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EDITORIAL

Harnessing plant biomass for biofuels and biomaterials

Modern societies have relied for more than a century on fossil carbon sources for the production of fuels or chemicals ranging from plastic polymers to drugs to food additives. The consequences of this utilization of fossil carbon-derived fuels – the release of carbon dioxide into the atmosphere – are no longer deniable. There is general agreement among leading scientists that the increased concentration of carbon dioxide in the atmosphere has contributed to the all-too-apparent global-warming trend. It is also clear that the increasingly high demand for fossil carbon will eventually deplete the existing stocks, with consequences not only in the area of energy but also in the wider chemical industry. Concerned citizens from scientists to policy makers have recognized the need for a reliable, renewable and affordable source of carbon in its chemically reduced form that can sustain future economic developments without having a negative impact on the environment. Discussion of solutions to overcome the current dependence on fossil carbon is conducted at all levels of society. The conversion of light energy into chemical energy by plant photosynthesis ranks prominently among the natural processes that can potentially meet the challenge. Plant biologists and biochemists are therefore at the forefront of developing schemes and ideas for an emerging bioeconomy that sustainably harnesses plant biomass.

To contribute to the ongoing discussion in this area, we present in this special issue a series of reviews that describe the multiple biochemical processes that plants can or could use to convert their fixed carbon into fuels and other useful products. Rather than advocate a specific process or compound, these invited peer-reviewed articles by leading plant biologists and biochemists focus on the scientific facts behind the production of plant biofuels such as ethanol or biodiesel, as well as other important chemicals that are often unique to plants. It should be remembered that the basic precursors for the synthesis of drugs, plastics and other industrially important products of the petrochemical industry are also derived from fossil carbon. While only a small proportion of fossil carbon is used for the production of these specialized feedstock chemicals, such chemicals are nevertheless just as important as fuels to our economy, and when fossil carbon sources are depleted or become too expensive, new sources for these chemicals will have to be found. Plants already synthesize many of these feedstock chemicals, and have the potential to economically produce many more, in particular some compounds that are extremely difficult to manufacture, e.g. compounds with chirally pure precursors. Therefore, we have also included articles on biomaterials and plant-derived compounds that one day might replace petrochemical compounds.

Traditionally, *The Plant Journal* focuses on fundamental questions in plant biology and does not publish articles with a heavy emphasis on plant biotechnology. There will be no change in this current editorial policy. However, discoveries in basic plant sciences ultimately provide the basis for solutions to applied problems. Thus, we have asked the authors to focus on the basic science behind the conversion of plant biomass into useful compounds. It is not the intention to provide a single best solution or to identify the most promising path to a sustainable bioeconomy. Rather, we have chosen to cover the most prominent areas currently discussed and have asked the authors to be critical with regard to the promise and potential of the proposed ideas.

We also requested from the authors to make their reviews as accessible as possible so that they can be used by interested individuals, educators and members of the media as a scientific backdrop to inform discussion. To this end, we are making all the articles available free online from the day of publication.

Starting with a review by Nikolau *et al.* (pp. 536–545), the concept of a biorefinery that produces biofuels and platform chemicals for the chemical industry from plant biomass is introduced. The most readily available biofuel, ethanol, is currently produced from grain starch or sugar cane sucrose. As Smith (pp. 546–558) suggests, the yield potential of easily converted carbohydrates such as starch and sucrose per unit of land is not even close to theoretical capacity. Crop plants with a high weight fraction of these carbohydrates in seeds and other tissues could substitute for lignocellulose as the feedstock for ethanol production until lignocellulose can be converted at an industrial scale and at reasonable costs. Lignocellulose, essentially plant cell walls, is by far the most abundant land-based plant biomaterial, and its conversion to transportation fuels holds great promise. However, plant cell walls are naturally designed to resist degradation by micro-organisms, making conversion of this biomass into biofuels a challenge. Currently, plant biologists are working on schemes to modify the carbohydrate components of plant cell walls, as discussed by Pauly and Keegstra (pp. 559–568), and the lignin matrix, as described by Li *et al.* (pp. 569–581). The overall goal is to improve conversion of the wall polymers into feedstocks for microbial fermentation processes without compromising plant growth. To provide a context for the conversion of plant biomass into fuels and chemicals, Doran-Peterson *et al.* (pp. 582–592) discuss the microbiological aspects of the process.

The other biofuel in current use is biodiesel. Durrett *et al.* (pp. 593–607) explain the advantages of biodiesel over ethanol as a liquid transportation fuel, but also the drawbacks and technical limitations to its implementation as a major substitute for fossil fuels. One such limitation is the low yield of land-based oil crops. The solution would be to engineer crops that produce substantial amounts of oil in non-seed tissues. To re-program a plant for this purpose, we must understand the regulation of storage compound deposition in seeds. Santos-Mendoza *et al.* (pp. 608–620) provide an overview of the extensive regulatory network governing Arabidopsis seed metabolism, highlighting some of the factors that might permit re-programming of storage compound deposition in a biofuel crop. Alternatively, the current low yield of land-based oil crops could potentially be overcome by producing oil from marine microalgae. Hu *et al.* (pp. 621–639) provide an overview of current efforts to harness the high yield potential of microalgae for the production of triacylglycerols.

Natural plant- and algae-derived oils in the form of triacylglycerols contain a large variety of fatty acids that can serve as desirable food ingredients or as feedstocks for the production of valuable compounds, including polymers. Moreover, as fatty acid esters of primary alcohols are the ingredients of biodiesel, the specific fatty acid composition of a given plant oil has an effect on fuel quality. Dyer *et al.* (pp. 640–655) discuss the biological basis for the diversity of fatty acids, and describe the impressive advances made in the engineering of the fatty acid composition of oils.

Triacylglycerols are not the only high-energy compounds directly produced by plants. Many plants synthesize a variety of terpenoids, ranging from isoprene, which is emitted in large amounts from many trees, to the heavier terpenes that constitute plant essential oils and resins. As discussed by Bohlmann and Keeling (pp. 656–669), the astonishing number of terpenoid compounds produced by various plants may provide a source of reduced carbon for fuels, as well as drugs, pigments and flavor compounds. Alkenes are key ingredients of mass-produced high-energy liquid transportation fuels that cannot be substituted by lower-energy alcohols in applications such as jet fuels. As Jetter and Kunst explain (pp. 670–683), waxes on the surface of plants are rich in alkenes. 'Cracking' the biochemistry of alkenes in plants may be the ultimate prize in our efforts to substitute high-energy jet fuel from fossil carbon by biomass-derived alkenes.

Plants not only produce, or can be engineered to produce, precursors for useful polymers, they already synthesize commercially important polymers such as rubber and cellulose, and there has been some progress in engineering plants to synthesize other types of polymers. Van Beilen and Poirier (pp. 684–701) describe the biosynthesis of rubber, protein fibers, and novel biodegradable polymers. The required introduction of several bacterial enzymes is an example of the emerging area of synthetic biology, in which entire metabolic pathways are moved from one organism to another.

Many unique and valuable plant compounds are produced in plant trichomes. Schilmiller *et al.* (pp. 702–711) discuss the biochemical processes operating in trichomes and the potential for harnessing these specialized pathways for chemical engineering purposes. Many volatile plant compounds affect flavor perception by humans and other herbivors, and, whether they are produced in vegetative organs for defense, or in fruits to attract seed dispersers, humans value their presence in their food. Some of these highly sought-after compounds fetch high prices. Schwab *et al.* (pp. 712–732) provide an overview of the biosynthesis of flavor compounds in plants. Similarly, Tanaka *et al.* discuss the dazzling array of plant pigments that can substitute for pigments made by the petrochemical industry (pp. 733–749). Beyond lignin, phenylpropanoids and the related polyketides give rise to a number of interesting, high-value natural compounds with proven or hypothesized health benefits, as discussed by Yu and Jez (pp. 750–762). Finally, the wealth of secondary compounds produced in plants provides the basis for the discovery of new drugs, which are often complex molecules with distinct chiral centers, many of which cannot be synthesized from petrochemical precursors. An example is the production of alkaloids. Their biosynthesis and synthetic biology efforts with respect to their large-scale production are described by Facchini and De Luca (pp. 763–784).

These latter examples demonstrate that knowledge of plant biology and biochemistry has far greater potential than just the biochemically simple conversion of photosynthate into ethanol. Plants and algae are amazingly versatile and efficient in capturing light energy and converting it into compounds and bulk feedstocks that have the potential to satisfy human needs in a sustainable way. As exciting as the potential of a plant biomass-based economy is, we should also be aware of the potential risks to the environment of moving towards an increasingly bio-based economy. For example, the consequences of establishing monocultures of novel biofuel crops, of expanding the range of agricultural land for biofuel crop production, or competion for resources needed for the production of biofuels versus food and feed need to be carefully analyzed. The discussion of the risks must be science-based. At the same time, we must understand the risks of not moving forward expeditiously to build a sustainable bioeconomy. Moreover, for the bioeconomy to function, it must be based on sound economics and supported by the political establishment. We, the editors, are aware that this discussion occurs in many forums and among people of varying expertise. Because this special issue focuses on plant biology and biochemistry, the range of expertise represented by the authors of this special issue may not encompass all facets of this debate. However, it is our intention to contribute to the public discussion by providing sound basic plant biological information on which experts and non-experts can rely. It should also be clear from the excellent peer-reviewed articles assembled in this issue that substantial technical hurdles must still be overcome to advance the bioeconomy. However, in view of the very real impact of anticipated shortages in fossil carbon supply and the global effects of fossil carbon consumption, the need for a sustainable bioeconomy is ever more urgent. Certainly, plant biologists and biochemists are determined, as illustrated in this special issue, to contribute rational solutions based on the fundamental principles of plant biology.

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