Woody aerogels: super-light yet versatile

The term "wood" usually conjures up an image of a hard, heavy, and bulky material. However, new research is proving that wood-based materials do not have to be this way. Dr Feng Jiang is a newly appointed assistant professor in the department of Wood Science who has been looking at rethinking and redesigning wood-based materials in order to make them, literally, as light as a feather. Feng has more than 10 years of research experience in the area of novel wood-based biomaterials. He is currently leading the Sustainable Functional Biomaterials lab at UBC – a group that aims to revolutionize materials (such as the feather-light aerogels described here) derived from wood.

Advancing research in wood-based materials has never been more urgent. Pollution of our oceans by plastics is happening at a rate of over 9 million tons per year and is an issue of increasing public concern. With a typical service life of 15 min, the plastic bag can take hundreds of years to be completely degraded, if it can be degraded at all. Commonly, plastic bags break down into tiny microplastics that are invisible to the human eye, but eventually end up in the human body through food chains. Solving this pollution issue has been haunting all living species since the invention of plastics over 150 years ago. Scientists from both academia and industry are now turning their attention to trees as a source of sustainable and biodegradable materials.

Trees consists of 3 major natural components (cellulose, hemicellulose, and lignin) that make up the volume of wood. Similar to the synthetic polymers that we encounter in our daily lives, wood's 3 natural components are polymers containing many small molecules strung together by chemical bonds. A natural cellulose chain can contain hundreds or thousands of glucose sugars. Derived from CO_2 and H_2O during the process of photosynthesis, glucose sugars can link together to form long cellulose polymer chains, which help to fix carbon and support the upright growth of trees. These individual cellulose chains bundle together to maximize axial strength and form the structural skeleton in the plant cell wall that reinforces trees in the same way that steel can reinforce concrete. The cellulose bundles, also called elementary fibrils or microfibrils, have a diameter of approximately 3.5 nm, are more than one ten-thousandth thinner than human hair, and have mechanical properties as strong as carbon nanotubes and glass fibres.

Although cellulose has been used in papermaking, this industry is declining due to the weak demand for newspaper. Fortunately, with the advances of more sophisticated nanotechnology, bundles of cellulose chains can now be separated from cellulose fibres by biological, chemical or mechanical means. Although isolation of nanocellulose (a bundle of cellulose chains in the form of short and rigid particles or long and flexible fibrils) was first described 70 years ago, its mass production and application have only become fully-fledged during the past decade. Canada, a country with vast forest resources, has pioneered the production of various types of nanocellulose from wood. Products have included a cellulose nanocrystal marketed by CelluForce, and microfibrillated cellulose developed by Performance BioFilaments.

Once isolated from wood cell walls, nanocelluloses can serve as building blocks for reconstruction into materials of various shapes and dimensions, rather like building with children's LEGO block toys. However, in contrast to the physical interlocking between LEGO blocks, nanocelluloses are held together by intermolecular forces of hydrogen bonding, the same forces that hold water molecules together within a river or as droplets on a windshield. The collective strength of hydrogen bonding depends on the available surface functional groups that interact with each other, making nanocelluloses ideal building blocks due to their high surface area. A nanocellulose with a diameter of 2 nm has a surface area of approximately 1,250 m^2/g. This means that, with a fully extended surface, it would take only 5 g of nanocellulose to completely cover a football pitch. With such exceptionally high surface areas and prevalent surface hydroxyl groups that are responsible for forming inter-fibril hydrogen bonds, nanocelluloses can package intimately with each other to form a 3-dimensional foam-like material without the addition of any chemicals.

Taking advantage of the ultrathin nature of nanocelluloses, and their exceptionally high specific surface area, Feng's lab group is developing super-light all-cellulose aerogels. The term "aerogel" is used to describe a 3-dimensional foam-like structure with a density as low as air (1.225 kg/m^3, or approximately 800 times lighter than water). The aerogel developed in Feng's lab has a density of 1.7 kg/m^3 and porosity of 99.9%. In other words, the nanocellulose aerogel contains 99.9% air by volume and only 0.1 % solid materials. On visual inspection, the aerogel appears as a honeycomb structure with a pore width of around 0.5 mm. This high porosity and low density make nanocellulose aerogel a super-absorbent material that can absorb approximately 300 g of water per gram. As a comparison, paper towels can absorb only about 10 g of water per gram. In fact, this absorbency value is the highest among all other bio-based aerogels or foams reported to date.

Conversion of 1-dimensional nanocellulose into 3-dimensional aerogel structures can introduce a wide variety of applications that could not have been imagined from the original wood or cellulose. The light and super-absorbent properties of aerogels can be useful in wound dressings, beauty products such as facial masks, or personal hygiene products. Feng's group has demonstrated that this woody aerogel can help in environmental remediation, with potential applications such as oil recovery from contaminated oceans, water filtration and purification, CO_2 adsorption, as well as catalyst support for degradation of toxic chemicals. Additionally, this highly porous aerogel structure demonstrates ultralow thermal and acoustic conductivity, properties useful for thermal or sound insulation in buildings. As an outdoor enthusiastic, Feng imagines huge potential for the nanocellulose aerogel in outdoor equipment, either in new water purification technologies, or as a lightweight insulation layer for thermal comfort.

Aerogel is only one of the products being investigated by the Sustainable Functional Biomaterials group. Feng's group is also interested in diversifying the products portfolio of bio-based nanomaterials, including strong filaments, transparent films, porous membranes, nanocomposites, and 3D printed structures. Nanocelluloses have high surface areas and abundant surface functional groups for chemical modification. Once modified, nanocelluloses can demonstrate novel functionalities not existing in traditional wood materials. Feng's ultimate goal is to develop bio-based materials for advanced applications in the emerging energy, healthcare, and environment areas, to potentially alleviate our reliance on the petroleum economy. Trees can produce 10^{11} – 10^{12} tons of cellulose annually, approximately 500 times more than the annual production of plastics. Clearly, natural polymers are in sufficient supply to meet human needs for materials. However, new technologies are needed in order to transform these natural polymers into materials with performances comparable or superior to our existing petroleum-based products. Feng and researchers around the world are working collaboratively towards this goal.

For further information, contact Dr Feng Jiang (department of Wood Science) at feng.jiang@ubc.ca.