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Yes, we can make money out of lignin and other bio-based resources

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ABSTRACT

Unlike a traditional review, this article does not summarise and discuss scientific progress in terms of traditional focus topics such as upstream processes or conversion and downstream processes, but instead provides examples proving that “Yes, we can make money from lignin and other bio-based resources”. The nine success stories from Scion’s research are differentiated by the size of the product from designing trees with customised lignin and modifying wood dried by supercritical processing to bioaromatics from lignin hydrogenolysis, the scale of the product – from wood fibre plastic composites at commercial scale and lignin-rich bioadhesives to bio-based materials for 3D printing and the value of the product(s) – from lignin-based nanofibres and supercritical extraction of chemicals and compounds to utilising biomass side streams.

1. Introduction

“You can make anything you want out of lignin – except money”; is a frequently heard statement in the scientific community or industry (Biofuels Digest, 2011). Fortunately, times are changing, and side and waste streams from both agriculture, and forest sectors are now being considered as crucial feedstocks for the rapidly growing bio-economy (German Bioeconomy Council, 2015). Economic analysis has proven that, in many cases, the use of biomass (such as lignin) for energy applications alone is not economically viable. Utilisation of the entire biomass through multiple processes is needed to change the economics (Doherty et al., 2011). Imagine a bio-economy where not only could agricultural and forest feedstocks such as lignin be turned into products but they would also be worth up to $2000 per tonne? To turn this vision into reality, biomass must be considered as more than simply a replacement for crude oil (Rinaldi et al., 2016; Upton and Kasko, 2015). A primary objective is to develop new bio-based products and materials with functionalities not provided by existing petroleum-based options such as: lower weight; heat and water resistance; durability; toughness; and flame retardancy. To gain market access, these renewables will need proven green credentials, freedom from harmful chemicals and to be cost-effective. By building on features designed by nature it is possible to develop products that deliver performance additions beyond the sustainability and renewability claims. These products will be able to compete with their existing petroleum-based counterparts not only on sustainability criteria but also on enhanced performance and novelty (above and beyond copying current petroleum-based products) (Scion, 2015).

Unlike a traditional review, this paper does not summarise and discuss scientific progress in terms of traditional focus topics such as upstream processes or conversion and downstream processes, but instead provides examples and success stories proving that “Yes, we can make money from lignin and other bio-based resources”. The content of this article is summarised in Fig. 1 and illustrates nine success stories from Scion’s research that are differentiated by the:

- Size of the product: from a designer tree to small molecules
- Scale of the product: from commercial scale to experimental 3D printing approaches
- Value of the product(s): from speciality/high performance materials to an “adding value to waste” concept.

2. Size of the product: from a designer tree to small molecules

2.1. Designing trees with customised lignin

Crops improved by genetic engineering (GE) have delivered wide-ranging economic and environmental benefits since their

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introduction in the late 1990s (Areal et al., 2013; Green, 2012; Klümper and Qaim, 2014). In 2014, approximately 18 million farmers grew biotech crops, of whom about 90% were poor farmers in developing countries (James, 2014). Most GE crops to date deliver either insect-resistance and herbicide-tolerance but other traits such as drought tolerance or crops with downstream consumer benefits have recently been commercialised (Hallerman and Grabau, 2016; James, 2014).

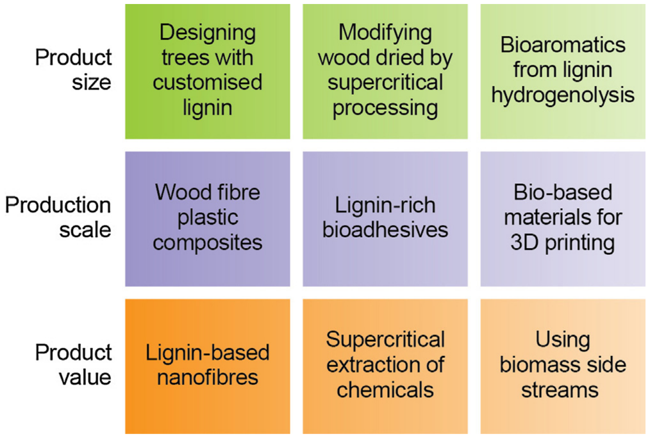
2.1.1. *Genetic engineering and forest trees*

So far, the commercial adoption of GE in forestry has been more limited than for shorter-rotation crops. However, insect-resistant poplars, carrying the *cry1a* genes from *Bacillus thuringiensis* were commercialised in China in 2003 (Fenning, 2014) and Brazil approved the planting of GE eucalypts engineered to grow 20% faster than equivalent non-engineered trees in 2015 (Nature Biotechnology, 2015). Also, extensive research is underway into GE modification of trees, and a broad spectrum of both silvicultural and processing traits has been manipulated successfully. Such traits include: growth; disease resistance; herbicide tolerance; biomass modification; and floral control (Costa et al., 2013; Dubouzet et al., 2013; Etchells et al., 2015; Porth and El-Kassaby, 2014; Strauss et al., 2016). A search by Walter et al. in 2010 (Walter et al., 2010) indicated that over 700 field trials have been undertaken with GE trees, and a number of traits are close to commercialisation.

2.1.2. *Tree biotechnology at Scion*

Forestry makes an important contribution to New Zealand's economy with its almost NZ$5 billion of export earnings making it the third largest contributor of gross domestic product (GDP) (New Zealand Forest Owners Association, 2014). This industry is based predominately on planted exotic softwood species comprising radiata pine (*Pinus radiata* D.Don; 90%) and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco; 6%), with small plantings of other softwoods and hardwoods. Scion has been conducting research on genetically modified trees since 1992 as part of its tree-improvement portfolio. This research encompasses a range of traits of importance to commercial forestry, including herbicide tolerance (Bishop-Hurley et al., 2001), insect resistance (Grace et al., 2005), floral control (Höfig et al., 2006), and extensive work on the modification of lignin. Scion has successfully developed transformation systems for a number of conifer species in the genera *Pinus*, *Picea* and *Abies* (Charity et al., 2005; Walter et al., 2001) and have carried out research both in the laboratory and in field trials.

Initial field trials at Scion focused on the establishment of transformation protocols, and assessment of the environmental impacts of genetic engineering on non-target species. These experiments found no evidence for impacts of any kind resulting from genetic modification (Burgess et al., 2011; Lottmann et al., 2010; Schnitzler et al., 2010; Shi et al., 2012).



Product size	Designing trees with customised lignin	Modifying wood dried by supercritical processing	Bioaromatics from lignin hydrogenolysis
Production scale	Wood fibre plastic composites	Lignin-rich bioadhesives	Bio-based materials for 3D printing
Product value	Lignin-based nanofibres	Supercritical extraction of chemicals	Using biomass side streams

Fig. 1. The nine success stories illustrating that money can be made from lignin and other bio-based resources.

2.1.3. *Lignin in conifers*

Wood is one of the most abundant composite materials on earth. It comprises predominantly of cellulose, non-cellulosic polysaccharides and lignin, and can be processed into a host of useful products including: timber; biofuels; bio-chemicals; wood pellets; pulp and paper; fibres; and bio-composites (Wagner and Donaldson, 2014). The resistance of lignin to chemical transformation presents a major barrier to the processing of wood biomass, most notably in the pulp and paper industry, but also provides challenges for the implementation of wider, forest-based bio-refineries (Mottiar et al., 2016).

The composition of softwood differs in many respects from hardwood. In softwoods, the tracheids – long fibrous cells with lignified cell walls – make up more than 90% of wood and have the role of both vessel elements and fibres in hardwoods (Wagner et al., 2012). The biochemical composition of tracheid cell walls differs substantially from those of vessel elements and wood fibres. Not only do conifers have a higher lignin content than most hardwoods but conifer lignin consists primarily of guaiacyl units derived from coniferyl alcohol and lacks the sinapyl alcohol-derived syringyl units that are commonly found in hardwoods (Wagner et al., 2015). A more condensed polymer, containing higher levels of carbon–carbon linkages between monomer-derived units, is generated by polymerising coniferyl alcohol rather than sinapyl alcohol. This structure, along with the high lignin content of softwoods, negatively impacts efforts to refine lignocellulosic materials from conifers (Wagner et al., 2012).

2.1.4. *Lignin modification*

Long-term work at Scion has been aimed at increasing the processability of conifer woody biomass by manipulating both lignin content and composition. Strategies to enhance processability by reducing lignin content have been largely unsuccessful. Even relatively modest reductions in lignin content have compromised tree growth by causing the collapse of tracheids (Wagner et al., 2009). However, a collaboration with the University of Wisconsin demonstrated, through the use of a tracheary element cell-culture system developed at Scion, that pine can be engineered to incorporate sinapyl alcohol into its lignin (Wagner et al., 2015). This engineered lignin contains syringyl units that are usually found in hardwoods, and opens up the possibility of producing biomass that is more easily processed than natural softwoods yet retains the desirable fibre properties. This approach, like others designed to introduce more labile linkages into the lignin backbone (Tsuji et al., 2015; Wilkerson et al., 2014), addresses a problem that the pulp, paper, biofuel and bio-products industries have faced for a long time – what is the best strategy to reduce the amount of energy it takes to break down plant woody biomass. The cost and energy reductions obtained by processing modified lignin could become a game changer in the way that dedicated energy forests are grown.

2.2. *Modifying wood dried by supercritical processing*

Drying timber with heated air kilns is a process used worldwide to rapidly reduce the water content of wood from its green state (Simpson, 1991). Kiln drying timber can be lengthy and extend to several days with some types of wood. It is also energy intensive with kilns typically maintained from 90–140°C through the drying period, and can induce stresses within the wood together with checking, warping and darker colouring (Oltean et al., 2007; Simpson, 1991). Alternatives to kiln drying have evaluated the use