FAO discussion paper ***for the 55th meeting of the FAO Advisory Committee on Sustainable Forest–based Industries (ACSFI), which will meet with International Council of Forest & Paper associations (ICFPA) in St. Petersburg, Russia 10-11 June***

Update on various traits of biotechnology in forestry to meet future needs in food, feed, fibre, and fuel

Editors: Arshadi, M.(1), Bergsten, U (1), Finell, M (1) & Witzell, J (2)

Swedish University of Agricultural Sciences (SLU), Faculty of Forest Sciences, Dept. of Forest Biomaterials and Technology, Umeå(1) & University of Eastern Finland, School of Forest Sciences(2)

Contributing authors: Berglund, L., Royal Inst. of Technology, Stockholm; Blomberg Saitton, D., SP Processum AB, Örnsköldsvik; Christakopoulos, P., Luleå University of Technology (LTU); Clark, J., Kettemann, C. & Matharu, A. S., York University; Gebart, R., LTU; Holmbom, B., Åbo Akademi University; Ioannis, D., SLU, Uppsala; Janssen, J., Hasselt University; Lestander, T. A., SLU; Mäkelä, M., SLU;; Rashmi, K., SLU;

Enhanced bio-energy products - Short-rotation woody crops

What's the technology and who is most advanced on it?

Short-rotation woody crops (SRWC) is based on short harvesting cycles, generally between one and 15 years, utilizing genetically superior planting material (mainly trees but also other woody plants), employing management techniques such as fertilization, irrigation and weed control, and often relying on coppice regeneration. Trees can be grown as single-stem or as a multiple-stem crop. High densities (5000-20000 stems ha^{-1}) and short rotations (1-5 years) are recommended for bioenergy feedstock production, since maximal conversion of solar energy is essential and raw material flexibility unimportant. When product flexibility is an objective or where a high wood:bark ratio is important, lower densities (1000-2500 stems ha^{-1}) and longer rotations (8-20 years) are the norm. Species widely employed in SRWC systems in (north-) temperate climates are poplars (*Populus spp.*) and willows (*Salix spp.*). Short-rotation coppice of willow is mainly cultivated in Sweden (ca 12000 ha by 2013), and in smaller surface in the UK, the US and Poland. Biomass yields highly depend on the management intensity and vary from 6 to 12 t ha^{-1} yr^{-1}. SRWC systems with poplar are well developed in Italy, China and India, with 9-18.5 t ha^{-1} yr^{-1} of biomass yields achieved in Italy, related to the adapted management as well. A few other species have been used in smaller scale for SRWC applications in temperate climates, such as *Alnus spp*., black locust (*Robinia pseudoacacia*), silver maple (*Acer saccharinum*), sycamore (*Platanus occidentalis*), sweetgum (*Liquidambar styraciflua*) and loblolly pine (*Pinus taeda*). In the tropics and subtropics, plantation culture of very fast-growing species of *Acacia*, *Eucalyptus*, *Gmelina*, *Leucaena*, and *Pinus* are well-established, often practiced in agroforestry context. However, Eucalyptus can also be intensively cultivated as coppice or after replanting, a system well-established in Brazil with biomass yields of 17-20 t ha^{-1} yr^{-1}. The IPCC suggests that the primary biomass energy supply will increase from 50 EJ in 2008 to 80 EJ in 2030 and 138 EJ in 2050. Based on this moderate IPCC scenario, the portion that could come from SRWC production by 2030 is estimated on 20 EJ. Direct genetic modification has added or modified genes and increased growth, stress tolerance and improved adaptability. Scientists are currently focusing on adaptations in the wood itself to ameliorate the production of biofuels and bioenergy. However, transgenic trees with reduced lignin content or increased wood density are not implemented in large-scale plantations yet.

Speed to Achieve Various Technologies

Despite technological development, dedicated wood production for energy is still limited nowadays and predictions for future increments are inconsistent. The main barrier is probably the economic uncertainty. Practitioners have to deal with high upfront establishment costs in combination with long payback periods, lack of established biomass markets, associated with future uncertainties concerning biomass yields and wood and energy prices, and a lack of policy coordination among sectors. To achieve a transition to large-scale production of woody biomass for energy, the economic competitiveness and thus market share of SRWC-based energy systems compared to fossil and other renewable options should be improved. SRWC systems offer a range of ecosystem services related to water, soil and biodiversity, compared to other biomass and energy production systems, and such advantages need to be optimized by careful design taking into account the economic sustainability of the system.

Industrial biotech trait potentials and adoption rate curve

The expansion of SRWC production is crucial for sustainable and independent future energy supply. Scientific knowledge increases production levels and improves biofuel and bioenergy generation, but the economic viability of SRWC is rather uncertain and depends on many factors related to the price development of both the energy and agricultural sectors. A great expansion of large-scale applications has so far not been realized and socioeconomic and policy aspects rather than technological aspects are fundamental to increase the supply of energy from SRWC.

Enhanced bio-energy products – Biomass gasification

What's the technology and who is most advanced on it?

Biomass gasification denotes a process for conversion of biomass into an energy-rich gas through partial combustion. The gas from a gasifier is called ”product gas” or ”syngas” depending on the intended use for the gas and it consists of a mixture containing CO, H_2, CO_2, CH_4 and higher hydrocarbons. The name syngas is used to denote a tar-free and clean gas mixture that can be used in a catalytic process for conversion into high value compounds, e.g. methanol or FT-liquids (a mixture of hydrocarbons similar to crude oil).

After the oil crisis in the 1970's biomass gasification became highly developed and several large stationary gasifiers based on these developments were later built, e.g. the 140 MW Vaasa Bio-gasification Plant, Finland. These gasifiers were mostly based on fluidized bed technology and the early development was aimed at synthetic fuels production (e.g. methanol) but in the late 1980's the interest shifted to power production via combustion in a gas engine or gas turbine. Recently, the focus has shifted back towards synthetic fuels with an aim to reduce greenhouse gas emissions from fossil fuels. Two of the most advanced biosyngas plants have been built in Sweden, one for black liquor to BioDME in Piteå (the LTU Green Fuels plant) and one for wood pellets to Biomethane in Gothenburg (the GoBiGas plant). The LTU Green Fuels plant which is based on the Chemrec technology has been in operation the longest. Two other biomass syngas plants of interest is the Güssing, Austria dual-bed gasifier and the Karlsruhe, Germany entrained flow Bioliq-plant.

Speed to Achieve Various Technologies

For power production there are several companies (e.g. Metso, Andritz-Carbona, Foster-Wheeler) that offer complete large-scale gasification plants with performance guarantee. For biosyngas applications the fluidized bed technology is still unproven in industrial scale. The black liquor gasification technology, based on the entrained flow principle, is currently the most advanced biosyngas process and a commercial project for BioDME-production was planned in Domsjö, Sweden. These plans however become rescheduled in 2012 due to uncertainties about legislation and other factors affecting the business case. The fluidized bed technology for biosyngas is still under development, in particular the upgrading of the tar-rich product gas into ultra-clean syngas needs to be proven through longer run times in pilot plants.

Industrial biotech trait potentials and adoption rate curve

Biomass gasification based syngas processes are highly efficient for production of renewable motor fuels. For the most efficient alternatives (methane, methanol and DME) more than 50% of the chemical energy in the biomass can be converted into motor fuel. Currently, the production cost is higher than for fossil fuels but if it is required that the users of fossil fuels should pay for the consequences of their use the new fuels will be highly competitive. When this happens, biomass gasification-based technology is ready for rapid deployment.

Enhanced bio-energy products - Up-grading of biomass by torrefaction

What's the technology and who is most advanced on it?

Torrefaction is a mild form of pyrolysis and is performed by heating lignocellulosic biomass to temperatures ranges of 200 to 350 ºC at low oxygen partial pressure in indirectly or directly heated reactors. This thermal pre-treatment is an interesting step for downstream conversion processes such as gasification but also as co-firing in CHP plants. During torrefaction biomass is partly devolatilized and its properties change, more the higher temperature and the longer time period of the treatment, and the remaining solid biomass is successively carbonised. One of the main drivers in the concept of black pellets is to develop a refined solid biomass feedstock that is carbonised and has high energy content, eliminates the need for covered (out-door) storages (increased hydrophobicity), and good flow and handling characteristics as well as being more homogenous and easy to mill into fine powders of great importance in gasification and co-combustion. In Europe there is an ongoing EU FP7 SECTOR project with 21 partners from 9 EU-countries involved in developing the torrefaction process: CENER in Spain and ECN in the Netherlands besides company initiatives like Topel in the Netherlands and BioEndev in Sweden, will together with the Danish Technology Institute, Umeå University and SLU provide knowhow and equipment for the core technologies of torrefaction and densification. Ordinary biofuel pellets from untreated wood is nowadays referred to as white pellets. The term 'black pellets' also include other treatments like hydrothermal pre-treatment and several commercial actors offer steam-exploded lignocellulose as feedstock for production of black pellets. There are also several project and commercial initiatives for pelletizing or briquetting torrefied biomass or biomass pretreated by other processes giving about the same characteristics as torrefaction. One company, Zilkha in USA, was early in the market providing black pellets. In US the national laboratories e.g. Idaho National Laboratory, and in Canada the University of British Columbia are involved in the development of different process steps.

Speed to Achieve Various Technologies

Torrefaction is demonstrated e.g. by CENER, ECN, Topel, BioEndev etc. New approaches have also been developed from the straight forward technique of just using heat treatment of wood to partly achieve set targets of black pellets. The current success rate of the torrefaction concept is also depending on the pelleting process of torrefied materials, as the current densification techniques are not fully developed and is still in an applied research phase. For materials based on lignin e.g. the LignoBost (Valmet AB, Sweden) or the Zilkha (Zilkha, USA) process, the pelletizing process seams easier to bring to the market. These examples show the potential of introducing black pellets utilizing existing pulp processes, and thus, compete with the concept of black pellets from torrefied biomass.

Industrial biotech trait potentials and adoption rate curve

The market of white (wood) pellets is expected to grow steadily but from a low level compared to the huge world market of pellets as feed for pets, cattle, poultry, fish etc. The adoption of developed techniques of torrefied materials produced as (black) pellets or briquettes will most probably first be commercialized in regions and counties having low biomass costs, e.g. large surpluses of harvest residuals (agriculture) and short distances to deep-see harbours for export. The full economical breakthrough will come when the prise of fossil coal per unit energy minus CO_2 refunding by using bioenergy is higher than that of black pellets. At that stage the market is enormous and one client in EU then consumes alone about 5 million ton black pellet in large-scale CHP co-combustion to replace fossil coal.

Enhanced bio-energy products – Liquid biofuels from fermentation

What's the technology and who is most advanced on it?

One of the most promising feedstocks for biofuels production is plant biomass that contains large amounts of sugar polymers, such as cellulose and hemicelluloses. When subjected to enzymatic hydrolysis, these polysaccharides are transformed into glucose and other fermentable pentoses, which might further be converted to liquid fuels such as bioethanol. The last few years, the processes involved in the conversion of cellulose and hemicellulose have been closely related to the word 'recalcitrance', to emphasize obstacles that can impede the conversion. Recalcitrance is linked to each step in biomass conversion, which can be costly, driving the production costs to exceed those of the transportation fuel competitors derived from fossil fuels or those derived from starch, sucrose, and vegetable oils (e.g., first-generation bioethanol and biodiesel). The strong glycosidic bonds of cellulose together with its associated crystal structure prescribe application of either harsh physicochemical conditions or use of a consortium of different cellulose acting enzymes. However, the protein production efficiency of cellulases has been increased more than 10-fold nowadays resulting in a serious decrease in their price, rendering enzymatic saccharification more economical than physicochemical methods. At present, recombinant strains of *Saccharomyces cerevisiae*, and in a lesser extent of *Escherichia coli* and *Zymomonas mobilis* strains, are considered as the most successful microorganisms for biofuel production in industrial scale. Bottlenecks and obstacles, such as the narrow range of fermentable sugars for some microorganisms, the imbalanced anaerobic metabolism for some others, or the low uptake rates for some sugars, are challenges which have to be nearly solved or overpassed. Although several improvements are yet to be done, significant progress has been done on all these issues. On the other hand, consolidated bioconversion or, in other words, direct conversion of cellulosic materials into advanced biofuels is, up to now, partially successful. Cell-surface display engineering enabled the expression of cellulolytic activities and minicellulosomes on *S. cerevisiae* cell surfaces.

Speed to Achieve Various Technologies

After some decades of scientific efforts, the production of cellulosic ethanol in commercial scale seems feasible, as demonstration and industrial scale ethanol plants pullulate year by year in various countries. The great majority of the scientific reports on the field have so far focused on one of three main targets: (1) the amelioration of the feedstock (plant or residue) with regard to a readily convertible and efficient substrate, (2) the improvement of the bioconversion process, and (3) the development of a desirable microbial factory which efficiently carries out the bioconversion. Enzymatic hydrolysis is advanced by the discovery of a new class of oxidative enzymes that cleave cellulose (LPMOs), offering an exciting possibility for the improvement of cellulose deconstruction. Metagenomic DNA and genetically engineered libraries should be explored for the discovery of novel enzymes with improved cellulolytic activity on natural substrates and increased inhibitor tolerance. The integration of the bioconversion process in a more wide production scheme, where all biomass components are exploited and, at the same time, different kind of products (fuels, chemicals, electricity, heat) are produced, is considered as the most effective way to make cellulosic ethanol production profitable.

Industrial biotech trait potentials and adoption rate curve

S. cerevisiae, the microorganism most widely and longer used in fermentation processes is still a paradigm and a model for most modifications and improvements. Powerful tools as the metabolic engineering and the inverse metabolic engineering based on evolutionary engineered *S. cerevisiae* strains advance day by day. Solutions to the problem of the cofermentation of pentoses and hexoses have been proved feasible through the combination of these techniques, showing the way for the integral exploitation of plant biomass. Moreover, the robustness of microorganisms is no longer considered as a black box belonging to industrial processes.

Production technology for bio-based polymers/biomass-based plastics

What's the technology and who is most advanced on it?

Bio-based polymers and biomass-based plastics (BBPs) from renewable raw materials have high potential to alleviate the environmental problems caused by conventionally made plastics. BBPs can both replace the conventional, petroleum-based polymers and provide new polymers with improved performance for different industrial, medical and agricultural applications. The production of BBPs is achieved 1) by extraction, separation and partial modification of natural polymers from renewable resources, 2) through microbial production or 3) using biotechnology and conventional synthesis. For example, a subgroup of BBPs, polyhydroxyalkanoates (PHAs; biological polyesters) is produced through bacterial fermentation, using a broad array of renewable waste feedstocks (e.g. cellulose, vegetable oils and municipal waste) as a carbon source. The production process proceeds through fermentation (48 hours) and cell growth, to concentration and drying of cells and extraction of PHAs with solvents (acetone, chloroform) from which the dissolved PHA is separated through liquid-solid extraction and precipitated. Over 150 PHA polymers are known, allowing production of BBPs with a wide range of properties. Applications for BBPs are found in a broad array of industries and day-to-day applications, including electronics (e.g. polylactic acid, PLA), packaging (e.g. starch, cellulose), textile industries (e.g. cellulose), medicines, pharmaceutics and cosmetics (e.g. starch, chitin, chitosan), agriculture (bio-based polyethylene) and food industries (e.g. pullulan). Advanced production of different BBPs occur throughout the world: in North America (e.g. Nature Works, USA: capacity 140 kton PLA/year; Metabolix, USA: capacity 50 kton PH/year), Europe (e.g. Novamont, Italy: capacity 120 kton starch/year; Synbra, the Netherlands: 50 kton PLA/year) and Asia (e.g. IPC-CAS, China: capacity 5 kton PBS, PBSA/year; Kaneka, Singapore: capacity 10 kton PHA/year).

Speed to Achieve Various Technologies

Large-scale production of a large spectrum of BBPs has been industrially feasible for over a decade now and so far their use has been held back mainly by the lower costs of oil-based products. The main challenges to be solved are considered to be related to management of raw materials, performance of BBPs to meet the end user's requirements, production costs, precise estimation of supply-demand balance, and lack of experience in new materials. It is estimated that the development of full scale of BBPs demands another 20 years.

Industrial biotech trait potentials and adoption rate curve

Given the solid biotechnology readiness and the increasing desire and need to replace petroleum-based materials with renewable, bio-based materials, the adoption rate curve for BBPs has a high and realistic potential to raise in the near future. Policy instruments supporting this development have already been established by EU (Lead Market Initiative) and USA (BioPreferred). The increasing interest is demonstrated the recent exponential increase in relevant research activities and scientific publications in the subject. These research investments should enable the expected 20-year horizon in development of full scale BBP industries. The first generation of BBPs were strongly based on use of feedstocks such as potatoes, rice and corn, but the hardening competition for feedstock due to the expected demographic and economic pressures is likely to promote a shift towards forest biomass as a raw material for BBPs. The cost-effectiveness and whole-life-cycle environmental value of BBP production from forest biomass may be promoted if increased efforts are made to utilize waste and bi-products from forest industrial process. Advanced in high through-put metabolomics, proteomics and other analysis methods will speed-up collection. Use of next generation sequencing and phenotype microarrays will facilitate biomining of microbial communities in forest biomass to find novel biochemical solutions.

Wood nanotechnology and its applications

What's the technology and who is most advanced on it?

The rapid progress in Wood Nanotechnology research (nanocellulose, nanolignin, nanostructured wood) provides opportunity for new "green" materials. Low cost wood nanocellulose for water-based processing can lead to the first high-volume markets for nanotechnology. Wood nanocellulose research carried out in France, Japan, Sweden, Finland, USA and Canada demonstrates dramatically improved hygromechanical performance in paper, board, packaging products and biocomposites. Nanocellulose can also provide transparent films for packaging and microelectronics, gas barrier coatings and new functionalities such as antimicrobial, magnetic, conducting, functional membranes etc. The use of nanocellulose in textile fibers could solve the problems of hazardous solvents in the viscose process. In addition to pulp, paper and board, forest resources will be processed into chemicals, nanoparticles, biopolymer building blocks, biopolymers and nanostructured wood templates. The new nanomaterials have superior performance to existing products, and can replace petroleum-based polymer products. The prime example is wood nanocellulose, where diameters are at the 10nm scale. Nanofibrillated celluloses (NFC) are long fibrils prepared in high yield from chemical pulp. Cellulose nanocrystals (CNC) are short whiskers prepared in lower yield (30% of pulp) by sulfuric acid hydrolysis. For CNC, one production facility is by CelluForce in Canada. The CNC market develops slowly and will not have significant global influence in the next 5 years. For NFC production in Europe, strong industries include UPM Kymmene, Borregaard, and Rettenmaier, but also Stora Enso are active. Public research is strongest in Finland and Sweden. Verso Paper in USA may be active in NFC development. In Japan, Daicel, Oji Paper, Nippon Paper are very strong in NFC packaging but also new markets. Markets under development include automotive composites (Toyota) flexible displays (Panasonic, Pioneer, Mitsubishi Chemicals). The strongest public research is at Kyoto University and University of Tokyo.

Speed to Achieve Technologies

NFC packaging applications will be in production already 2014 (coatings, strengthening agent), and will grow rapidly. 2014 is important for upscaling of NFC production (30 million euro investment at Borregard, also Nippon Paper). Thermoplastic NFC biocomposites become commercial in 2015. The development is due to breakthroughs in terms of energy efficient disintegration of pulp fibers by pulp pretreatment using enzymes or chemicals. Industrial scale breakthroughs in new applications are likely to take place in Japan, although Finland and Sweden will be quick to use nanocellulose industrially in existing paper and board products (2014). A challenge is industrial scale production technologies for materials based on NFC.

Industrial biotech trait potentials and adoption rate curve

The industrial potential of NFC is tremendous, the production cost for the NFC itself is not so high (the cost will be below 2 euro per kg dry content) and product advantages demonstrated at lab-scale are dramatic. In 5 years NFC raw material will be important (5% of chemical pulp market value, in 10 years it will be a substantial part of the forest products industry (15% of chemical pulp market value). Packaging industry applications will drive the development. This will lead to wide-scale commercial production of NFC. Then niche-applications can develop where the full technical potential of NFC materials can be realized in terms of performance (high nanopaper strength, toughness, moisture stability). Biocomposites with superior mechanical performance, polymer foams with NFC reinforcement, transparent packaging films, transparent coatings for moisture and gas barrier performance, hydrophobic surfaces, oleophobic coatings, additive to polymer coatings and paints, adhesives etc. The consequences of nanocellulose for forestry are probably not so strong since the starting material is chemical pulp. Wood structure in terms of microfibril angle and other factors are not so important since the pulp fibers will be disintegrated in the process.

Wood-based composite materials

What’s the technology and who is most advanced on it?

The term wood-based composite materials refers to products that often use finer wood particles or fibres bonded with a variety of plastic based materials but they also include, low-grade solid wood which has been hardened by chemical or thermal treatment or by impregnation, to produce sustainable alternatives to tropical hardwoods. Wood-plastic composites (WPC) which consist of short wood fibres (<1mm long) or wood flour in a thermoplastic polymer matrices (commonly polypropylene PP, polyethylene PE and polyvinyl chloride PVC), are well-established materials in non-structural construction applications e.g. decking and window frames, where their low-maintenance offers a clear advantage. The most important applications for WPCs are decking. There is good market penetration in the USA, where 1.1 million tonnes were produced in 2012 but up-take is slower in Europe 260,000 tonnes produced, whilst China (at 900,000 tonnes) is set to overtake North America (nova-Institute, 2013).WPC also find application in the automotive industry for interior systems where their light-weighting confers fuel efficiency. In 2012 the European automotive industry used 90,000 tonnes of natural fibre composites and 60,000 tonnes of wood plastic composites. Of the 150,000 tonnes total, wood was the main fibre used. On average, every new car produced in Europe contains around 4 kg natural fibres in composite materials, rising to 25-30 kg in some cases. At the end of life, natural fibre composites can be recycled, biodegraded, or can be incinerated for energy recovery (unlike glass fibres). Market leaders are UPM with their Formi cellulose fibre biocomposite product and Grada, thermoformable wood; German manufacturer, Tecnaro with Arboform a bioplastic made from lignin mixed with natural fibres (cellulose, hemp & flax); and Mondi with their FIBROMER an injection mouldable pulp and polymer mix. Bioresins from cashew nut shells and vegetable oils (rapeseed, soybean, sunflower) offer sustainable alternatives to phenol-formaldehyde and isocyanate resins derived from petro-chemicals. There is also a plant protein adhesive based on soya. Although plywood has been around for 100 years, Cross-Laminated Timber (CLT) is held together with newly-formulated strong glues or dowelling. CLT can be used to replace traditional steel or concrete, allowing the construction of multi-story buildings that can be largely pre-fabricated.

Speed to Achieve Various Technologies

2004 was the starting point for bio-based composites as construction materials with natural hemp fibers fused with poly hydroxy alkanoate (PHAs), especially polyhydroxy-butyrate (PHB) variations, as construction materials. 2005 the cradle-to-cradle solution for PHAs based composites was established, it was patented 2008 together with a methodology for the fabrication of the composites using pretreated granulated PHAs and pretreated natural fiber textiles. In 2008 and 2010 PHB- and PLA-based foams in sandwich panels were used as building materials. 2010 was the commercialization year of the microorganism based cradle-to-cradle solution for PHAs. In 2010 wood plastic composites (WPC) were made based on wood flour and PHB variations. In 2013 a publication of a patent and a scientific article on a lignin-PLA glue for applications in wood and WPC products were presented.

Industrial biotech trait potentials and adoption rate curve

Key areas of focus in the future to meet consumer demands of a ‘greener’ product, thermoplastic resins based on lignin and the light-weighting of composites achieved through the use of foams and/or nanocellulose fibres. Bio-derived inorganic binders for biomass will remove the need for petroleum-based binders. WPCs based on PHB and PLA may replace WPCs with fossil fuel based plastics, e.g., polyethylene. The WPC industry is large and expanding providing water resistance products that require little maintenance with great flexibility in origin of wood raw materials and product shapes, but they have poor mechanical properties. The lignin-PLA based glue creates strong joints and has thereby great potential for more demanding applications e.g. in load carrying glued laminated timber beams.

Processing by-products of pulp processing

What's the technology and who is most advanced on it?

Pulping of wood leaves complementary streams containing organic compounds and polymers such as; extractives (tall-oil and turpentine) and lignin (black liquor). Both extractives and lignin are typically used for energy purposes but contain interesting compounds with properties suitable for different applications such as; bio-diesel, emulsifiers, detergents and surfactants. Tall-oil is refined to obtain fatty acids, rosin acids and sitosterol. Fatty acids are used as bio-diesel and as a building block for production of surfactants. Rosin acids are used as a component in glue, as pigment for producing ink and as emulsifier. Refining of tall-oil is a rather mature industry and are found in Sweden (SunPine, Arizona Chemical), Finland (ForChem), USA (Arizona Chemical), France and Japan (Harima). Turpentine from the pulping industry is usually a mixture of α-pinene, β-pinene and 3-carene that are used as precursors for production of insecticides and perfume. Turpentine can also be converted to *p*-cymene to be employed both as solvent and fuel, but also as an additive in perfume. Borregaard A/S and Domsjö Fabriker AB produces lignosulfonates that can be used as dispersing agent, binding agent, dust suppressant and extrusion aid. Lignosulfonate are also used as precursor to vanillin production at Borregaard A/S. Kraft- and hydrolysis lignin are today an interesting field of research, both for applications towards bio based materials, as a source for aromatic compounds and modification to obtain a liquid fuel.

Speed to Achieve Various Technologies

Different technologies exist already today as described above with a lot of applications based on different complementary streams from the pulping industry. To further evolve this area there are a need for research within different fields with a multidisciplinary approach. The time line is dependent on the financial side of the processes and products. Also, the investment needs to increase in the field to enhance the rate of implementation. The current progress is also strongly connected to the price of oil and gas where you have a well-developed process industry competing with cost effective products.

Industrial biotech trait potentials and adoption rate curve

A bioeconomy is on the verge to happen in a broader perspective but needs a strong political agreement on the terms for "green" products. Usually the conditions are set for a short period of time and the industry needs long term rules for making the bioeconomy real. Techniques are at hand and offer a great potential both in terms of economy and environment.

Extraction and utilisation of non-structural wood and bark components

What’s the technology and who is most advanced on it?

Trees constitute a rich and vast source of various low-molecular compounds, besides the structural polymers, i.e., cellulose, hemicelluloses and lignin. These components, commonly called “extractives”, play important roles in the life processes in trees, as well as in their chemical defence in a hostile environment, thus having key bioactive functions. Generally, these extractives have specific, fairly complicated structures, which are not easily synthesised in laboratories and manufactured in plants. Therefore, Nature´s own sustainable synthesis constitutes the basis of the molecular value of these natural compounds.

Speed to Achieve Various Technologies

There is already an established industry for extraction, purification and further refining of oleoresin and lipid components in trees, providing products such as turpentine, rosins, fatty acids and sterols. However, there is still a large potential for further conversion of these fractions into new derivatives for new applications in the market place. Polyphenols of various types are key defence substances in trees, having strong antioxidative and radical-scavenging properties. Some polyphenols such as certain lignans and alkaloids, stilbenes and tannins have been documented to have anticarcinogenic properties. However, this area is still in its infancy and new effective ingredients for health-promoting substances in nutritional supplements, functional foods and pharmaceuticals can be expected to emerge as a result of transdisciplinary research between chemists and biomedical researchers. Serving as the skin of trees, bark contains substances that protect the trees from drying and which provide defence against attack by fungi, bacteria and plant-eating animals. Thus, bark contains large proportions of tannins and other polyphenols, as well as suberins and waxes. Birch outer bark is exceptional in containing up to 30 % of a single compound, betulinol, a substance with interesting potential as such, but also as a starting material for semi-synthesis of related compounds. Bark is removed at both pulp and sawmills and is at present used almost exclusively for energy production. However, there is good potential for extraction of different bioactive substances of higher value. Gums and exudates from trees containing mainly carbohydrates or terpenoids have been collected and utilised since ancient times. Modern research and new technologies can provide new opportunities and open up markets for novel products which could replace synthetic oil-based chemicals.

Industrial biotech trait potentials and adoption rate curve

Development of small-scale production of specialty products for special markets requires cooperation between scientists in different fields, such as chemistry, chemical engineering and biosciences. Furthermore, entrepreneurs are needed to develop emerging ideas into tangible products which will find novel growth markets. For such specialty products to become large enough and profitable they need to be global. When it comes to products for health-promoting applications, regulations are becoming increasingly stricter and competition with the big pharmaceutical industry can be tough. Today, there is an increasing awareness of the risks of synthetic, artificial chemicals for the environment and human health. The gradual replacement of risky unnatural substances by more benign natural ones is an important challenge in the field of chemistry.

Biodegradable disposable cardboards for packaging, tableware and "paper bottles"

What's the technology and who is most advanced on it?

Paper and paperboard is the largest segment of the global packaging market, worth an estimated $210 billion in 2010 and expected to rise to $250 billion in 2016 (Smithers Pira, 2012). Whilst paper-based products are intrinsically biodegradable, the coatings required to make them fit-for-purpose for food packaging can render them unsuitable for recycling. A key example is Tetra Pak, the dominant market leader, with an estimated 80% of liquid paper based packaging. Its traditional aseptic packaging and more recent development of the 'paper bottle', rely on a cardboard composite which comprises up to 7 layers of plastic and frequently aluminium, requiring separation before recycling. Paper packaging with barrier properties is emerging as an alternative to plastic packaging (GMV 2014). The challenge is to develop coatings that are biodegradable yet have the functionality required to contain, preserve and protect the contents. A coating must provide a barrier against water vapour, oxygen, grease, odours or UV light but also be stable over a wide temperature range. Where recycled card is used, there is an addition problem caused by the migration of residual mineral oils from the paper into the food. Traditionally coatings have been oil-based plastics, polyethylene (PE) or polyethylene terephthalate (PET) but biopolymers such as polylactic acid (PLA) are now being used (Leminen et al, 2013; Guazotti, Marti, Piergiovanni, Limbo, 2014). Drawbacks for biopolymers include price, coating/deposition and sensitivity to water.

Speed to Achieve Various Technologies

Several products are already on the market: BASF teamed up with Hosti, to produce a range of paper plates and trays coated with their ecovio FS product (biodegradable polyester and PLA). Ahlstrom have developed their NatureMold product which comprises a paper tray optionally laminated with vegetable parchment and/or PLA conferring resistance, grease and high wet strength. Iggesund Paperboard offers Invercoat Bio a paper coated with Novamont's Mater-Bi film. Polymate has developed Green Coat, a cellulose based coating that demonstrates good oxygen and water barrier and comparable functionality to conventional polyethylene and biodegradable films. York Green Chemistry has developed starch-based Starbons® to provide control over surface energy including water resistance. As part of the Safe Food Packages for the Future project, a team at Lappeenranta University of Technology are investigating dispersion coating chemicals made from wood-based resources (Leminen et al, 2013). Promising chemicals include modified carboxymethyl celluloses and 2,3-dialdehyde cellulose , traditionally a product used as an adhesive in papermaking. Other options for bio-coatings include those based on starch but these are sensitive to water; mineral coatings but these are adversely affected by the folding procedures required to transform a flat sheet into a 3D container; or bio-based latex. As part of the same study, partners VTT have developed a thermoplastic starch dispersion barrier to replace oil-based products which provide grease resistance. Such coatings could be applied using traditional in-line coating or printing methods and would be used for modified atmosphere packaging (MAP) of meat products.

Industrial biotech trait potentials and adoption rate curve

There is considerable research into the use of cellulose nanofibres as a means of improving the mechanical strength of paper products. Galland et al (2014) report that the normally hydrophilic nature of cellulose nanofibres can be modified in a photopolymerisable acrylate matrix to produce robust, high-barrier organic films which were resistant to moisture and oxygen. Other products include a biofoam comprising starch and nanocellulose which could be a biodegradable replacement for expanded polystyrene, and all-cellulose composite or PLA mix as a food packaging foil. Paper and board products with functional barrier properties for packaging and food applications present a real alternative to plastics. Bioplastic coatings based on biopolymers that can be composted (industrial or domestic) rather than biodegradable polymers offer a more sustainable option.

Detoxification of solid waste and processing biomass for obtaining bio-fertilizers, for agricultural use and soil remediation

What's the technology and who is most advanced on it?

As opposed to uncontrolled biological transformations of waste materials at landfill sites, controlled biological treatments such as composting and anaerobic digestion enable the use of waste materials as valuable feedstock for agricultural purposes and soil remediation. Especially anaerobic digestion (i.e., biomethanation), providing renewable biogas to counteract the effect of fossil fuels and a solid recyclable digestate, has recently received wide attention globally and especially in Europe. A variety of municipal and industrial streams can be anaerobically mono- or co-digested; organic municipal waste, municipal wastewater treatment sludge, industrial wastewater from agro-food and fermentation industries, livestock wastes and e.g. various energy crops. Only strongly lignified compounds and cellulose might be barely decomposable during the anoxic digestion process. However, several ubiquitous compounds potentially toxic to human health and the environment pass through controlled biological treatment systems. Such xenobiotic compounds present in foodstuff, urban waste, municipal and industrial effluents, and contaminated soil include, amongst others, persistent organic pollutants (POPs) and other phenolic compounds, phthalates (plasticizers), herbicides, pesticides and estrogens. Hoyos-Hernandez et al. investigated phenol biodegradation during anaerobic digestion of municipal solid waste and suggested that phenol degradation to methane was supported by micro-organisms under thermophilic conditions. Benabdallah El-Hadji et al. reported that laboratory-scale anaerobic digestion of activated sludge degraded polychlorinated biphenyls (PCBs) and adsorbed organic halogen (AOX) compounds. PCB degradation efficiency respectively increased upon transition to thermophilic conditions, as AOX removal remained lower. However, according to Brändli et al., PCB concentrations during anaerobic treatment of source-separated organic waste in a full-scale plant remained unaffected, as low-chlorinated PCBs increased and higher chlorinated counterparts slightly decreased during open windrow composting at full-scale. As discussed by Valeiro, the use of mixed co-cultures in composting might positively affect poly-aromatic hydrocarbon (PAH) biodegradation.

Speed to Achieve Various Technologies

Recently the fate of estrogens considered as endorcrine disrupting chemicals (EDCs) in biological treatment systems has been discussed. EDCs are characteristically hydrophobic and thus end up in the solid residuals of, e.g., wastewater treatment plants. Bozkurt and Sanin reported that a model nonylphenol (NP) compound, NPs listed as EDCs and used as surfactants in tannery, textile, paper, detergent and personal care product industries, was biodegraded during lab-scale anaerobic digestion of municipal sludge under mesophilic conditions. However, Muller et al. stated that the fate of estrogens in sludge are not well documented and indicated that plant-scale digestion processes performed poorly in removing estrogens in contrast to reported lab-scale observations. The authors showed that the final concentration of summed estrogens in digested sludge were high and stated that final sludge stabilization and dewatering tend to increase the estrogen content probably enhancing their extractability.

Industrial biotech trait potentials and adoption rate curve

In a recent review, Hamid and Eskicioglu corroborated these concerns identifying a research gap regarding studies on the fate of estrogens especially during anaerobic sludge and animal waste digestion, and the need for understanding the effects of pretreatment methods prior to anaerobic or aerobic biological treatments. At least Fenton oxidation and ozone treatments have been reported as efficient pretreatments for sludge.

Appendix - References

Enhanced bio-energy products - Short-rotation woody crops

- Dickmann D.I. (2006). ‘Silviculture and biology of short-rotation woody crops in temperate regions: Then and now’. *Biomass and Bioenergy*, vol. 30, pp. 696-705.
- de Wit M., Junginger M. and Faaij A. (2013). ‘Learning in dedicated wood production systems: Past trends, future outlook and implications for bioenergy’. *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 417-432.
- Hinchee M., Rottmann W., Mullinax L., Zhang C., Chang S., Cunningham M., Pearson L. and Nehra N. (2009). ‘Short-rotation woody crops for bioenergy and biofuels applications’. *In Vitro Cell.Dev.Biol. – Plant*, vol. 45, pp. 619-629.
- Hauk S., Knoke T. and Wittkopf S. (2014). ‘Economic evaluation of short rotation coppice systems for energy from biomass – A review’. *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 435-448.
- IPCC. Edenhofer O., Pichs-Madruga R., Sokona Y., Seyboth K., Matschoss P., Kadner S., Zwickel T., Eickemeier P., Hansen G., Schlömer S., von Stechow C., editors (2011). ‘Chapter 1: Renewable energy and climate change’ in IPCC special report on renewable energy sources and climate change mitigation. Intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2011. p. 1554.

Enhanced bio-energy products - Gasification

- Landälv, I., Gebart, R., Marke, B., Granberg, F., Furusjö, E., Löwnertz, P., … Salomonsson, P. (2014). Two years experience of the BioDME project-A complete wood to wheel concept. *Environmental Progress & Sustainable Energy*, *00*(00), n/a–n/a. doi:10.1002/ep.11993.

Enhanced bio-energy products - Up-grading of biomass by torrefaction

- Stelte, W., Clemons, C., Holm, J. K., Sanadi, A. R., Ahrenfeldt, J. , Shang, L. , Henriksen, U. B., (2011). Pelletizing properties of torrefied spruce. Biomass Bioenergy 35, 4690-4698; (http://dx.doi.org/10.1016/j.biombioe.2011.09.025).
- Prins, M.J., Ptasinski, K.J. and Janssen, F.J.J.G. (2006). Torrefaction of wood, Part 1. Weight loss kinetics. J. Anal. Appl. Pyrolysis, 77, 28-34.
- Li, H., Liu, X., Legros, R. , Bi, X. T. , Jim Lim, C., Sokhansanj, S. , (2012). Pelletization of torrefied sawdust and properties of torrefied pellets. Applied Energy 93, 680-685; published online Epub5//(http://dx.doi.org/10.1016/j.apenergy.2012.01.002).
- Tumuluru, Jaya Shankar, Sokhansanj, Shahab Hess J. Richard, Wright Christopher T., and Boardman Richard D. (2011). A review on biomass torrefaction process and product properties for energy applications Industrial Technology 7; 384-401

Enhanced bio-energy products - Liquid biofuels from fermentation

- Lynd LR, Laser MS, Brandsby D, Dale BE, Davison B, Hamilton R, Himmel M, Keller M, McMillan JD, Sheehan J, et al. (2008). How biotech can transform biofuels. Nat Biotechnol, 26:169–172.
- Popper ZA, Michel G, Herve C, Domozych DS, Willats WGT, Tuohy MG, Kloareg B, Stengel DB. (2011). Evolution and diversity of plant cell walls: from algae to flowering plants. Annu Rev Plant Biol., 62:567–588.

- Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, Frederick WJ, Hallett JP, Leak DJ, Liotta CL, et al. (2006). The path forward for biofuels and biomaterials. Science, 311:484–489.
- Matano Y, Hasunuma T, Kondo A. Display of cellulases on the cell surface of Saccharomyces cerevisiae for high yield ethanol production from high-solid lignocellulosic biomass. (2012). Bioresource Technol., 108:128–133.
- Dimarogona M, Topakas E, Christakopoulos P. (2013). Recalcitrant polysaccharide degradation by novel oxidative biocatalysts. Applied Microbiology and Biotechnology, 97: 8455-8465.
- Cai Z, Zhang B, Li Y. (2012). Engineering *Saccharomyces cerevisiae* for efficient anaerobic xylose fermentation: reflections and perspectives. Biotechnol J, 7:34–46.

Production technology for bio-based polymers/biomass-based plastics

- Babu R et al. (2013). Current progress on bio-based polymers and their future trends. Progr Biomater 2:8, 1-16.
- Chen G.Q. (2009). A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. Chem Soc Rev. Aug; 38(8):2434-46.
- Doug S (2010). Bioplastics: technologies and global markets. BCC research reportsPLS050A. http://www.bccresearch.com/report/bioplastics-technologies-markets-pls050a.html.
- Hatti-Kaul R. et al. Industrial biotechnology for the production of bio-based chemicals – a cradle-to-grave perspective. Trends in Biotechnol 25:119 – 124.
- Lead Market Initiative: http://ec.europa.eu/enterprise/policies/innovation/policy/lead-market-initiative/index_en.htm#h2-3

Wood nanotechnology and its applications

- Eichhorn, S.J., et al.(2009). *Review: current international research into cellulose nanofibres and nanocomposites.* J Mater Sci,45(1): p. 1-33.
- Moon, R.J., et al. (2011). *Cellulose nanomaterials review: structure, properties and nanocomposites.* Chem Soc Rev, 40(7): p. 3941-3994.
- Berglund, L.A. and T. Peijs. (2010). *Cellulose biocomposites—from bulk moldings to nanostructured systems.* MRS Bull, 35(3): p. 201-207.

Wood-based composite materials

- UNECE/FAO Forest Products Annual Market Review 2011-2012
- Biocomposites: Technology Overview 2014, Materials KTN/NetComposites
- nova-Institute, press release, 26th November 2013
- http://www.wki.fraunhofer.de/en/services/vst/projects/wpc-coatings.html
- http://www.pfi.no/Info-Center/Focus-on/Topics/Wood-fiber-reinforced-thermoplastic-composites/
- http://ncc-foam.eu/project/overview
- http://www.3ders.org/articles/20131223-could-wood-based-material-lead-2014-3d-printing-priorities.html

Extraction and utilisation of non-structural wood and bark components

- Biorefining of Forest Resources (Ed. R. Alén), Paperi ja Puu Oy, Helsinki 2011. (ISBN 978-952-5216-39-4).
- Holmbom, B., Sundberg, A. and Strand, A.(2010). Surface-active compounds as forest-industry by-products. In: Surfactants from Renewable Resources (Eds. M. Kjellin and I. Johansson), John Wiley & Sons, Ltd, New York, Chapter 3, pp. 45-62. (ISBN 978-0-470-76041-3).

- Gallis, C., Di Stefano, M., Moutsatsou, P., Sarjala, T., Virtanen, V., Holmbom, B., Buhagiar, J.A. and Katalanos, A.(2011). Forests products with health-promoting and medicinal properties. In: Forests, Trees and Human Health (Eds. Nilsson, K., Sangster, M, Gallis, C., Hartig, T., de Vries, S., Seeland, K. and Schipperijn, J.), Springer Science, Berlin, Chapter 3, pp. 41-77. (ISBN 978-90-481-9805-4).
- Gallis, C., Sangster, M., Tellnes, G., Sanesi, G., O´Brien, L., Holmbom, B. and Batt-Rawden, K. (2012). Research into forests and human health – Current status and trends in Europe, In: Forest Medicine (Ed. Qing,L.), Chapter 22, Nova Science Publishers, New York, Chapter 22, pp. 277-310. (ISBN 978-1-62100-000-6).

Biodegradable disposable cardboards for packaging, tableware and "paper bottles"

- Ahlstrom http://www.ahlstrom.com/en/Products/Food-and-Beverage/Cooking-and-Baking/Ahlstrom-NatureMold/ accessed May 2014-05-25
- BASF http://www.basf.com/group/pressrelease/P-12-360 accessed May 2014
- Galland, S., Leterrier, Y., Nardi, T., Plummer, C.J.G., Månson, J.A.E., Berglund, L.A. (2014). UV-cured cellulose nanofiber composites with moisture durable oxygen barrier properties. Journal of Applied Polymer Science,
- GMV 2014 http://www.packagingeurope.com/Packaging-Europe-News/58212/Paper-Packaging-as-an-Alternative-to-Plastic.html
- Guazzotti V1, Marti A, Piergiovanni L, Limbo S. (2014). Bio-based coatings as potential barriers to chemical contaminants from recycled paper and board for food packaging. Food Addit Contam Part A Chem Anal Control Expo Risk Assess. 31(3):402-13
- Iggesund Novamont http://www.plasteurope.com/news/NOVAMONT_t227479 accessed May 2014
- Leminen V. et al. (2013). Aspects on Packaging Safety & Biomaterials, 26th Symposium on Packaging, June 10-13, Espoo, Finland
- http://www.polymateltd.com/files/6_GreenCoat.pdf accessed May 2014
- (2012), The Future of Global Smithers Pira Packaging

Detoxification of solid waste and processing biomass for obtaining bio-fertilizers, for agricultural use and soil remediation

- Nkoa R. (2014). Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates. Agronomy for Sustainable Development, 34: 473-92.
- De Meester S, Demeyer J, Velghe F, Peene A, Van Langenhove H, Dewulf J. (2012). The environmental sustainability of anaerobic digestion as a biomass valorization technology. Bioresource Technology, 121: 396-403.
- Hoyos-Hernandez C, Hoffmann M, Guenne A, Mazeas L. (2014). Elucidation of the thermophilic phenol biodegradation pathway via benzoate during the anaerobic digestion of municipal solid waste. Chemosphere, 97: 115-9.
- Benabdallah El-Hadj T, Dosta J, Torres R, Mata-Álvarez J. (2007). PCB and AOX removal in mesophilic and thermophilic sewage sludge digestion. Biochemical Engineering Journal, 36: 281-7.
- Brändli RC, Bucheli TD, Kupper T, Mayer J, Stadelmann FX, Tarradellas J. (2007). Fate of PCBs, PAHs and their source characteristic ratios during composting and digestion of source separated organic waste in full-scale plants. Environmental Pollution, 148: 520-8.
- Valerio F. (2010). Environmental impacts of post-consumer material managements: recycling, biological treatments and incineration. Waste Management, 30:2354-61.

- Bozkurt H, Saning FD. (2014). Toxicity of nonylphenol diethoxylate in lab-scale anaerobic digesters. Chemosphere, 104: 69-75.
- Muller M, Combalbert S, Delgeńes N, Bergheaud V, Rocher V, Benoît P, Delgeńes J-P, Patureau D, Hernandez-Raquet G. (2010). Occurrence of estrogens in sewage sludge and their fate during plant-scale anaerobic digestion. Chemosphere, 81: 65-71.
- Li Y, Zhang A. (2014). Removal of steroid estrogens from waste activated sludge using Fenton oxidation: influencing factors and degradation intermediates. Chemosphere, 105: 24-30.