Chapter 8.

Developments in bio-based production

Much innovation has been achieved in biorefining in the last few years, often in the absence of significant policy support. This chapter highlights the potential of biorefining to replace fossil-derived manufacturing in terms of materials that can be produced. While the examples demonstrate that a wide variety of materials is already available in the market, the chapter also gives a sense of perspective: the real test for the future of bio-production in manufacturing is its ability to produce all these promising materials at a scale appropriate to society.

Introduction

Since the publication *Future Prospects for Industrial Biotechnology* (OECD, 2011), interesting bio-based materials have proliferated (Table 8.3). Promoting chemistry at a political level poses challenges as chemicals are largely invisible, and yet they play an essential role in virtually all manufactured goods. This is compounded by the challenge of an industry that struggles with a poor public image (Moreau, 2005). This chapter will examine some of these new bio-based materials spanning a range of different product types and bringing a visibility not seen before. It will also illustrate the range of different bio-based chemicals that are close to commercialisation.

What would be involved in replacing the oil barrel?

The day could come when light and medium transport can be electrified (Delucchi et al., 2014), thereby eliminating the need for liquid road transport fuels. For example, Scania of Sweden is introducing a hybrid truck for city use that can be driven electric-only or with renewable fuels (Scania, n.d.). For its part, Tesla unveiled an all-electric truck in late-2017. The Swedish government aims to have a fossil-independent vehicle fleet by the year 2030 (Hellsmark et al., 2016). France and the United Kingdom declared in mid-2017 that they will be rid of new petrol and diesel cars by 2040.

For shipping and aviation, alternatives to liquid fuels are hard to envisage. Aviation is responsible for up to 3% of global human-made CO_2 emissions. Unlike other forms of transportation, aviation has fewer green alternatives to significantly reduce its carbon footprint. To this end, Los Angeles and Oslo were the first airports in the world to incorporate biofuel into the regular refuelling process (Il Bioeconomista, 2016). Several airlines are now purchasing bio-aviation fuel e.g. KLM and United Airlines. In May 2016, Cathay Pacific commenced a two-year programme of flights from Toulouse to Hong Kong, People's Republic of China (hereafter "China") using renewable jet fuel. In September 2016, Gevo announced it had entered into a heads of agreement with Deutsche Lufthansa AG to supply up to 8 million gallons per year of alcohol-to-jet fuel (ATJ). SkyNRG is a market leader for sustainable jet fuel, supplying more than 20 carriers across five continents (SkyNRG, n.d.).

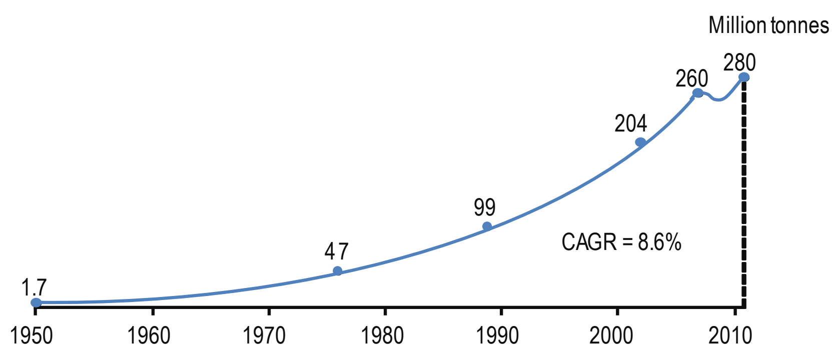
Without fuels production, petrochemicals might be much less profitable. In the current model, petroleum refiners would have great difficulty producing chemicals at low cost if demand for gasoline or diesel fuel were radically reduced. The business model for upstream oil companies would be radically different, especially as new sources of oil become more expensive.

However, the high standard of living attained in OECD countries is not imaginable without the vast plethora of chemicals in everyday use. As a simple illustrative example, there would be no smart phone without chemistry, or any telephone at all. As 96% of all manufactured goods require at least one chemical (Milken Institute, 2013), petrochemicals will be clearly much harder to replace than fossil fuels. If coal, crude oil and natural gas were conserved (by ending the practice of burning them as fuels), a ready feedstock of fossil resources would be available for future generations to make petrochemicals. In the short term, however, it is extremely unlikely that fossil fuels will no longer be burned. Therefore, interim and long-term policy solutions need to be pursued.

The chemicals sector is the largest industrial energy user, accounting for about 10% of global final energy use (Broeren et al., 2014). It is also the third largest industrial source of emissions after the iron and steel, and cement sectors (IEA, 2012). As some countries struggle to meet their emissions reduction obligations, it is puzzling that the chemical sector has been relatively ignored in this respect compared to fuels and electricity (Philp, 2015).

Later this century, increasing demand for chemicals and plastics may cause a competition with fuels for available crude oil. Between 1950 and 2011, plastics consumption rose with a compound annual growth rate (CAGR) of 8.6%, and is now close to 300 million tonnes per annum (Figure 8.1). Future growth in plastics consumption is predicted to be about 4% per annum (ANZ Insights, 2012). Since the mid-1980s, the global chemical industry overall has grown by 7% annually. Asia has driven most of the growth in the past 25 years. If trends continue, global chemical markets could grow on average at 3% per annum in the next 20 years (AT Kearney, 2012).

Figure 8.1. **World plastics consumption, 1950-2011**



Note: CAGR = compound annual growth rate.

Source: Redrawn from ANZ Insights (2012), "Global plastics industry: Market update".

On that basis, plastics consumption could increase about four-fold by 2050. Approximately 8% of world oil production is used in plastics manufacture: 4% as raw material for plastics and 3-4% as energy for manufacture (Hopewell et al., 2009). Therefore, by mid-century, consumption of crude oil to make plastics could increase to 28-32% of current levels of production. This, in turn, would put plastics in competition with fuels for crude oil. Such growth is completely out of step with new oil discoveries, which are at their lowest in 60 years.

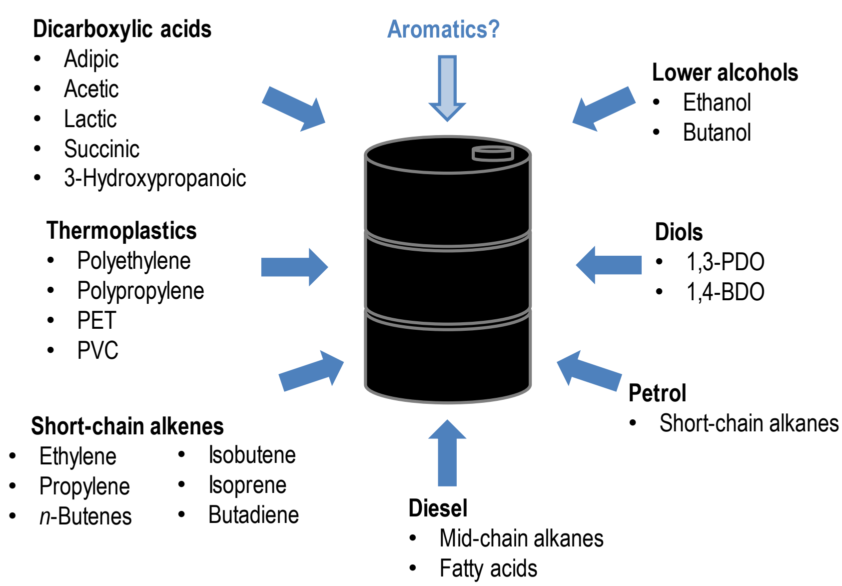
Renewable feedstocks offer the most compelling route to drop-in (exact equivalent) or same-function (different molecule that has the same function) sustainable chemicals. This would previously have been almost entirely the province of chemistry. For example, the whole history of wood chemistry has been largely forgotten since the petrochemicals era (e.g. USDA, 1956), and a lot more can now be done since this early report. More recently, there has been a drive towards "eco-friendly" chemicals, such as the Ecover brand of washing-up liquids. Biotechnology is a relative newcomer as a route to commodity chemicals; it was less than three decades ago that Frost and Lievense (1994) discussed biotechnological routes to aromatics in reference to "environmental considerations and the scarcity of petroleum".

The idea of biotechnological routes to entirely unnatural chemicals only took hold with the emergence of metabolic engineering in the 1990s (Wong, 2016). Many petrochemicals in everyday use have no natural equivalent. They are highly reduced in nature compared to carbohydrates, and often toxic to a microbial catalyst (Yim et al., 2011). This means a daunting task for creating biochemical pathways to a molecule never seen in nature, thus requiring truly synthetic steps. It also requires building other features into a microbial catalyst, such as solvent tolerance. This would create a "robustness" in the microbe, allowing it to survive the conditions of the bioprocess and the toxicity of the desired product.

Despite the challenges, a biotechnological route offers several advantages over a strictly chemical route. Microbial metabolism is extremely diverse, and therefore provides a choice of large numbers of biochemical reactions (one database contains 130 000 hypothetical enzymatic reactions). Biology is often specific and selective, implying that side effects that limit productivity could be minimal or minimised. Microbial processes occur at low temperatures and mostly at ambient pressures, therefore making the biotechnological route attractive in environmental and economic terms.

To date, green, renewable chemistry remains far ahead compared to "renewable biotechnology" in the production of commodity chemicals. Figure 8.2 sums up the challenge.

Figure 8.2. **Chemicals made through metabolic engineering of microorganisms**



Note: PET = polyethylene terephthalate; PVC = polyvinyl chloride; PDO = propanediol; BDO = butanediol.

Source: Adapted from Jiménez-Sánchez and Philp (2015), "Omics and the bioeconomy: Applications of genomics hold great potential for a future bio-based economy and sustainable development".

Most of the chemicals in Figure 8.2 remain as research successes; many may never reach commercialisation. The technical and financial reasons for this limitation are interlinked. In terms of cost, more efficient biotechnologies would bring down production price and make bio-based (either drop-in or equivalent function) more cost-competitive with petrochemistry. In terms of technical issues, scale-up often significantly reduces performance of engineered strains (e.g. Takors, 2012). Fundamentally, bio-based production without public policy support faces a mountainous challenge given the economies of scale possible in petrochemistry. For example, IRENA/ETSAP (2013) estimated the worldwide production costs of bio-based ethylene to be on average 50% higher compared to the production of ethylene in the steam cracking process.

However, a relatively small number of chemicals represent a large proportion of total organic chemicals production. US DOE (2004) identified 12 building block chemicals that can be produced from sugars via biological or chemical conversions (Table 8.1). Building block chemicals are considered to be molecules with multiple functional groups that can be transformed into new families of useful molecules. They can therefore otherwise be termed "platform chemicals".

Table 8.1. **The US DOE top value-added chemicals from biomass feedstocks**

Chemicals
1,4 diacids (especially succinic, fumaric, malic)
3-hydroxypropionic acid
Levulinic acid
Glutamic acid/MSG
Sorbitol
Xylitol/arabinitol
2,5 furan dicarboxylic acid
Aspartic acid
Glucaric acid
Itaconic acid
3-hydroxybutyrolactone
Glycerol

Note: MSG = monosodium glutamate.

Source: Adapted from US DOE (2004), "Top value-added chemicals from biomass (results of screening for potential candidates from sugars and synthesis gas, Vol. 1)".

Saygin et al. (2014) estimated that seven polymers could *technically* replace half of the total common plastics in use in 2007 (Table 8.2). These polymers were bio-PE, bio-PET, PHA, PTT, PLA, starch polymers and cellulosic films.

Table 8.2. **Top seven polymers (and ethylene) that could technically replace half of total polymers production in 2007**

Material	CO_2 emissions savings (tonnes CO_2 per tonne)
Bio-ethylene	1.9-5.3
Bio-polyethylene (PE)	2.4-4.2
Bio-polyethylene terephthalate (PET)	1.9-2.5
Polyhydroxyalkanoates (PHA)	1.4-4.0
Polytrimethylene terephthalate (PTT)	1.1-1.9
Polylactic acid (PLA)	1.2-2.1
Starch polymers	1.7-3.6
Cellulosic films	0-1.9

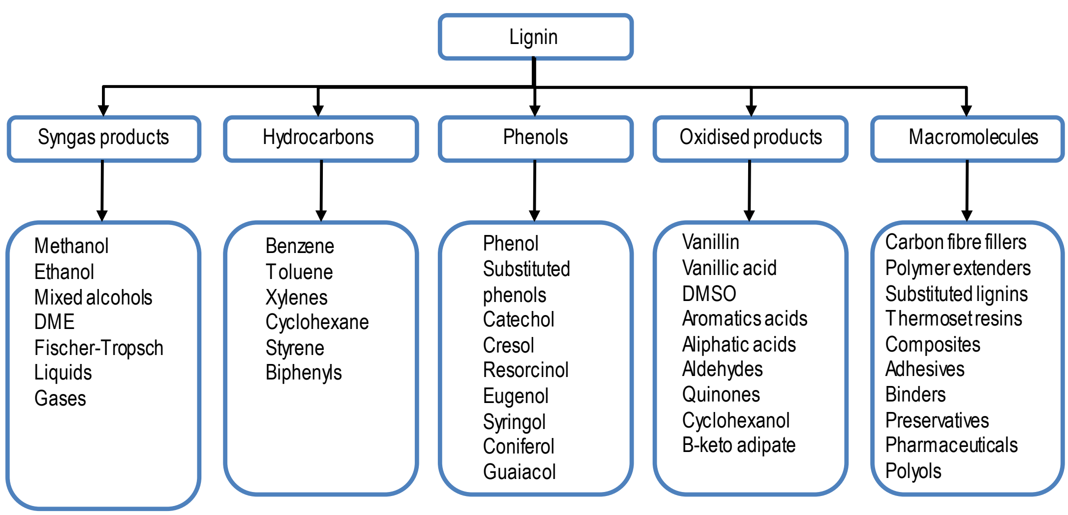
Source: Adapted from Saygin et al. (2014), "Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers".

One significant development has been the arrival of the bio-based equivalents of the major thermoplastics that dominate the market – polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). Bio-PE and bio-PP are produced chemically from monomers that are made through fermentation. They have identical performance characteristics to the petro-based equivalents and, importantly, can directly enter existing recycling systems. They can be categorised as bioplastics as their carbon content comes from renewable resources. As a result, they can make a potential contribution to GHG emissions savings. The global trend in bioplastics production will change significantly, becoming dominated by durable bio-based thermoplastics (OECD, 2013) rather than biodegradable plastics. The most dynamic developments are still expected to be in drop-in bio-based polymers (Aeschelmann et al., 2015).

A question mark exists for the aromatics. Biotechnological routes to aromatics are particularly challenging. As high-volume chemicals with a large range of functions, they cannot easily be replaced: for example, benzene has specific uses in its own right, but has important value chains that lead to even more valuable chemicals. However, commodity aromatics are toxic to microbial cells. Indeed, most microbiological studies with aromatics look at their biodegradation as pollutants rather than their synthesis. Several studies have focused on microbial aromatics production from biomass (Kawaguchi et al., 2016), but not aimed at commodity aromatics.

On the other hand, clear environmental drivers for replacing aromatics exist. The BTX compounds (benzene, toluene and xylene) are mainly produced by catalytic reforming. Typically, this uses hydrogen and catalysts under high temperature (500°C) and high pressure (10-50 bar) (Eriksson, 2013). The largest renewable reservoirs of aromatic materials are lignin and hemicellulose. Lignin creates the greatest challenges for renewable sources of aromatics, but should still not be ignored (Figure 8.3). The total lignin availability in the biosphere exceeds 300 billion tonnes and increases annually by around 20 billion tonnes (Smolarski, 2012).

Figure 8.3. **The potential for renewable aromatics production from lignin**



Note: DMSO = dimethyl sulfoxide.

Source: Redrawn from IEA Bioenergy Task 42 Biorefinery (2012), "Bio-based chemicals. Value added products from biorefineries", www.ieabioenergy.com/publications/bio-based-chemicals-value-added-products-from-biorefineries.

Anellotech of the United States has renewable chemistry solutions to the aromatic challenge. In its process, non-food biomass such as wood, sawdust, corn stover and sugar cane bagasse are gasified and immediately converted into hydrocarbons by a proprietary, reusable zeolite catalyst. The resulting mixture of benzene, toluene and xylenes (bio-BTX) is identical to the petroleum-derived counterparts.

The BTX compounds are integral to the production of a wide range of plastics including polyurethane, polycarbonate, polystyrene and nylon. Hence Toyota Tsusho and Anellotech have an alliance (Biofuels Digest, 2016): Toyota Tsusho is a multinational strategic equity investor in Anellotech and a corporate partner in the renewable aromatic chemicals supply chain. Aromatics are widely used in the automotive industry, and the Toyota Group has championed the use of renewables in vehicles (OECD, 2011).

This report frequently emphasises the alliance of industrial biotechnology with green chemistry. Their convergence has already solved challenges that one or the other could not solve alone. The aromatics challenge is another example of the need to support both, but it also reinforces the fact that solutions for biotechnology lag behind those for chemicals.

Bio-based production gaining visibility

For the public and policy makers, bio-based production has lacked visibility. Table 8.3, however, shows this visibility has increased dramatically in recent years. Nevertheless, this revolution in production could remain unheralded because a bio-based and fossil product look identical e.g. tyre, smart phone screen, drinks bottle. Certification and labelling would help improve this visibility enormously, giving confidence to manufacturers and helping with public perception and acceptance. The increased political impetus from 2015 onwards, especially COP21 and the drive towards a circular economy, could be used as levers to increase this visibility.

Brands and recent deals

The interest of brands has helped improve visibility as noted in Table 8.3. New business alliances ensure that new bio-based products are taking their place in the market (Box 8.1). Brands can also leverage their marketing and global outreach capacities to open markets for bio-based products.

Around 30 key bio-based chemicals are close to full market stability

European Commission (2015) reports more than 90 bio-based chemicals have reached a Technology Readiness Level (TRL) of at least 3. While there are only 3 such chemicals at TRL 9, there are 23 at TRL 8.5 and another 8 at TRL 8. According to EARTO classification (EARTO, 2014), this places them at least at the level of: "Manufacturing fully tested, validated and qualified", which agrees roughly with other TRL classification systems.[1] Therefore it would appear that a reasonable number of important bio-based chemicals are progressing towards TRL 9, which is effectively stable, competitive manufacturing. However, this says little about their market share or future prospects.

Many of these chemicals may not be recyclable or non-toxic; in many cases, they replace petro-based equivalents. The truly biodegradable, non-toxic ones usually take the same or similar function as a petro-based chemical. Their favourable GHG emissions compared to petro-counterparts is the overarching reason for their development.

A common denominator: The challenge of scale

Industry struggles to produce the vast majority of bio-based products and chemicals at a scale that can influence a market. For custom and specialty chemicals, the challenge is more easily surmounted than for commodity chemicals. Biofuels have proven difficult to transition from the laboratory to commercial production due to the huge volumes required to affect the market. In some countries, the margins on petrol and diesel production are so low that it remains difficult to make biofuels at a competitive price.

Table 8.3. **Bio-based products are becoming more familiar**

Latex from dandelions	Prototype tyres containing bio-based latex were showcased in December 2009 at the United Nations Climate Change Conference in Copenhagen. The Fraunhofer Society in partnership with the tyre company Continental has built a pilot plant to produce rubber from dandelions. The Russian dandelion thrives in soils unsuitable for agriculture.
Bottles from sugar	Both the Coca-Cola and PepsiCo companies have plastic bottles that are at least partly bio-based. The Coca-Cola bottle contains mono-ethylene glycol derived from fermented sugar. It is mixed with other components to make bio-polyethylene terephthalate. The long-term aim is to replace petro-PET. Avantium (Netherlands) and BASF intend to produce a different bioplastic for bottles (polyethylene furanoate).
Straw to fuel	In many OECD countries, bioethanol is moving from first generation (cellulosic feedstocks) to second generation. The first of the second-generation biorefineries are open. Clariant of Switzerland uses technology that breaks down lignocellulose enzymatically, and yeast ferments the sugars to ethanol.
Soybean to graphene	Graphene is more than 200 times stronger than steel and conducts electricity better than copper. About 1% of graphene mixed into plastics could turn them into electrical conductors. Graphene is, however, expensive compared to other materials. Researchers at CSIRO, Australia, have created a new method of graphene synthesis from soybean oil (Seo et al., 2017).
Castor nuts to wall plugs	DuPont extracts a chemical building block from castor oil to make a 68% bio-based polyamide, which is as strong as the nylon normally used to make wall plugs.
Bioplastics in cars	One of the earliest uses of bioplastics was replacing metal or petro-plastics components in vehicles, saving GHG emissions and/or weight. Among others, Ford and Toyota are investigating and using bioplastics as textiles in car interiors. Daimler and DSM worked together to create an engine cover that is a 70% bio-based plastic.
Sugar to carpets	Dupont and Mohawk combine bio-based propanediol and a petrochemical building block to make a carpet fibre that is soft, durable and easy to clean. The textile is 37% bio-based.
Yeast to face creams	Korres grows yeast cultures that produce hexapeptides when treated with ozone or irradiated with UV light. The compounds are added as anti-ageing active ingredients in face creams. Amyris has engineered specialised yeast strains that can produce squalene from sugar. Squalene is used as an emollient in moisturiser lotions (Servick, 2015).
Ice cream from lupins	Prolupin has developed a process to extract protein from the seeds of lupins. The protein is used to make ice cream that contains neither lactose nor gluten. Evolva uses a synthetic, biology-derived yeast for fermentation to synthetic vanillin. Other food materials through synthetic biology include stevia (sweetener) and nootkatone (smell of grapefruit).
Biopharmaceuticals	Antibiotics have been traditionally produced from microbes. Synthetic biology has been used to make a potent anti-malarial. Sanofi delivered the first large-scale batches of anti-malarial treatments manufactured with a new semi-synthetic artemisinin derivative to malaria endemic countries in Africa in 2014.
Bacteria in toothpaste	The probiotic Lactobacillus Pro-action, which can be added to toothpaste, specifically targets bacteria in the mouth that cause cavities. It can be added to toothpaste. The bacteria are produced by BASF and the toothpaste marketed by Neva Cosmetics.
Nutrition and food/feed supplements	Cargill makes a sweetener with a synthetic biology yeast to convert sugar molecules to mimic the properties of stevia, with no need for the plant itself. It awaits a commercial launch date. Calysta specialises in the production of microbial proteins for the commercial fish feed and livestock markets.
Enzymes in detergents	Biological detergents contain a range of enzymes that allow washing at lower temperatures, such as 30°C, thus saving energy, emissions and money.
Spider silk to medical implants	Spider silk, an exceptionally strong material, is used in sutures, scaffolds, grafts and some medical implants. Oxford Biomaterials, Orthox Ltd and Neorotex Ltd are investigating a range of biomedical applications of genetically engineered spider silk. The US army is testing protective garments for soldiers made from spider silk. An *E. coli* variant of spider silk could replace Kevlar in air bags.

Note: The first six examples are truly about replacements for petrochemicals, while the others demonstrate the eclectic range of bio-based possibilities. The source of this table gives more examples.

Source: Global Bioeconomy Summit (2015), “Bioeconomy in everyday life”.

Box 8.1. Some recent business developments and alliances in bio-based production

February 2016. BRAIN Biotechnology Research and Information Network AG (BRAIN AG) had a stock market launch to become Germany's first listed bioeconomy company. Large parts of the chemical industry, in particular, have growth potential; experts foresee a rising share of biotechnology products and procedures. BRAIN AG focuses on specialty chemicals and the consumer chemicals divisions. The company received gross proceeds of EUR 31.5 million from the initial public offering (IPO). Deutsche Börse classified BRAIN as belonging to the speciality chemicals sector.

February 2016. Chinese renewable energy investment company Kaidi announced plans to build a biodiesel refinery in Finland. The value of the investment is EUR 1 billion, making it the biggest Chinese investment in Finland to date. The first of its kind, it will produce biofuels by using wood-based biomass. This includes energy wood, harvesting remains and even leftover bark from the forest industry as the main feedstock. The plant will produce 200 000 tonnes of biofuel per year, of which 75% will be renewable diesel and 25% renewable gasoline.

February 2016. Mitsui & Co., BioAmber's partner in the Sarnia (Canada) bio-based succinic acid plant, is investing an additional CAD 25 million in their joint venture. Mitsui will play a stronger role in the commercialisation of bio-succinic acid.

February 2016. Gevo, a renewable products and technology company, announced a license agreement and a joint development agreement with Porta Hnos, a leading alcohols company in Argentina, to construct multiple isobutanol plants in Argentina using corn as a feedstock.

March 2016. Air New Zealand and Virgin Australia announced a partnership to investigate options for locally produced aviation biofuel. The alliance partners are issuing a Request for Information (RFI) to the market to explore the opportunity to procure locally produced aviation biofuel.

April 2016. A new version of the Tetra Pak (Sweden) Tetra Top package will make its global debut in the United States. The new generation carton bottle now comes with a cap and top made from high-density polyethylene (HDPE) derived from sugarcane. Combined with the FSC-certified paperboard used in the main sleeve of the carton, this pushes its renewable content up from 53% to 82%, with no impact on its recyclability.

May 2016. Virent of Wisconsin, United States announced the world's first 100% plant-based polyester shirts. The development of the Virent technology platform is supported through strategic partners including Cargill, the Coca-Cola Company, Honda, Shell and Tesoro.

May 2016. Aemetis and Edeniq, both headquartered in California, entered into a definitive agreement under which Aemetis will acquire all of Edeniq's outstanding shares in a stock plus cash merger transaction. Aemetis is an advanced fuels and renewable chemicals company. Edeniq is a cellulosic ethanol technology company that has developed innovations that unlock cellulosic and starch sugars through a combination of mechanical and biological processes.

June 2016. PTT (formerly known as Petroleum Authority of Thailand) group joined with Japan's Mitsubishi Chemical Holding Corp to form a USD 100 million joint venture to build Thailand's first polybutylene succinate plant with an annual capacity of 20 000 tonnes.

July 2016. Ginkgo Bioworks and Amyris partnered to enable the companies to jointly develop products more efficiently and cost effectively, accelerating time to market. The deal aims to generate USD 300 million in incremental value. Ginkgo is building Bioworks2, a next-generation automated foundry where its organism engineers can develop new designs at massive scale. Amyris has commercialised five products from highly engineered organisms, going into markets from skin care and fragrances to industrial lubricants, tyres and jet fuel.

July 2016. The Ford Motor Company and Jose Cuervo announced an alliance to explore the use of the tequila producer's agave plant by-product to develop more sustainable bioplastics to employ in Ford vehicles.

August 2016. Amyris, in co-operation with Renmatix and Total New Energies in the United States, will work to develop a manufacturing-ready process using wood as the cellulosic feedstock to produce farnesene in a multi-million contract with the US DOE.

August 2016. Sacramento County, California, partnered with Neste of Finland for the trial supply of Neste renewable diesel in its fleet of more than 400 trucks and heavy equipment.

Box 8.1. **Some recent business developments and alliances in bio-based production** (*continued*)

September 2016. Toyobo, one of Japan's top fibres and textile manufacturers, and Avantium, a scale-up renewable chemicals company of the Netherlands, partnered on polyethylene furanoate (PEF) polymerisation and PEF films. The two companies have jointly developed thin films made from PEF, a 100% bio-based plastic. Avantium is working in collaboration with brand partners Danone and the Coca-Cola Company to bring 100% bio-based PEF bottles to the market.

September 2016. Neste of Finland and IKEA of Sweden announced a partnership to deliver renewable, bio-based plastics. The partnership combines IKEA's commitment to reduce dependence on virgin fossil-based materials and Neste's expertise in renewable solutions.

September 2016. LanzaTech has produced 1 500 gallons of jet fuel, derived from waste industrial gases from steel mills, via a fermentation process. The fuel has passed all its initial performance tests. It is the result of a partnership between Virgin and LanzaTech.

September 2016. Virent established a strategic consortium with Tesoro, Toray, Johnson Matthey and the Coca-Cola Company focused on completing the development and scale-up of Virent's BioForming technology to produce low-carbon bio-based fuels and bio-paraxylene (a key raw material for the production of 100% bio-polyester).

September 2016. Global Bioenergies, Preem, Sekab and Sveaskog announced having joined forces to develop a high-performance fuel entirely based on forest resources. The consortium has signed a collaboration agreement to carry out a conceptual scope study for a first plant in Sweden. This work will be carried out as part of the "Bio-Based Gasoline Project" with support from the Swedish Energy Agency.

September 2016. Mater Biotech, a 100% company owned by Novamont, opened its first commercial bio-BDO plant using Genomatica's technology that converts renewable feedstocks into 1,4 butendiol (BDO) in Bottrighe di Adria (Rovigo, Italy). Thanks to an investment of EUR 100 million, Novamont has managed to revive an abandoned manufacturing site of Bioitalia. The plant will produce 30 000 tonnes of renewable BDO per year by 2017.

September 2016. Loblaw of Canada announced the launch of compostable President's Choice (Loblaw's in-house brand) single-serve coffee pods. They are made almost entirely from plant materials and reclaimed coffee bean skins. They are the result of Canadian innovation and collaboration between the University of Guelph's Bioproducts Discovery and Development Centre (BDDC), Club Coffee (a Toronto-based company) and Competitive Green Technologies (Leamington, Ontario, a producer of bio-polymers/plastics and bio-composites).

October 2016. Ginkgo Bioworks and Genomatica announced an alliance to deliver biology-based solutions for the world's highest-volume intermediate and specialty chemicals more rapidly. Mainstream chemical producers can now in-license technology to manufacture their widely used chemicals with cost-effective and sustainable whole-process solutions that include engineered microorganisms, complete process designs and technology transfer support.

November 2016. The Danish Minister for Environment and Food launched the white paper on Danish circular economy at the conference "Danish Pioneers of Sustainability" hosted by the Confederation of Danish Industry.

November 2016. Global Bioenergies of France announced completion of its demonstrator plant in Leuna, Germany. This is the only facility in the world dedicated to the direct fermentation of gaseous hydrocarbons.

November 2016. Corbion of the Netherlands is building its new polylactic acid (PLA) bioplastics polymerisation plant at an existing Corbion site in Rayong, Thailand. Upon completion in 2018, it will be able to produce a portfolio of PLA neat resins: from standard PLA to innovative, high heat-resistant PLA.

December 2016. Leaf Resources of Australia announced a collaboration with Novozymes to further increase the yields and efficiency associated with Leaf Resources' innovative biomass conversion technology, Glycell, which is a combination of well-established process engineering and innovative chemistry.

December 2016. The South African Department of Agriculture, Forestry and Fisheries has approved four NexSteppe sorghum hybrids for commercial sale in the country. NexSteppe is a US company pioneering the next generation of sustainable feedstock solutions for the biofuels, biopower, biogas and bio-based products industries.

Box 8.1. **Some recent business developments and alliances in bio-based production** (*continued*)

January 2017. The US Department of Energy's Bioenergy Technologies Office (BETO) selected LanzaTech of New Zealand and the United States to receive USD 4 million to design and plan a demonstration-scale facility. They will use industrial off gases to produce 3 million gallons per year of low-carbon jet and diesel fuels. The facility will recycle industrial waste gases from steel manufacturing.

January 2017. In conjunction with the Institute for Materials and Wood Technology at the Bern University of Applied Sciences, AVALON Industries is launching a research project to replace formaldehyde in PF resins with the bio-based, non-toxic platform chemical 5-HMF (5-Hydroxymethylfurfural). Government-sponsored by the Swiss Commission for Technology and Innovation, the project will build on the positive results in a similar research project to develop non-toxic urea-HMF resins.

February 2017. Clariant of Switzerland, together with Mercedes-Benz and Haltermann Carless, tested the use of sustainable cellulosic ethanol from agricultural residues in a fleet test with Mercedes-Benz series vehicles over 12 months for the first time in Germany. The fuel by Haltermann Carless, which has a cellulosic ethanol content of 20% by volume (E20), was produced at Clariant's Sunliquid plant in Straubing, Germany. The cellulosic ethanol allows GHG emission savings of up to 95% across the entire value chain without competing with food production or tying up agricultural land.

February 2017. Global Bioenergies, France, announced the production of ETBE (ethyl-tertiary-butyl ether) purely from renewable resources. It can be used as an additive in vehicle fuel, up to a maximum of 23%, thereby increasing the proportion of biofuels in blends with fossil fuels. It is made by combining renewable ethanol with renewable isobutene. This first production of entirely renewable ETBE was supported by a grant of the German Ministry of Education and Research.

March 2017. Danone and Nestlé Waters, the world's two largest bottled water companies, have joined forces with Origin Materials, a Californian start-up, to form the NaturALL Bottle Alliance. Together, the three partners aim to develop and launch at commercial scale a 100% bio-based PET plastic bottle.

March 2017. The initial public offering (IPO) of Avantium raised EUR 103 million on Euronext Amsterdam and Euronext Bruxelles. Funds raised will be used to further commercialise Avantium's inventions into viable production processes. This will start with the commercialisation of the YXY technology, in a joint venture with BASF, by building the first commercial-scale reference plant for FDCA. On the basis of the share price, Avantium's market capitalisation reached EUR 277 million.

On the other hand, high-value specialty and fine chemicals are mostly produced in more manageable, low volumes (and market sizes) with which a young industry can cope. They also offer larger margins. The successful production of low-volume chemicals via metabolic engineering routes may provide greater market confidence than failure to make high-volume fuels. Companies adopting this strategy may be considered as the second generation of synthetic biology, or metabolic engineering, companies.

Even if successful in the marketplace, high-value speciality and fine chemicals may not have a huge impact on overall GHG emissions. Large volume, low margin commodity chemicals generally generate the largest GHG emissions. In the analysis by Saygin et al. (2014), seven bio-based materials had an estimated technical CO_2 emissions reduction potential of 0.3-0.7 Gigatonnes (Gt) CO_2 in 2030. Assuming the same potential for the remainder of organic materials production, they estimated a total technical reduction potential of up to 1.3-1.4 Gt CO_2 per year by 2030 compared to 3.2-3.7 Gt CO_2 for fuels.

Conclusions

The nascent bio-based materials industry has accomplished much of its achievements with little policy support beyond a subsidy for research and development (OECD, 2014). This is understandable as there is a mere handful of liquid fuels and vast numbers of chemicals, complicating the possibilities for mandates. However, not supporting bio-based materials in public policy misses significant opportunities for GHG savings. It also fails to take advantage of other policy goal benefits such as making a good fit with circular economy ambitions, reindustrialisation and decentralised manufacturing. These policy goals find excellent alignment with the integrated biorefinery concept, the most ambitious, but also most complex, biorefinery model. Ignoring bio-based chemicals and materials in public policy makes the economics of integrated biorefineries questionable; the margins for many chemicals are usually better than for high-volume fuels. The widespread policy support for biofuels and bioenergy systematically allocate biomass for these purposes, and not for materials.

Note

1. Technology Readiness Levels (TRLs) are a method of estimating technology maturity, generally ranging from 1 (basic research) to 9 (launch and operations): https://en.wikipedia.org/wiki/Technology_readiness_level.

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