Executive Summary of the BREW Study

Medium and Long-term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources

- The Potential of White Biotechnology

The BREW Study

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In the last few years, enormous progress has been made in biotechnology including genetic engineering. Further major scientific and technological breakthroughs are expected for the coming years and decades. While biotechnology has already taken shape in the production of pharmaceuticals, fine chemicals and speciality chemicals and is expected to expand considerably in these sectors in the short to medium term, there is substantial uncertainty about when, how and to which extent biotechnology will also play a role in the production of *bulk* chemicals. High expectations are connected to the developments in this field of "White Biotechnology" with regard to their benefits for science, technology and society in the medium to long term. In the recent past important steps have been made in research, companies and policy, with the goal of developing White Biotechnology for the production of chemicals. While there is a strong drive behind these developments there is so far only very little quantitative information available in the public domain on the current and future economic, environmental and societal implications. This report is a contribution to close this gap of knowledge.

In terms of scope, this report studies processes which convert biomass-derived feedstocks (e.g. fermentable sugar) into *organic bulk* chemicals (e.g., lactic acid, acetic acid, butanol and ethanol) by means of White Biotechnology, i.e. by fermentation or enzymatic conversion, either *with* or *without* genetically modified organisms. Apart from White Biotechnology, also conventional chemistry is involved in all processes. All White Biotechnology products are compared to functionally equivalent petrochemical products. The focus is on industrial chemicals while food, animal feed and fuels *only* are excluded.

The key research questions addressed in this report are which products could be made with White Biotechnology, whether these products can contribute to savings of energy use and greenhouse gas (GHG) emissions, under which conditions the products become economically viable, which risks may originate from a shift towards White Biotechnology chemicals including the use of genetically modified organisms (GMO) in fermentation and what the public perception is.

In **Chapter 2** of this report, an overview is provided of chemicals which can be produced by White Biotechnology. Starting from an extensive list of possible bio-based chemicals (see Figure 2-1 and Table 2-28 and 2-29) a selection was made based on the product-tree approach, leading to a selection of 19 building blocks plus derivatives of natural fats and oils and finally genetically modified crop plants. These products have been discussed in detail in Chapter 2.1 to 2.7. For each product, the key features of production and use are discussed (e.g., biotechnological options, level of maturity, commercial status, world-wide production volume, challenges and drivers). Further assessment within the BREW team led to a selection of 21 products as top candidates for White Biotechnology (see Table 2-42; these products are analysed in-depth in Chapter 3 and 4). Two key strategies for their market entry are firstly *Direct substitution of a bulk petrochemical* and secondly *Functional competition of bio-based bulk chemicals with fossil-based ones*. Some of the selected 21 White Biotechnology chemicals belong to both categories.

Based on the insight gained in Chapter 2 we conclude that **White Biotechnology offers numerous opportunities for the manufacture of new and existing organic bulk chemicals** from a variety of feedstocks and that, given the early stage of development for most products and processes, **very substantial progress can be expected** for the future. **According to our assessment, the large-scale manufacture of White Biotechnology chemicals is technologically challenging but there is a wide range of interesting options and it does seem feasible for the longer term.**

While, from a (bio-)chemical and a technological point of view, the opportunities are interesting and promising, the attractiveness for industry and policy depends to a very large extent on whether White Biotechnology products offer advantages in economic and in environmental terms.

In **Chapter 3** we therefore conduct detailed environmental and economic assessments (in specific terms, i.e. per tonne of product) for the 21 White Biotechnology products selected in Chapter 2. So far, quantitative analyses on the environmental impacts and the economic aspects related to bio-based bulk chemicals produced by White Biotechnology are scarce, fragmented and incomparable due to different assumptions and boundary conditions. In contrast, we apply a uniform methodology with common background data (BREWtool). We conduct our analyses for different prices for fermentable sugar but only one oil price (US$ 25/barrel crude oil; for natural gas, a price of 4 €/GJ was assumed for final users in the chemical sector; Appendix A3-2). Chapter 3 discusses also the so-called Generic Approach which is the methodology we developed and applied to assess future processes, for which very little information is available.

In summary, our finding is that White Biotechnology for bulk chemicals production is **primarily an economic challenge** while it **offers very substantial opportunities for the chemical industry to reduce their non-renewable energy use, greenhouse gas emissions** and related environmental impacts. Nearly all of the products studied are environmentally attractive (non-renewable energy use and greenhouse gas emissions) already with *current* technology and using maize as feedstock (30% cradle-to-factory gate non-renewable energy savings as arithmetic mean without adipic acid and acetic acid compared to petrochemicals), and even more so in future (50% energy savings). Larger savings are achieved if lignocellulosic feedstocks can be used in future (up to 75% non-renewable energy savings) and even higher savings can be realized if fermentable sugar from sugar cane is used, where for future technology up to 85% non-renewable energy can be saved on average compared to the production of petrochemicals nowadays. Moreover, White Biotechnology chemicals score clearly better than liquid biofuels (ethanol) with regard to the non-renewable energy savings per unit of agricultural land used (GJ energy saved per hectare land used).

The *economic* challenge of White Biotechnology chemicals in competition with their petrochemical counterparts is closely linked to technological progress. In conclusion, technological breakthroughs (both in the bioprocess step and in product separation and purification) are more important in order to achieve economic attractiveness than to improve environmental attractiveness.

In **Chapter 4**, three scenario projections are developed for Europe (EU-25) until the year 2050. We distinguish between a scenario LOW with rather unfavourable conditions for bio-based chemicals (oil price up to 30 US$/barrel; sugar price of up to 400 €/t; 0% p.a. physical growth in the chemical sector), a scenario MEDIUM (up to 66 US$/barrel, up to 200 € /t sugar and 1.5% p.a. physical growth of organic chemicals) and a scenario HIGH (up to 83 US$/barrel, approx. 70 €/t sugar and 3.0% p.a. physical growth of chemicals).

Absolute non-renewable energy savings for Europe (EU-25) depend on the scenario chosen. In the scenario LOW in 2050, about **7%-10%** of the non-renewable energy demand for the (conventional) production of the selected chemicals studied are saved, while in the scenarios MEDIUM and HIGH this percentage is about **20%-30%** and **39%-67%**, respectively (lower values for starch, higher values for lignocellulosics; see Section 4.5.2 and Appendix 11-13). In other words, up to two thirds (67%) of the current non-renewable energy use for the production of the selected chemicals could be saved by 2050 if substantial progress is made in White Biotechnology and if the use of lignocellulosic feedstocks is successfully developed. Instead of comparing the savings of energy and GHG emissions to the *production of the selected chemicals*, they can also be compared to the *total production of all organic chemicals*. In this case the saving percentages are roughly half of the ones just quoted.

The total land use for bio-based chemical production is relatively low in most scenarios. If starch is used as basis for fermentable sugar, the total land use ranges from 1.0 to 38.1 million ha in the three scenarios. If lignocellulose is used as biofeedstock, only 0.4 to 15.6 million ha are needed. For comparison, the agricultural area in the EU-25 was about 180 million ha in 2002. Land requirements are hence not likely to become a critical issue in the next few decades (Section 4.5.2).

In 2050, White Biotechnology hence offers substantial macroeconomic savings in the scenarios MEDIUM and HIGH (6.7 and 74.8 billion €) while it entails relatively small additional expenses in the scenario LOW (–0.13 billion €, see Section 4.5.2). The macroeconomic savings imply improved international competitiveness. The annual added value of the bio-based chemicals is estimated for 2050 at about 1.8, 8.8 and 33.2 billion € in the scenario LOW, MEDIUM and HIGH respectively.

We conclude from Chapter 4 that, under favourable conditions (see also the four requirements given at the end of this executive summary), White Biotechnology becomes a reality, enabling substantial savings of non-renewable energy use and greenhouse gas emissions, parallel to economic advantages. Given the scenario results we conclude that the large-scale production of White Biotechnology products will most likely occur first in countries with low prices for fermentable sugar (in particular, in Latin America). European industry is likely to develop White Biotechnology in Europe, to apply it first on a large scale abroad and finally to exploit its opportunities in Europe.

In **Chapter 5**, the risks related to the use of White Biotechnology are studied. The main purpose of this chapter is to give insight into the main risk components influencing the overall risk and of the knowledge gaps. Both conventional risks (e.g., human toxicity and accidents) and risks related to generic modification (e.g., horizontal gene transfer) are analyzed:

- **Conventional risks** of biotechnologically produced chemicals (risks related to genetically modified micro-organisms and crops excluded) are found to be comparable to those of chemicals derived from fossil fuels); however, if White Biotechnology materializes, new raw materials, intermediates and final products will be handled and as a consequence, suitable safety procedures need to be developed.
- The **risks related to the use of genetically modified organisms** in White Biotechnology are manageable if adequate precautionary measures are taken; in view of existing knowledge gaps, the specification of these measures requires further work; the challenges are larger for Green Biotechnology compared to White Biotechnology, which is hence closer to large-scale production in chemical industry.

In **Chapter 6**, public perception and stakeholder perception is discussed because this may play an important role for the implementability of White Biotechnology on a large scale. We conclude that stakeholders and the public seem to have a **basically positive attitude** towards organic chemicals made from White Biotechnology, with environmental considerations and the use of renewable raw materials primarily determining this perception. This conclusion is, however, based firstly on studies which partly have a different scope than the BREW study and secondly on the BREW survey among stakeholders which may differ from the perception of the public. While more certainty can hence only be ensured by means of a study dedicated to public perception, the available information indicates that public perception is no critical issue and is, on the contrary, supportive under current circumstances.

Finally, the findings are summarized and conclusions are drawn in **Chapter 7**. It should be kept in mind that the **assumptions made in the BREW study** for the future with regard to the bioprocess (see especially Table 3-2) and downstream processing are crucial for the outcome of the calculations. Moreover, **innovations in fossil-based chemicals production** have not been taken into account in the BREW project, including the production of olefins from coal, which could become the largest menace to (bio-based) White Biotechnology for bulk chemicals.

We conclude from our analysis that the following **four core requirements** must be fulfilled in order to make clear steps towards a bio-based chemical industry, namely:

1. **Substantial technological breakthroughs in the bioprocess step**
2. **Major progress in downstream processing**
3. **Prices for fossil fuels must be high.**
4. **Prices for fermentable sugar must be low.**

For each of these factors we provide suggestions for measures which could be taken and we propose **accompanying activities** (see Chapter 7.2).

To conclude, we strongly recommend to **develop an integrated White Biotechnology strategy** taking into account the four core requirements and the proposed accompanying activities, provided that the European Union arrives at the conclusion to actively support White Biotechnology.