gas reduction per ton living animal

Enzymatic meat protein extraction uses enzyme, water and heat - but saves meat and soy bean meal. Greenhouse gas reduction per ton living animal is estimated by environmental modeling of the uses and savings. Modeling is based on data in Table A5.

Table A5: Uses and savings per ton living animal and data sources used in estimation of greenhouse gas reduction.

	Material/utility	Unit	Quantity	Calculation	LCA data source
Used	Enzyme	kg	0.2	15% of 1.5 kg	a)
	Water	m^3	0.15	15% of 1 m^3	Ecoinvent (2007)
	heat	MJ	44	$0.15\ m^3 \cdot (85-15)^{o}C \cdot 4.2\ MJ/\ (m^3 \cdot {}^{o}C)$	Ecoinvent (2007)
Saved	Meat	kg	17	75% · 1000 kg · 4.5% · 50%	LCAfood (2003)[b)]
	Soy bean meal	kg	17	75% · 1000 kg · 4.5% · 50%	Ecoinvent (2007)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006), b) weighted average of pork, chicken and beef.

The results show that greenhouse gas emission caused by the uses is around 6.3 kg CO_2e per ton living animal whereas the savings are in the order of 260 kg CO_2e per ton living animal.

The net greenhouse gas saving is thus estimated to be 260-6.3 ~ 250 kg CO_2e per ton living animal if the remaining meat on the bones after cutting was utilized for human consumption instead of wasting it.

8. Enzymatic fish protein extraction

Fish are often filleted at fish factories before being sold to the consumers. Much fish meat remains, however, with the bones after the filleting process and ends up as animal feed because it is difficult remove and utilize for human consumption.

The remaining fish meat on the bones can, however, be extracted easily from the bones with the help of enzymes and the "fish protein extract" can be injected into fish fillets or used in processed fish products such as smoked fish and fish pate. (Novozymes 2006)

Using the enzyme to get more out of the fish reduces pressure on wild fish or reduces demand for other types of food. Fishing as well as producing other food products causes greenhouse gas emissions and increasing the yield of fish can help reducing the pressure on the climate.

Enzymatic fish protein extraction was introduced in full scale production in the 1990'ties but spreading has so far only been limited.

The amount of greenhouse gasses which could be avoided in food supply if enzymes were implemented globally in fish processing to reduce waste is estimated in the following based on data and information from specialists in Novozymes.

Figure A10: Contribution to climate change would reduce if fish bones were cleaned completely and all meat was used for human consumption.

Reference situation

The majority of the remains after the filleting process (hereafter called fish co-product) is currently utilized as feed for animals and a situation where <u>all</u> meat remaining on the bones is used as feed has been used as reference. It is assumed roughly that one kg fish meat has the same feed value as 1.5 kg soy bean meal because fish contains about 50% more protein than soy bean meal (Vils 2005) and it is assumed that 1.5 kg soy bean meal has to be produced and processed extra for compensation per kg fish co-product which is not available for animals anymore.

Fish proteins (meat) can also be extracted by cooking the fish co-product. Extracting the remaining fish meat by cooking is, however, negligible today and is not given attention as an alternative to the enzymatic process.

Description of the enzymatic process

Fish co-products are mixed with water and enzyme. Enzymes degrade the fish meat on the bones and all fish meat is extracted into the water and a fish protein extract and fish oil is created. Enzymes are deactivated by heating after the extraction process. The fish protein extract is injected into fish fillets or used in processed foods without further treatment. Water consumption: 1 m^3/ton bone/fish meat. Process temperature and time: 55°C, ~30 minutes. Enzyme deactivation temperature and time: 85°C, 15 min. Temperature of fresh bones/fish meat mix: ~0°C. Enzyme class: Protease. Enzyme quantity: 1-2 kg/ton fish co-product.

Assumptions

- 50% percent of a fish becomes fish fillet in the filleting process and 50% becomes fish co-product (rough assumption based on Thrane (2004).
- 60 - 100 kg fish (fish oil and meat depending on specie) can be utilised as fish protein extract per ton fish co-product.
- Increased use of fish protein has no influence on fish catching because fish catching to a large extent is regulated by quotas. It is assumed that increased yield of fish replace cultivated fish (farmed trout; 1:1 on a weight basis).
- Temperature of incoming process water: 15°C
- Specific heat capacity of bone is low and energy for heating bones is ignored.

Estimation of greenhouse gas reduction per ton living fish

Enzymatic fish protein extraction uses enzyme, water and heat - but saves farmed trout. Greenhouse gas reduction per ton fish is estimated by environmental modeling of the uses and savings. Modeling is based on data in Table A6.

Table A6: Uses and savings per ton fresh fish and data sources used in estimation of greenhouse gas reduction.

	Material/utility	Unit	Quantity	Calculation	LCA data source
Used	Enzyme	Kg	0.75	50% of 1.5 kg	a)
	Water	m^3	0.5	50% of 1 m^3	Ecoinvent (2007)
	heat	MJ	147	0.5 $m^3 \cdot (85\text{-}15)^{o}C \cdot 4.2$ $MJ/(m^3 \cdot {}^{o}C)$	Ecoinvent (2007) Industrial oil furnace
	Soy bean meal	Kg	120	To compensate for missing feed for animals.	Ecoinvent (2007)
Saved	Farmed trout	Kg	80		LCAfood (2003)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

The results show that greenhouse gas emission caused by the uses is around 100 kg CO_2e per ton living animal whereas the savings are in the order of 180 kg CO_2e per ton living fish.

The net greenhouse gas saving is thus estimated to be in the order of 80 kg CO_2e per ton fish if enzymatic protein extraction was implemented as alternative to using the fish co-product as animal feed.

9. Enzymatic improvement of animal feed value

Enzymes are essential in all living organism's conversion of food into energy and building blocks for the body. Additional exogenous enzymes can be supplemented to production animals' feed to improve the digestion. Improved digestion increases the energy and protein value of the feed and allows the farmer to produce the same amount of meat etc. with a slightly smaller amount of feed.

Enzymes for improving the value of animal feed were commercially introduced in the 1980-ties.

Feed saving reduces CO_2 emission from energy use in crop production and reduces emissions of other greenhouse gasses such as N_2O and CH_4 from stables, manure storage systems etc. See Kirk et al. (2004) and Nielsen et al. (2008).

The amount of greenhouse gasses which could be avoided in animal production if enzymes were implemented globally in pigs and poultry's feed is estimated in the following based on data and information from specialists in Novozymes unless otherwise noted.

Figure A11: Contribution to climate change is reduced when production animals' digestion is improved with enzymes.

Reference situation

A reference situation where enzymes are not added to animals' feed has been assumed in the present estimation of the greenhouse gas reduction potential of using enzymes in animal feed.

Description of the enzymatic process

Enzymes are added to pigs' and poultries' feed. The enzymes improve the digestibility of the feed and thereby animals can eat less without compromising the growth. Enzyme categories: xylanase, amylase and glucanase etc. Enzyme composition: varies depending on feed type and animal species etc. Enzyme consumption: less than one ‰ (W/W) of the feed (varies).

Use of enzymes in ruminants' feed (e.g. cattle) is still at an early stage and has not been given attention here.

Assumptions

Feed savings obtained by enzyme use varies considerably depending on the feed composition, the considered animal species, growth stadium, enzyme composition, production practice etc. On average the feed saving potential of using enzymes in animals' feed is estimated to be in the order of 2.5%.

Animals' feed is composed of several ingredients and varies considerably depending on where in the world production is going on, time of the year, traditions etc. A very simple feed composition scenario has been assumed here and applied for both pigs and poultry: Feed is composed of 2/3 wheat and 1/3 soy bean meal.

Animals' feed consumption depend on the breed, production practice etc. and is assumed to be 270 and 4 kg during lifetime for pigs and chickens respectively.

In addition to feed saving, feed enzymes allow a change in feed composition without compromising nutrient value. This has, however, been ignored here and is likely to underestimate the environmental advantage. See Nielsen et al (2008).

Reduced input of carbon (C) and nitrogen (N) with the feed leads to reduced output of C and N with the manure per produced unit of meat. Reduced output of C and N with the manure is assumed to lead to reduced generation of CH_4 and N_2O from stables, manure storage systems and fields and has been accounted for in the study. See Nielsen et al. (2008).

Manure is often used as fertilizer in agriculture. Reduced N content in the manure as a result of enzyme use reduces fertilizer value of the manure. Reduced fertilizer value of the manure is assumed to be compensated for by increasing the use of artificial fertilizer. See Nielsen et al (2008).

Estimation of greenhouse gas reduction per ton feed

Greenhouse gas reduction per ton feed is estimated by environmental modeling of the uses and savings in accordance with Nielsen et al. (2008). Modeling is based on data in Table A7.

Table A7: Uses and savings per ton feed

	Material/utility	Unit	Quantity	Comment	LCA data source
Used	Enzyme	kg	0.2	-	a)
saved	Wheat	kg	17	2.5% of 1000 kg · 2/3	Ecoinvent (2007)
	Soy bean meal	kg	8	2.5% of 1000 kg · 1/3	Ecoinvent (2007)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

The results show that greenhouse gas emission caused by enzyme production is negligible whereas the savings are in the order of 20 Kg CO_2e per ton feed. The net greenhouse gas saving is thus estimated to be in the order of <u>20 kg CO_2e per ton feed</u> if enzymatic feed saving was implemented in production of pigs and poultry.

10. Bleach boosting of kraft pulp

Paper is produced from wood in a long series of processes. The main processes are shown in the Figure A12.

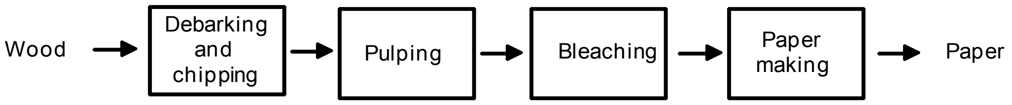


Figure A12: Main processes in paper production.

Wood contains lignin, a brownish substance that needs to be removed from the pulp to make bright paper qualities. Hubbe (2005). Enzymes can be used to open the structure of the wood fibers and facilitate the washing out of lignin from the pulp and make the pulp more susceptible to bleaching chemicals. The technique is called 'bleach boosting' (Kirk et al. 2004) and significantly reduces the need for bleaching chemicals in kraft pulp production.

Enzymatic bleach boosting was introduced in full scale production in the 80'ties but spreading has so far only been limited.

Figure A13: Non-bleached pulp (left), semi-bleached pulp (middle) and bleached pulp (right). Enzymes can boost the bleaching process and reduce chemical use and emission of greenhouse gasses.

Production of bleaching chemicals uses energy and causes greenhouse gas emission and reducing the use of chemicals in bleaching of pulp reduces contribution to climate change. The magnitude of greenhouse gas reduction when enzymes are implemented in thermo-mechanical pulp production has been estimated by Skals et al. (2008). The result show that CO_2 reduction is in the order of 40 kg/ton pulp and that greenhouse gas emission from producing the enzyme is in the order of 3 kg/ton pulp. The net saving is thus estimated at 37 kg CO_2/ton kraft pulp acknowledging that it can vary considerably from wood type to wood type and from factory to factory etc.

11. Enzyme assisted refining of thermo-mechanical pulp

Paper is produced from wood in a long series of processes. The main processes are shown in Figure A12.

In the pulping process wood chips are converted into a mash of wood fibers by either mechanical or chemical means. The first process in mechanical pulping is refining where wood chips are separated into free fibers. Hubbe (2005). Refining is a mechanical process and it consumes large amounts of electricity. A small amount of enzymes can, however, soften the wood chips so that the necessary refining time can be shortened and electricity saved. Pere et al. (2000).

Enzyme assisted refining has been tested in full scale production (Pere *et al.* 2002) but spreading has so far only been limited.

Production of electricity causes CO_2 emission and reduced refining time reduces contribution to climate change from pulp production. The magnitude of CO_2 reduction when enzymes are implemented in thermo-mechanical pulp production has been estimated by Skals et al. (2008). The result show that CO_2 reduction is in the order of 150 kg/ton thermo-mechanical pulp and that greenhouse gas emission from producing the enzyme is negligible in comparison. The net saving is thus estimated at around 150 kg CO_2e/ton thermo-mechanical pulp acknowledging that it can vary considerably from wood type to wood type and from factory to factory etc.

70 *Figure A14: Wood chips. Enzymes can help softening the woodchips and save energy in the refining process.*

12. Enzymatic desizing in the textile industry

Fabrics are made by weaving or knitting yarn. In the case of woven fabrics made from cotton or cotton blends, the yarn is coated with an adhesive substance known as a size prior to weaving. This is to prevent the threads from breaking during weaving because these threads are subject to considerable wear. The most common size is starch or starch derivatives. After weaving, the size must be removed again in order to prepare the fabric for finishing.

The desizing process may be carried out by treating the fabric with chemicals such as acids, bases or oxidizing agents. However, an enzyme can easily degrade the starch and remove the size as well. Lenting (2007). Enzymes have been used in desizing for several decades.

Energy is used in production of chemicals, and chemical saving in the textile industry reduces contribution to climate change. The amount of greenhouse gasses which could be avoided if enzymes were implemented globally as an alternative to chemicals is estimated in the following. Data and process information is delivered by specialists in Novozymes unless otherwise noted.

Figure A15: Contribution to climate change is reduced when enzymes replace chemicals in the desizing process in the textile industry.

Reference situation

Chemical desizing is used as reference in the study. Native or modified starch is degraded with hydrogen peroxide and caustic soda and degradation products are removed with water. Chemical and water consumption varies from factory to factory and a typical scenario has been used as reference:

Sodium hydroxide, NaOH (100%): 300 kg/ton fabric
Hydrogen peroxide, H_2O_2 (35%): 400 kg/ton fabric
Process temperature: 60°C
Water use: 6 m^3/ton fabric

Enzymatic process

The size is degraded with an enzyme and degradation products are removed with water. Process conditions vary likewise from factory to factory and a typical scenario has been applied:

Enzyme use: 10 kg Aquazyme LTL/ ton fabric
Acetic acid (30%): 1 kg/ton fabric
Process temperature: 40-50°C
Water use: 6 m^3/ton fabric.

Estimation of greenhouse gas reduction per ton fabric

Water consumption and temperature is nearly the same for the two processes and water and heat consumption is ignored in the assessment. Enzymatic desizing uses enzyme and acetic acid but saves sodium hydroxide and hydrogen peroxide. Greenhouse gas reduction per ton fabric is estimated by environmental modeling of the uses and savings. Modeling is based on data in Table A8.

Table A8: Uses and savings per ton of fabric.

	Material/utility	Unit	Quantity	LCA data source
Used	Enzyme	Kg	10	Aquazyme LTL[a)]
	Acetic acid	Kg	1	Ecoinvent (2007)
saved	Sodium hydroxide, NaOH	Kg	300	Ecoinvent (2007)
	Hydogen peroxide H_2O_2	Kg	400	Ecoinvent (2007)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

Greenhouse gas emission caused by enzyme and acetic acid production is estimated at 45 kg CO_2e per ton fabric and the avoided greenhouse gas emission caused by NaOH and H_2O_2 saving is estimated at 910 kg CO_2e per ton fabric. The net greenhouse gas reduction obtained by replacing chemicals with enzymes is thus estimated to be in the order of 870 kg CO_2e per ton fabric.

13. Enzymatic bleach clean-up in the textile industry

Textiles are produced in a long series of processes from cotton and other fibers. One important process in the textile production chain is the dyeing of yarn or fabrics. Fabrics and yarns intended for light and bright colored products are often bleached prior to the dyeing process to achieve even and reproducible dyeing results. Bleaching is usually performed with hydrogen peroxide (H_2O_2) and the excess of bleaching agent must be removed after the bleaching process to avoid bleaching of the dye in the subsequent dyeing process.

Bleach removal has traditionally been performed by rinsing in several baths with water or by adding a reducing agent such as sodium thiosulphate. Both of these traditional processes use considerable amounts of water and energy for heating the water. Sodium thiosulphate is also regarded as an environmentally undesirable product to have in the effluent stream. Enzymes can, however, easily convert the bleaching agent into oxygen and water and enzymes are now used as an alternative by many textile mills. Lenting (2007). Enzymatic bleach clean-up was introduced in 1980'ties.

Figure A16: Contribution to climate change is reduced when enzymes are used in bleach clean-up for light colored textile products.

Enzymatic bleach clean-up can be performed at lower temperatures than the traditional bleach clean-up and with less water. Implementation of enzymes in bleach cleanup thus saves energy and reduces contribution to climate change from textile production.

The amount of greenhouse gasses which could be avoided in the textile industry if enzymes replaced rinsing with water in the bleach clean-up process has been estimated by Nielsen et al. (2009). The study referred to a single factory in China and results showed that saving was in the order of 400 kg CO_2e per ton fabric or yarn.

14. Enzyme assisted leather production

Leather is produced from animal hides and skins in a long series of processes. Some of the first processes are soaking and unhairing which have traditionally been conducted with large amounts of aggressive chemicals. Small amounts of enzymes can, however, help the process running more smoothly and small amounts of enzyme can replace large amounts of chemicals. Thorstensen (1995), Kirk et al. (2004) and Nielsen (2006).

Energy is used in production of chemicals and chemical saving in the leather industry reduces contribution to climate change. The amount of greenhouse gasses which could be avoided in the leather industry if enzymes were implemented globally as an alternative to chemicals is estimated in the following based on data and information from specialists in Novozymes.

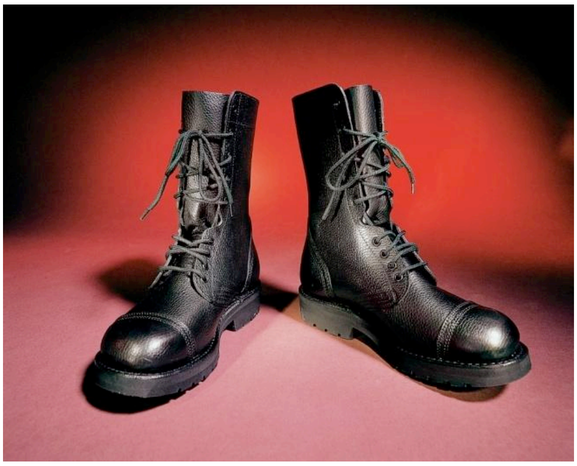


Figure A17: Contribution to climate change is reduced when enzymes replace chemicals in leather industry.

Reference situation

The first process in leather making is soaking. In this process the hides/skins are put into a large drum with water and chemicals. The drum is turned around for 8 to 16 hours until the skins or hides have become wetted and soft. After the soaking process the skins or hides are ready for the unhairing process which is conducted in the same drum with fresh water and another mixture of chemicals. Unhairing is conducted in a two-step procedure which is also called liming. Unhairing takes around four hours.

Enzymes are used in many tanneries in the developed world and many have already switched from the pure chemical process. Enzyme use is rarer in the developing countries (where most skins and hides are processed) and here the described reference situation is very realistic.

Description of the enzymatic process

Enzymes can assist the chemicals in the soaking and unhairing process and enzymes can replace some of the chemicals that are traditionally used. Apart from the change of active ingredients in the processes, the soaking and unhairing process and all the following processes remain nearly the same.
The enzymatic process addressed here is based on the newest and most innovative enzymes and savings are larger than known from most practical applications. GHG reductions can therefore also be achieved in the developed countries where existing enzyme assisted processes can be replaced with new.

Assumptions

- Chemicals destroy the hair during the unhairing process and create large amounts of waste. Enzymes do not destroy the hair and the hair can be used for other purposes. This has however been ignored in the assessment.
- Enzymes increase the speed of the soaking process slightly and save a small amount of electricity for turning the drum. This has, however, been ignored in the assessment.
- The yield of leather increases slightly when enzymes replace chemicals because enzymes are gentler to the hides/skins. This has, however, been ignored in the assessment.

Estimation of greenhouse gas reduction per ton wet salted skin or hide

Enzyme assisted soaking and unhairing uses enzyme but saves sulphide, lime, and surfactant. Greenhouse gas reduction per ton skin or hide is estimated by environmental modeling of the uses and savings. Modeling is based on data in Table A9. See Nielsen (2006).

Table A9: Uses and savings per ton salted goat skin or cattle hide.

	Material/utility	Unit	Quantity		LCA data source
			Goat skin	Cattle hide	
Used	Enzyme	Kg	~ 1	~ 1	Mixture[a)]
Saved	Na_2S	Kg	20	30	Zhou (2005). Average of modern and traditional technology in China.
	Lime $Ca(OH)_2$	Kg	50	50	Ecoinvent (2007)
	Surfactant[b)]	Kg	80	10	Ecoinvent (2007)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006). b) 40%solution. Many different surfactants are used in different factories. Ethoxylated alcohol has been used here.

Greenhouse gas emission caused by enzyme production are small compared with the savings (see Table A10) and the net greenhouse gas reduction obtained by replacing chemicals with enzymes is estimated to be around 130 to 190 kg CO2e per ton skin or hide respectively.

Table A10: Greenhouse gas (GHG) balance when enzymes are replacing chemicals in soaking and unhairing processes. All data are in kg CO_2e/ton hide or skin.

Skin/hide	GHG emission caused by enzyme production	GHG emission avoided by chemical saving	Net GHG saving
Goat skin	5	133	~130
Cattle hide	5	194	~190

15. Save detergents and energy with laundry detergent enzymes

Enzymes have been used in laundry detergents since the 1960ties and are widely used today because they degrade stains at the laundry efficiently at low temperatures (Kirk et al. 2004). The potential of enzymes in laundry detergents is, however, yet not fully utilized. Using the newest and most innovative enzymes can help replacing large amounts of chemicals in detergents and furthermore allow further temperature reductions without compromising the overall wash performance.

Producing detergents and heating the wash water requires energy and leads to greenhouse gas emissions. Washing at lower temperatures with slightly more enzyme and considerably less chemicals reduces greenhouse gas emissions. Nielsen and Skagerlind (2007).

The amount of greenhouse gasses which could be avoided if the most innovative enzyme solutions were implemented globally in detergents is estimated in the following based on data and information from specialists in Novozymes.

Figure A18: Contribution to climate change is reduced when enzymes replace chemicals in laundry detergents and wash temperature is reduced.

Reference situation

Wash water heating

Europeans are traditionally washing their laundry in rather small amounts of water at rather high temperatures. Water is often heated directly in the washing machine with electricity. North Americans are traditionally washing at somewhat lower temperatures but with much more water than Europeans. Water is often taken from the tap (heated with a private boiler; electric or fuelled with oil or gas). Asians and South Americans and many others in the world wash in rather large amounts of water but do traditionally not heat the water for washing. A very rough average wash scenario has been established and applied as reference in the study. See Table A11.

Table A11: Simplified model of wash characteristics applied as reference in the study.

Region	Wash temperature	Wash water per kg laundry	Wash water heating system
Asia	Tap water temperature	40 l / 3 kg laundry = 13 l/kg	None
Europe	40°C	14l /3 kg= 4.7 l/kg	Electrical
South America	Tap water temperature	50 l / 4 kg = 12.5 l/kg	None
North America	30 °C	60/5 = 12 l/kg	Warm tap water from central heating system

Detergent

Laundry detergents are usually composed of surfactants (which remove the dirt from the laundry) builders (which neutralize the effects of hardness of the water), bleachers (which decolorize difficult stains such as wine and tea), enzymes (which degrade stains) and others (fillers, perfumes etc.). Detergents are made in numerous different formulations depending on local conditions and traditions. Most detergent formulations are confidential and a detergent which has an open ingredient list ("IEC-A bleach") has been used as reference. See Figure A19.

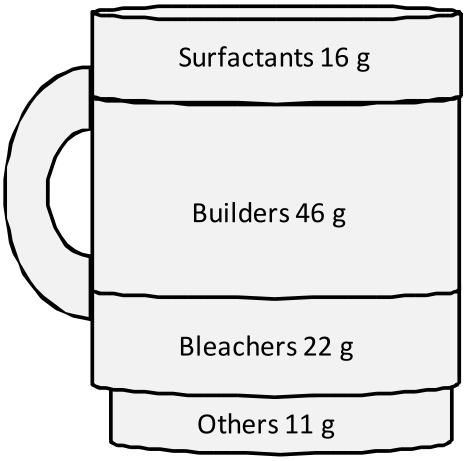


Figure A19: Detergent before (reference-detergent). Data refer to the amounts used for washing 3 kg laundry. For further details see Nielsen and Skagerlind (2007).

Description of the enzyme assisted process

Enzymes are added to the detergent as a replacement to surfactants and builders and wash temperature is reduced.
It is estimated by detergent experts that enzymes can replace around 30% of surfactants and that enzymes can replace builders completely. It is furthermore estimated that the use of enzymes can allow a wash temperature reduction to 25°C in Europe and North America without compromising the overall wash performance.

78

Assumptions

<u>Heat saving</u>
Wash temperature is reduced from 40 to 25°C in Europe (reduction: 15°C) and from 30 to 25°C in the USA (reduction: 5°C). Temperature reduction is not possible in the rest of the world because wash temperature is already low. It is assumed that electricity used for heating water in Europe is produced by combusting natural gas. It is assumed that warm tap water used in the wash process in North America is heated in a private furnace (50%) and by electric heating (50%). The private furnace is assumed to be fueled with oil. The public electricity supply is assumed to be based on natural gas.

<u>Surfactant and builder saving</u>
The reference detergent contains 16 g surfactant and 46 g builder per 3 kg laundry (see Figure A19) and surfactant and builder saving are assumed to be 5 and 46 g/kg laundry respectively. See Figure A20. Other smaller reformulations of the detergent are necessary to achieve the required performance but are ignored here for simplicity.

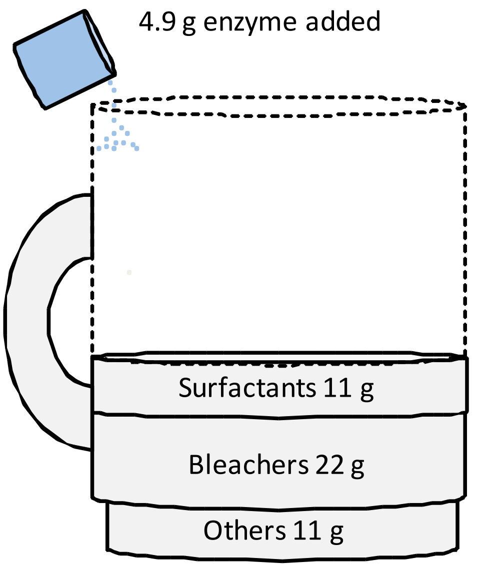


Figure A20: Detergent after. Enzymes have replaced builders and 30% of surfactants. Data refer to the amounts used for washing 3 kg laundry.

The reformulated detergent is more compact than the reference detergent. This reduces packaging and transportation needs. It is assumed that the detergent is packed in a cardboard box (80 g cardboard per kg detergent) and that the detergent is transported 500 km in a truck from manufacturer to user.

Estimation of greenhouse gas reduction per ton laundry

Reformulation of detergents as described above uses enzyme but saves surfactant, builder, packaging and transport as well as heat for the washing process. Greenhouse gas reduction per ton laundry is estimated by environmental modeling of the uses and savings. Modeling is based on data in Table A12. See Nielsen and Skagerlind (2007.)

Table A12: Uses and savings per ton laundry and data sources used in estimation of greenhouse gas reduction.

	Material/utility	Unit	Quantity	Comment	LCA data source
Used	Enzyme	kg	1.6	4.9 g / 3 kg · 1000 kg	Mixture a)
Saved	Surfactants b)	Kg	1.7	(5 g / 3 kg) · 1000 kg	Ecoinvent (2007)
	Builders c)	Kg	15	(46 g / 3 kg) · 1000 kg	Ecoinvent (2007)
	Cardboard	Kg	1.4	(51 g/ 3 kg) · 1000 g/kg · 80 g	Ecoinvent (2007)
	Transport	Kg·km	26	(5 + 46) g · 500 km	Ecoinvent (2007)
	Heat Europe	MJ	300	15°C · 4.7 liter/kg · 1000 kg · 4.2 kJ/(°C · liter) = 300 MJ	Ecoinvent (2007)
	Heat USA	MJ	250	5°C · 12 liter/kg · 1000 kg · 4.2 kJ/°C · liter = 250 MJ	Ecoinvent (2007)

a) Mixture of protease, amylase, lipase, mannanase and cellulase. Greenhouse gas emission is estimated by modelling according to Nielsen et al. (2006).

b) Linear alkylbenzene sulfonate (LAS), Ethoxylated alcohol and sodium soap.

c) Zeolite, sodium etc. carbonate.

Greenhouse gas emission caused by enzyme production is in the order of 12 kg CO_2e per ton laundry whereas avoided emissions obtained by the surfactant, builder, heat, transport and cardboard savings vary from region to region. See Table A13.

Table A13: Greenhouse gas (GHG) balance when enzymes are replacing surfactants and builders in detergents and wash temperature is reduced. All data are in kg CO_2e/ton laundry

Region	GHG emission caused by enzyme production	GHG emission avoided by surfactant and builder saving	GHG emission avoided by heat saving	GHG emission avoided by cardboard and transport saving	Net GHG saving
Europe	12	55	49	1.4	93
North America	12	55	36	1.4	80
Asia+ South America + Rest of world	12	55	0	1.4	44

16. Save detergents and energy with automatic dishwashing enzymes

Enzymes were introduced in automatic dishwashing detergents during the 1980'ties and are widely used today because they effectively remove difficult and dried-on soils from dishes at low temperatures. See Kottwitz (2007).

The potential of enzymes in automatic dish washing is, however, yet not fully utilized. Use of the newest and most innovative enzymes in dishwashing can help replacing large amounts of chemicals in detergents and allow wash temperature reductions from the current level.

Producing dishwashing chemicals and heating the dishwashing water requires energy and leads to greenhouse gas emissions. Washing at lower temperatures with slightly more enzyme and considerably less chemicals reduces greenhouse gas emissions. The amount of greenhouse gasses which could be avoided if the most innovative detergent enzyme solutions were implemented globally is estimated in the following based on data and information from specialists in Novozymes unless otherwise noted.

Figure A21: Contribution to climate change is reduced when chemicals are saved in automatic dishwashing detergents and dish washing temperature is reduced.

Reference situation

Many different machines and wash programs are used in automatic dishwashing and energy and water consumption varies. Wash temperature is, however, typically around 50°C in the USA and Europe and water consumption typically 5 liters per wash. These wash conditions have been used as reference, acknowledging that it can be different in other parts of the world. Detergent use is also subject to variation but a typical average value of 20 g per wash is assumed.

Description of the enzyme assisted process

0.8 g enzymes are added to the detergent per wash (4% of 20 g detergent). It is estimated that enzymes can play an important role in replacing phosphate (sodium tripolyphosphate, STP) and that the use of enzymes can allow a wash temperature reduction to around 40°C without compromising the overall wash performance. Phosphate content of detergents varies, but a typical value of 8 g per wash has been assumed (40% of 20 g).

The reformulated dishwashing detergent is more compact than the reference detergent. This reduces packaging and transportation needs. It is assumed that the detergent is packed in a cardboard box (80 g cardboard per kg detergent) and that the detergent is transported 500 km in a truck from the manufacturer to the user.

Assumptions

It is assumed that all wash water is heated with electricity and that electricity is produced by combusting natural gas.

Estimation of greenhouse gas reduction per automatic dish wash cycle

Reformulation of detergents as described above uses enzyme but saves phosphate, packaging and transport as well as heat for the washing process. Greenhouse gas reduction per automatic dish wash cycle is estimated by environmental modeling of the uses and the savings. Modeling is based on data in Table A14.

Table A14: Uses and savings per automatic dish wash cycle.

	Material/utility	Unit	Quantity	Comment	LCA data source
Used	Enzyme	g	0.8		Mixture of proteasea and amylases a)
Saved	Phosphate	g	8	STP	
	Cardboard	g	0.6	(8 –0.8) g · 0.08 g/g	Ecoinvent (2007)
	Transport	kg ·km	3.9	(8 – 0.8+ 0.6)g · 500 km	Ecoinvent (2007)
	Heat	kJ	210	10^{o}C · 5 liter · 4.2 kJ/ (^{o}C · liter)	Ecoinvent (2007)

a) Greenhouse gas emission is estimated by modeling according to Nielsen et al. (2006).

Greenhouse gas emission caused by enzyme production varies depending on the mixture but is typically in the order of a few grams of CO$_2$e per dishwashing cycle whereas avoided emissions obtained by the phosphate, heat, transport and cardboard savings are in the order of 85 g CO$_2$e per wash cycle.

The net saving is therefore estimated to be in the order of 80 g CO$_2$e per wash.

17. References

Berlin J (2002): Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. *International Dairy Journal* 12:939–953.

Biotimes (2006): Unlocking the magic of barley brewing. Novozymes. Download.

Biotimes (2008): Vinozym® Process – We make the wine. November 27, pp. 3-4. Download.

Cowan D, Oxenbøll KM and Holm HC (2008): Enzymatic bioprocessing of oils and fats. *Inform*. April 210-212. Download.

DMG (2005): Green account 2004, Danish Malting Group A/S, 4760 Vordingborg, Denmark.

Ecoinvent (2007): The Ecoinvent Data Base v2.0. www.ecoinvent.com

Ekvall T and Weidema BP (2004): System boundaries and input data in consequential life cycle inventory analysis. *International journal of LCA* 9: 161–

171.

Høier E, Lilbæk H, Broe ML, Sørensen NK (2006): Enhancing cheese yield by phospholipase treatment of cheese milk. *Aust J Dairy Technol* 61:179–182.

Hubbe MA (2005): Paper. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

Kirk O , Damhus T, Borchert TV, Fuglsang CC, Olsen HS, Hansen TT, Lund H, Schiff HE, Nielsen LK (2004): Enzyme Applications, Industrial. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc.

Kottwitz B (2007): Enzymes in automatic dishwashing. In Enzymes, 4. Non-food Application. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co.

LCAfood (2003): LCA food database. www.lcafood.dk

Lenting (2007): Enzymes in Textile Production. In Enzymes, 4. Non-food Application. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co.

Nielsen PH (2006): Environmental assessment of enzyme application in the tanning industry. *Leather International*. August/September 2006. 18-24. Download

Nielsen PH, Oxenbøll K and Wenzel H (2006): Cradle-to-Gate Environmental Assessment of Enzyme Products produced in Denmark by Novozymes. *International Journal of LCA*. 12: 432-438. Download

Nielsen PH and Wenzel H (2006): Environmental assessment of Ronozyme P5000 CT phytase as an alternative to inorganic phosphate supplementation to pig feed used in intensive pig production. *International Journal of LCA*. 12: 514-520. Link.

Nielsen PH and Skagerlind P (2007): Cost-neutral replacement of surfactants with enzymes - a short-cut to environmental improvement for laundry washing. *Household and Personal Care Today*. 4: 3-7. Download.

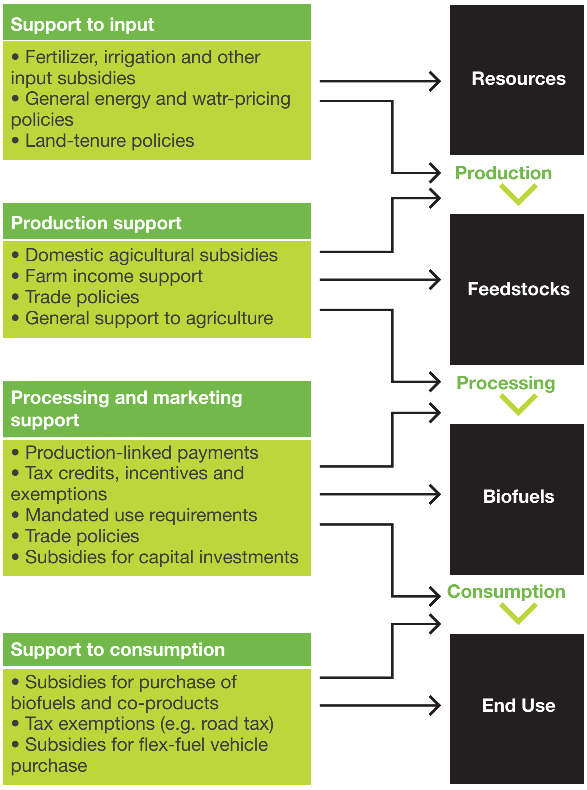
Nielsen PH, Dalgaard R, Korsbak A and Petterson D (2008): Environmental assessment of Ronozyme WX CT xylanase used in Danish pig production. *International Journal of LCA*. 13: 49-56. Download.

Nielsen PH and Høier E (2008): Environmental assessment of yield improvements obtained by the use of the enzyme phospholipase in mozzarella cheese production. *International Journal of LCA*. 14. 137-143. Link.

Nielsen PH, Kuilderd H, Zhou W and Lu X (2009): Enzyme biotechnology for sustainable textiles. In Blackburn RS: Sustainable textiles: Life cycle and environmental impact. Woodhead Textiles Series No. 98. Woodhead Publishing Limited. http://www.woodheadpublishing.com/en/book.aspx?bookID=1506 (in print)

Appendix 4

Various policies affect the biofuel value chain at different stages (see the figure below).



Policies affecting the take up of biofuels – Source FAO 2008

Appendix 5

Biofuels scenarios assumptions

Scenario name: Target 5 Fast tech

Overall Ethanol Blend share into gasoline

	2010	2015	2020	2025	2030	2035	2040
OECD North America	2.0%	3.0%	4.0%	5.0%	5.0%	5.0%	5.0%
OECD Europe	2.0%	3.0%	4.0%	5.0%	5.0%	5.0%	5.0%
Japan	1.0%	2.0%	4.0%	5.0%	5.0%	5.0%	5.0%
SK AU NZ	1.0%	2.0%	4.0%	5.0%	5.0%	5.0%	5.0%
FSU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Eastern Europe	1.0%	2.0%	4.0%	5.0%	5.0%	5.0%	5.0%
China	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Other Asia	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
India	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%	14.0%
Africa	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Share of ethanol from cellulosic and other low-GHG processes

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
OECD Europe	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Japan	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
SK AU NZ	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
FSU	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Eastern Europe	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
China	0.1%	5.0%	20.0%	60.0%	40.0%	40.0%	40.0%
Other Asia	0.1%	0.1%	5.0%	20.0%	0.2%	0.2%	0.2%
India	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Middle East	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Latin America	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Africa	0.1%	0.1%	5.0%	20.0%	40.0%	40.0%	40.0%

Overall other biofuels Blend share into diesel

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.4%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
OECD Europe	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Japan	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SK AU NZ	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
FSU	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Eastern Europe	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
China	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other Asia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
India	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Africa	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Share of other biofuels biotechnologically produced

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
OECD Europe	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
Japan	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
SK AU NZ	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
FSU	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
Eastern Europe	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
China	0.0%	0.1%	5.0%	20.0%	40.0%	90.0%	90.0%
Other Asia	0.0%	0.1%	5.0%	20.0%	0.2%	90.0%	90.0%
India	0.0%	0.1%	5.0%	20.0%	0.1%	90.0%	90.0%
Middle East	0.0%	0.1%	5.0%	20.0%	90.0%	90.0%	90.0%
Latin America	0.0%	0.1%	5.0%	20.0%	0.1%	90.0%	90.0%
Africa	0.0%	0.1%	5.0%	20.0%	40.0%	90.0%	90.0%

Scenario name: Target 20 slow tech

Overall Ethanol Blend share into gasoline

	2010	2015	2020	2025	2030	2035	2040
OECD North America	2.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
OECD Europe	4.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Japan	1.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
SK AU NZ	1.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
FSU	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Eastern Europe	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
China	0.1%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Other Asia	0.2%	0.2%	1.0%	4.0%	10.0%	15.0%	15.0%
India	2.5%	5.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	14.0%	16.0%	18.0%	20.0%	20.0%	20.0%	20.0%
Africa	0.1%	0.1%	1.0%	4.0%	10.0%	15.0%	15.0%

Share of ethanol from cellulosic and other low-GHG processes

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
OECD Europe	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Japan	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
SK AU NZ	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
FSU	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Eastern Europe	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
China	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Other Asia	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
India	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Middle East	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Latin America	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Africa	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Share of other biofuels biotechnologically produced

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.4%	2.0%	8.0%	15.0%	20.0%	20.0%	20.0%
OECD Europe	4.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Japan	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
SK AU NZ	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
FSU	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Eastern Europe	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
China	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Other Asia	0.0%	0.2%	1.0%	4.0%	10.0%	15.0%	15.0%
India	0.0%	5.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Africa	0.0%	0.1%	1.0%	4.0%	10.0%	15.0%	15.0%

Scenario name: Target 20 high tech

Overall Ethanol Blend share into gasoline

	2010	2015	2020	2025	2030	2035	2040
OECD North America	2.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
OECD Europe	4.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Japan	1.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
SK AU NZ	1.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
FSU	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Eastern Europe	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
China	0.1%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Other Asia	0.2%	0.2%	1.0%	4.0%	10.0%	15.0%	15.0%
India	2.5%	5.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	14.0%	16.0%	18.0%	20.0%	20.0%	20.0%	20.0%
Africa	0.1%	0.1%	1.0%	4.0%	10.0%	15.0%	15.0%

Share of ethanol from cellulosic and other low-GHG processes

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
OECD Europe	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Japan	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
SK AU NZ	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
FSU	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Eastern Europe	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
China	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Other Asia	0.1%	0.1%	5.0%	20.0%	40.0%	40.0%	40.0%
India	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Middle East	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%	90.0%
Latin America	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Africa	0.1%	0.1%	5.0%	20.0%	40.0%	40.0%	40.0%

Overall other biofuels Blend share into diesel

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.4%	2.0%	8.0%	15.0%	20.0%	20.0%	20.0%
OECD Europe	4.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Japan	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
SK AU NZ	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
FSU	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Eastern Europe	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
China	0.0%	4.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Other Asia	0.0%	0.2%	1.0%	4.0%	10.0%	15.0%	15.0%
India	0.0%	5.0%	10.0%	15.0%	20.0%	20.0%	20.0%
Middle East	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Latin America	0.0%	0.0%	1.0%	4.0%	10.0%	15.0%	15.0%
Africa	0.0%	0.1%	1.0%	4.0%	10.0%	15.0%	15.0%

Share of other biofuels biotechnologically produced

	2010	2015	2020	2025	2030	2035	2040
OECD North America	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
OECD Europe	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Japan	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
SK AU NZ	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
FSU	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Eastern Europe	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
China	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Other Asia	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
India	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Middle East	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Latin America	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%
Africa	0.0%	0.1%	5.0%	20.0%	60.0%	90.0%	90.0%