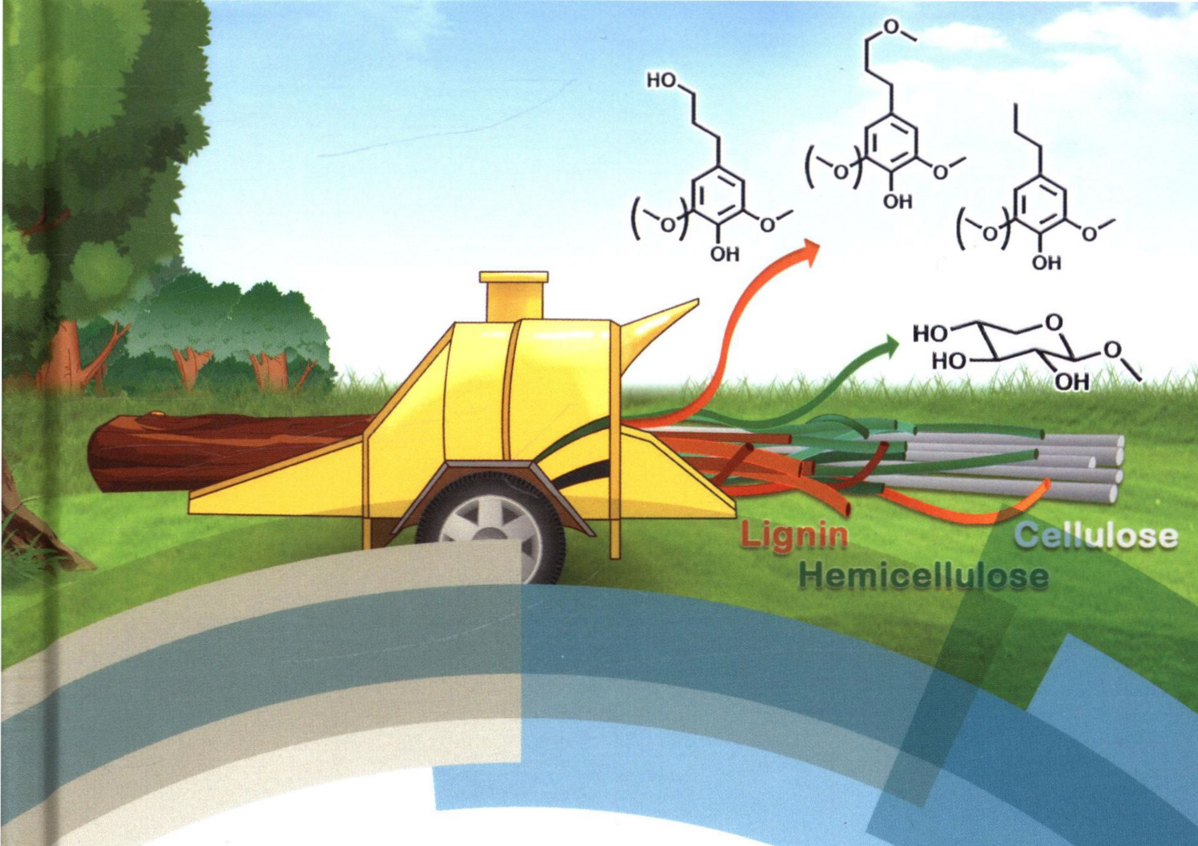

Faraday Discussions

Volume: 202

Bio-Resources: Feeding a Sustainable Chemical Industry

ROYAL SOCIETY OF CHEMISTRY

There is currently a rapid growth in interest in the use of renewable resources and, in particular, bio-resources for the manufacture of sustainable chemicals and materials. This movement has been encouraged by end-user concerns over the security of supply (for products based on traditional but diminishing feedstocks), legislation forcing substitution of many common (typically petroleum-based) chemicals, new standards for bio-based products designed to stimulate the markets in Europe and the USA, incentives, and consumer pressure.

The first significant market movement in this direction was with biofuels, but the rush to produce these without proper consideration of competing uses for the resources or the efficiency of the manufacturing processes lead to considerable debate over the true sustainability of the products and processes. With increasing pressure in Europe, the USA and elsewhere to move towards bio-based chemicals, it is essential that the bio-economy is underpinned by sound and well-debated science and technology and that we embrace key chemical technologies including catalysis.

This volume addresses some of the critical issues in this field by bringing together experts from different but complementary areas of the chemical sciences. The topics covered include:

- Bio-based materials
- Bio-based chemicals
- Conversion technologies
- Feedstocks and analysis

The cover image describes a catalytic method to extract and upgrade lignin into mono-aromatics from lignocellulosic biomass.

Front cover image courtesy of Xiaoming Huang

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ISBN 978-1-78262-954-2

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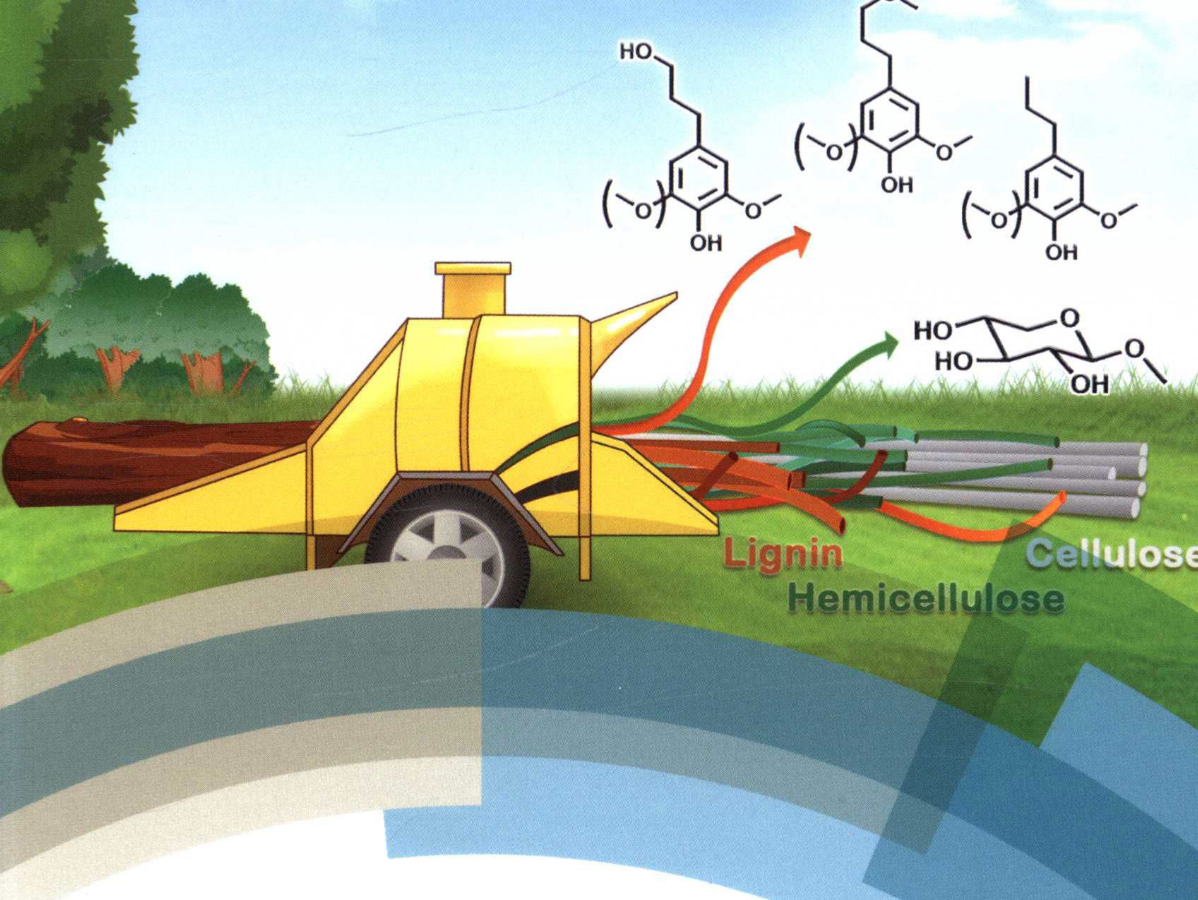
2017



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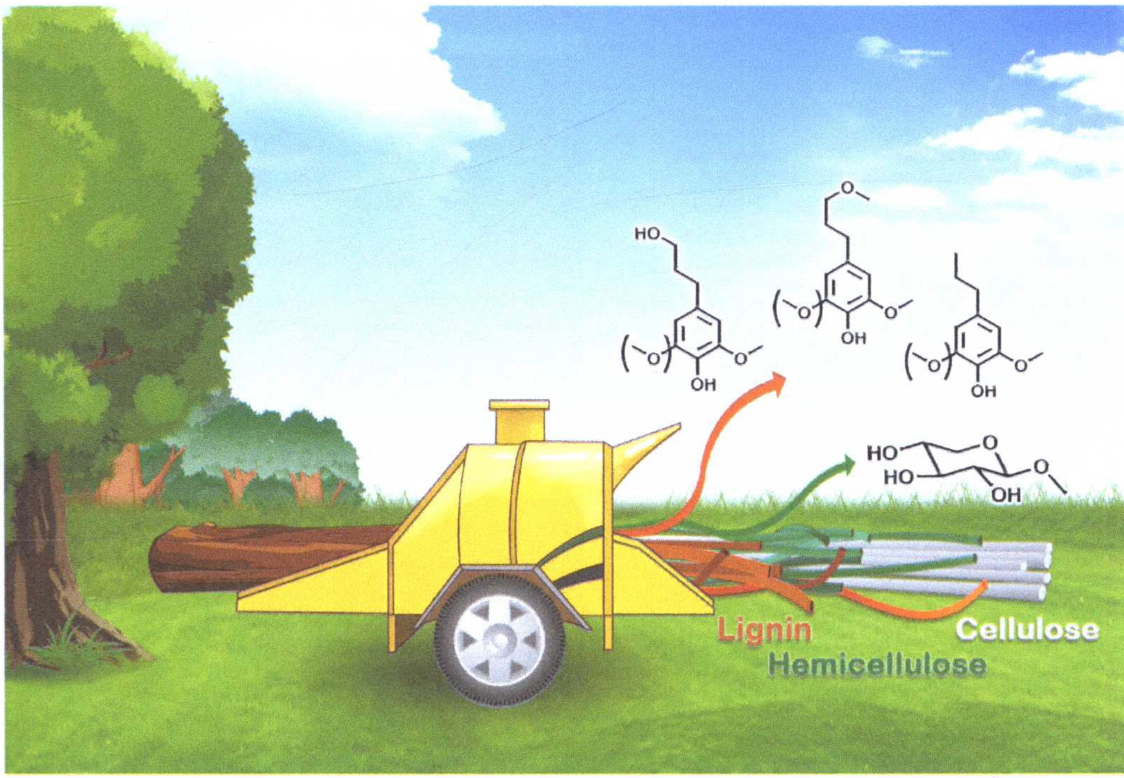
19–21 June 2017



FARADAY DISCUSSIONS

Volume 202, 2017

ROYAL SOCIETY OF CHEMISTRY

The Faraday Division of the Royal Society of Chemistry, previously the Faraday Society, was founded in 1903 to promote the study of sciences lying between chemistry, physics and biology.

Faraday Discussions (Print ISSN 1359-6640, Electronic ISSN 1364-5498) is published 10 times a year by the Royal Society of Chemistry, Thomas Graham House, Science Park, Milton Road, Cambridge, UK CB4 0WF.

Volume 202 ISBN 13: 978-1-78262-954-2

2017 annual subscription price: print+electronic £1010 US $1782; electronic only £962, US $1693. Customers in Canada will be subject to a surcharge to cover GST. Customers in the EU subscribing to the electronic version only will be charged VAT.

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Bio-resources: feeding a sustainable chemical industry

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A General Discussion on Bio-resources: feeding a sustainable chemical industry was held in London, UK on the 19th, 20th and 21st of June 2017.

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ISSN 1359-6640; ISBN 978-1-78262-954-2

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See Emiel J. M. Hensen *et al.*, *Faraday Discuss.*, 2017, **202**, 141–156.

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Faraday Discussions

PAPER

Feeding a sustainable chemical industry: do we have the bioproducts cart before the feedstocks horse?

Bruce E. Dale

Received 8th June 2017, Accepted 11th July 2017
DOI: 10.1039/c7fd00173h

A sustainable chemical industry cannot exist at scale without both sustainable feedstocks and feedstock supply chains to provide the raw materials. However, most current research focus is on producing the sustainable chemicals and materials. Little attention is given to how and by whom sustainable feedstocks will be supplied. In effect, we have put the bioproducts cart before the sustainable feedstocks horse. For example, bulky, unstable, non-commodity feedstocks such as crop residues probably cannot supply a large-scale sustainable industry. Likewise, those who manage land to produce feedstocks must benefit significantly from feedstock production, otherwise they will not participate in this industry and it will never grow. However, given real markets that properly reward farmers, demand for sustainable bioproducts and bioenergy can drive the adoption of more sustainable agricultural and forestry practices, providing many societal "win–win" opportunities. Three case studies are presented to show how this "win–win" process might unfold.

How we got here: a very brief history of sustainable bioproducts and bioenergy

The current sustainable bioproducts effort descends from the "farm chemurgic" movement in the United States during the mid-1930s.[1,2] U.S. farms produced vastly more agricultural commodities than Americans could consume, and as a result, agricultural prices were depressed. The four U.S. Department of Agriculture Regional Laboratories were established to develop industrial uses of agricultural materials, increase demand for crop products and raise crop prices to benefit rural economies. Raising crop prices and strengthening rural economies were explicit policy goals. Since then, many bioproducts have been developed but have had to compete against inexpensive, entrenched petroleum-based products, and market penetration has been slow in most cases.

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Crop yields have continued to grow, leading to increased U.S. emphasis on exporting its crop commodities, including through various food aid projects. A serious unintended consequence of this food aid is that domestic agriculture in the countries receiving aid has sometimes been undermined.[3] Since agriculture is the most basic economic activity of many countries, whole societies have also been undermined. Driven by corn surpluses, U.S. sugar tariffs enabled the high fructose corn syrup (HFCS) sweetener industry. A serious unintended consequence of the flood of HFCS has been increased obesity and diabetes, both of which are directly linked to over-consumption of HFCS.[4,5]

I raise these issues to point out the fact that there are serious unintended consequences of not finding good industrial uses of our agricultural products. It is neither necessary nor wise to use all agricultural output to produce food and feed.

This Faraday Discussion is devoted to supplying feedstocks for biobased products. A little simple arithmetic is sufficient to reveal an uncomfortable fact about biobased products relative to feedstock supply.

In recent years, the U.S. corn crop has averaged about 14 billion bushels per year, or roughly 356 million tonnes per year. The amount of available starch increases by about 1.0 percent per year as corn yields continue to increase, or about 2.67 million tonnes of "new starch" per year. The Cargill–Dow wet milling plant in Blair, Nebraska, produces about 127 000 tonnes per year of polylactic acid (PLA) from corn starch at about 90% yield. Thus, the total demand of the Blair plant for corn starch to make PLA represents about 5% of one year's increase in the corn crop.

Corn and the other grains can meet just about any conceivable market demand for biobased products made from starch or sugar. There is really no reason to look elsewhere for feedstocks, except for a multitude of sustainability concerns. I will return to this subject later in this paper, but in the meantime, we will focus on agricultural oversupply. As we have seen, the demand for biobased products cannot, by itself, change the problem of agricultural oversupply. Agriculture needs other markets. And by far the largest of these markets is energy.

Using agriculture to produce modern energy has been underway for decades. In the early 1970s, a series of oil supply restrictions began that raised oil prices four fold in just a few years. One result was increased U.S. policy and legislation that encouraged increased blending of gasoline with corn-based ethanol. That effort has continued, with ups and downs, and about 56.8 million cubic meters of ethanol are currently blended with gasoline in the US, roughly 10% of all gasoline used. Most recently, corn ethanol production rose from about 6.1 million cubic meters per year in 2000 to 50.3 million cubic meters per year in 2010.[6] This was truly exponential growth with a doubling time of about 3.0 years, as shown in Fig. 1. Ethanol use now consumes about 35–40% of the U.S. corn crop. There will not be any more rapid doublings of American corn ethanol production, given the competing uses for the crop. A different model is needed to continue to grow ethanol or other biofuels in the U.S.

A similar situation unfolded in Brazil in the 1970s when greatly increased oil prices essentially wiped out the country's hard currency reserves, causing social disruption and a lot of hardship. Brazil turned to its sugarcane industry to produce ethanol to substitute for imported oil. From 1975 to 2007, the Brazilian ethanol program grew from about 0.6 million cubic meters per year to 18 million

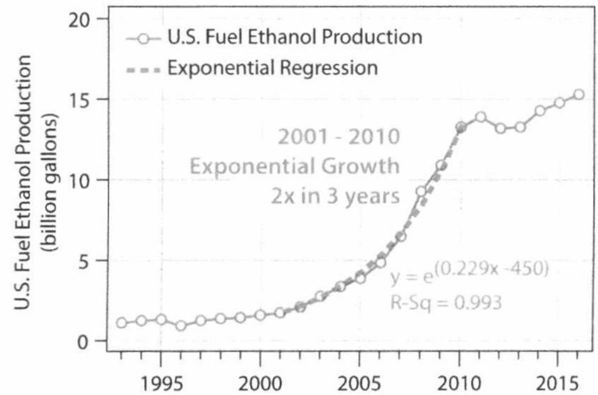

Fig. 1 Recent growth of corn ethanol production in the United States.

cubic meters per year.[7] Today, about 25% of all motor fuel consumed in Brazil is ethanol and all gasoline there is blended with some ethanol.

However, growth in sugarcane ethanol production has slowed greatly. The primary reason is that Brazilian ethanol is a coproduct of cane sugar and the global markets for sugar are saturated. Like the U.S., Brazil needs a different model for ethanol production from cane in order to continue to grow.

Thus, agricultural markets and energy markets, especially petroleum markets, are increasingly intertwined. Let's consider now some lessons from the petroleum industry. (Note: hereafter I will refer to all energy derived from agriculture or forestry as "bioenergy", regardless of whether the fuels are solids, liquid biofuels or gases.)

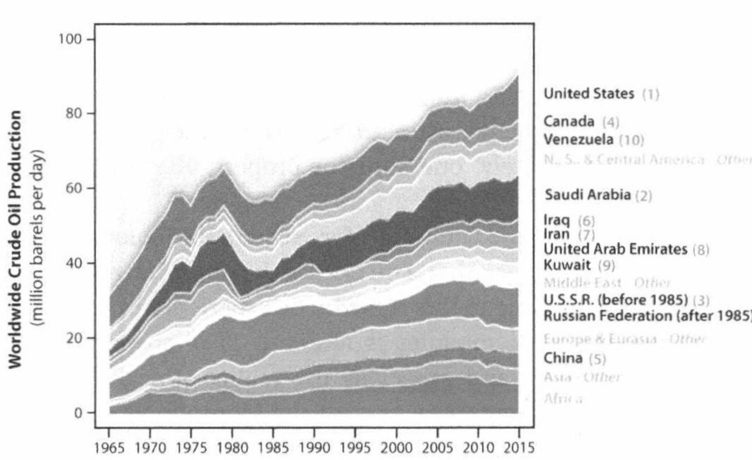

Fig. 2 Historical growth of the petroleum industry worldwide. Image reproduced with permission from ©John Wiley and Sons, 2014 (ref. 8).

Emergence of the petrochemical industry—some lessons for us

The past century can rightly be called the Age of Oil. World oil consumption grew from about 20 million tonnes per year in 1900 to nearly 4000 million tonnes per year in 2005—a 200 fold increase.[8] The economic activity enabled by oil consumption also greatly increased both human wealth and the human population over the last century. But the Age of Oil is winding down. Fig. 2 shows the total world liquid fuels production, including biofuels, deepwater oil, oil from tight shales, and tar sands oil. Production of conventional (cheap) oil has been flat since about 2005 in spite of trillions of dollars spent to explore for new oil fields. We apparently cannot produce cheap oil any faster than we are now producing it. All growth in oil supply has been from higher cost and more environmentally-problematic resources.

The bioproducts industry often seeks to replace petroleum-derived chemicals and materials. It may be instructive therefore to understand how the petrochemical industry emerged. The answer is clear. Petrochemicals grew out of the established petroleum refining industry—not the other way around. The same thing will probably occur for commodity bioproducts also: a robust bioproducts industry will most likely be built on robust bioenergy systems. The large corn wet mills producing multiple products are one example. We do not see commodity bioproducts (such as PLA) made in a dedicated plant. They are produced as coproducts in a large integrated biorefinery.

Why is this so? Important reasons include access to feedstock at marginal cost and very large scale, availability of supporting technical talent under one roof, sharing of expensive utilities including co-generation plants and wastewater treatment plants, access to internal capital for investment, and the marketing prowess and vertical integration of big firms. While I can imagine a specialty bioproduct being produced in a dedicated, smaller plant, I cannot imagine a commodity bioproduct being made anywhere other than in a large-scale biorefinery.

Since the existing markets for materials and chemicals have been largely satisfied, the bioproduct newcomers must adapt themselves to the existing market realities. Unless the bioproducts industry can offer totally new products, with greatly superior properties, there is no reason to use biobased products unless they cost much less than the products they are seeking to replace. Otherwise, drop-in replacements, with strong cost advantages, will be preferred over new products. Fortunately, one superior property that bioproducts might offer is sustainability.

So I argue that increased demand for sustainable bioenergy will pull commodity bioproducts along with it. I do not see the opposite trend occurring, in spite of much hopeful thinking in this regard. The experience of Amyris and other would-be cellulosic biofuel companies is relevant. They encountered the hard realities of the marketplace and especially the reality of scale, and are either defunct or have refocused themselves as specialty bioproducts companies.

If this is true, then to scale up bioproduct commodities we must first scale up bioenergy production and/or make bioproducts along with bioenergy commodities, as corn wet mills are currently doing. We must therefore understand why

