An overview of wood's amazing capacities: from macro to nanoscale

Matheus Cabral (director: Pierre Blanchet, codirector: Costel Barbuta)

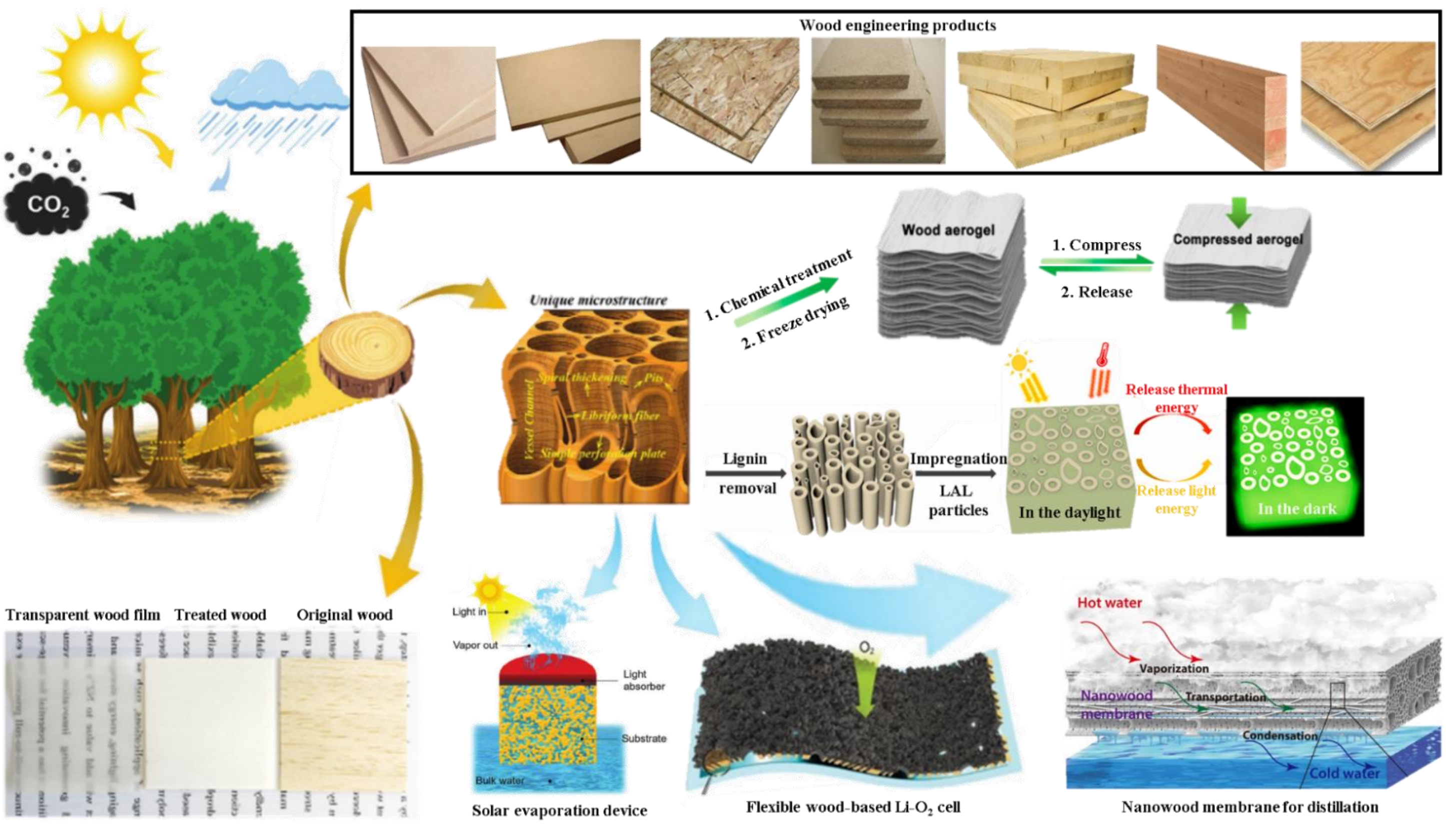
Roberta Dagher (director: Véronic Landry, codirector: Tatjana Stevanovic)

Mariana Frias (director: Pierre Blanchet, codirector: André Bégin-Drolet)

Aurélien Hermann (director: Véronic Landry, codirector: Dominique Burr)

****

Graphical abstract



All the pictures used in the graphical abstract were found in the literature cited in this article [3-7]

** All authors contributed equally to this manuscript – names alphabetically ordered*

Introduction

Since our intellectual development, humans have been using materials such as stone, leather, wood, plant fibers, ceramics, glass, metals, and more recently they started using polymers. Nowadays, the progress in the development of commercial aircraft, the manufacture of electronic equipment, the diffusion of information, the surgical instruments, the construction of buildings structures, among other applications, is highly dependent on the development of new materials that are adapted to our needs. Furthermore, due to environmental concern, a lot of progress should be made to reduce the carbon footprint caused by materials production (e.g., cement, polymers and steel). Therefore, the use of bio-based materials or bio-composites has emerged as an interesting strategy to mitigate this negative impact of traditional engineering materials.

Wood is a renewable, degradable and environmentally friendly material which has been used in a wide range of applications including building materials, furniture, indoor and outdoor decorations. It is also a main source of a huge number of composites. Wood has a porous structure with different sizes of pores: macropores (0.5–58 µm), mesopores (80–500 nm) and micropores (1.8–80 nm) [1]. The cell walls are composed of three biopolymers: cellulose, hemicellulose and lignin. Approximately, cellulose and hemicellulose represent about 40-45% and 15-25%, respectively, while lignin represent 20-30%, however, these values may vary according to the wood species [2]. Cellulose, which is the major component in wood, is a linear polymer of anhydroglucose units. Hemicelluloses are branched-chain polymers of sugar units (e.g., galactose, mannose, etc.) and lignin is an aromatic macromolecule that has a more complex structure, which is based on phenylpropane units. Cellulose chains in the cell wall are arranged in microfibrils that are entangled to form fibers. The hemicelluloses are linked to the cellulose chains by hydrogen bonding and are chemically linked to lignin. Other compounds, which do not have a structural role, are also present in the porous structure of wood.

The high mechanical properties of wood make it a suitable material for structural applications and construction segment. It is also a flexible structure composed by natural polymers that can either be removed from wood to formulate new materials of a smaller scale or be modified in order to create a functionalized wood material. Due to its porous structure, wood is also well suited as a matrix or a structural support that can be impregnated with sensible chemicals. In this review, we are going to highlight some of wood's applications, from construction segment to smaller scale such as flexible electronics.

Tailored wood-based products

Engineering wood products

Taking into account the use of wood on the macroscale, several materials can be highlighted, which include the wood use as logs and lumbers or in the form of engineering products especially those used for building applications. The advantages of wood engineering products (WEP) as they are made from glued laminated timber, adhesives and other materials include increased dimensional stability, more consistent mechanical properties, and increased durability. The most used WEP (Figure 1 a) and some examples of wood in buildings (Figure 1 b) are shown. Subsequently, WEPs are described below based on the review of Ramage et al. (2017) [3].

Figure 1. Wood engineering products: CLT – Cross Laminated Timber; MDF – Medium Density Fiberboard; HDF – High Density Fiberboard; OSB – Oriented Strand Boards; MDP – Medium Density Particleboard (A) and wood in buildings (B).

Cross Laminated Timber (CLT) and glulam are among the most used engineering wood products in mass timber buildings. CLT is a structural composite which was developed in the 1990s in Austria and

Germany. Since then, it has been widely used in Europe and more recently in North America. CLT is usually made up of an odd number of layers, usually three, five or seven which are arranged and glued crosswise to each other with a structure adhesive. Crossing the layers provide high-dimensional stability and load-bearing capabilities in more directions. CLT can be produced in large sizes which can vary up to 0.5 m thick, 4 m wide and 24 m long. This product is used for walls, floors and roofs in buildings.

Glulam is made from small pieces of lumber which can range from 6 to 45 mm thick, forming a single and strong structural material. Glulam is used as a vertical column or a horizontal beam as well as in arched curved shapes. Glulam is available in custom and stock sizes and can be classified according to its appearance as premium, architectural, industrial or framing.

Particleboard is another group of WEP. This group includes medium density (MDF) and high density (HDF) fiberboards, oriented strand board (OSB), medium density particleboard (MDP) and plywood. MDF and HDF are made with wood fibers (hardwood or softwood) and a formaldehyde adhesive and are fabricated by applying high temperature and high pressure. These boards are used for many interior and exterior applications (e.g., furniture, cabinets, window and door frames, walls and roof coverings).

OSB is made from thin wood strands instead of wood fibers, which are also bonded with a formaldehyde adhesive and are formed by applying high temperature and high pressure. Typically, OSB is made up of three layers of strands. The outer faces having longer strands aligned in the direction of the board and the middle layer with the smaller strands or the thin ones aligned or randomly laid. OSB is mainly used for wall cladding, roof decking or as a sub-floor for various floor coverings.

MDP is a non-structural product typically used in interior and exterior uses (e.g., flooring, walls, ceilings, office dividers, notice boards, cabinets and furniture). It is made from wood particles and an adhesive which are pressed together under a high temperature. Additives such as paraffin emulsions and catalysts (ammonium chloride or ammonium sulfate) are commonly applied with the binder to reduce the board's hygroscopicity and to accelerate the binder setting. Plywood is made from an odd number of veneers, orthographically bonded with a binder, to minimize the strength anisotropy of the material. This product can partially replace solid wood in furnishings, floors, decoration, packaging and construction.

Delignified wood composites

As we saw in the first section, wood is a go-to structural material in many construction projects. This is especially due to its mechanical resistance and interconnected vessel arrangement. By removing lignin from wood, a higher absorption of chemicals can be achieved and delignified wood would still carry the same shape stability [4]. Therefore, it can then be used as a supporting material to form mechanically stable composites.

Yang et al. designed a self-luminous wood composite for thermal energy and light energy storage, which was fabricated by impregnating delignified wood with phase change materials (PCM) and long afterglow luminescence particles [4]. A synergistic effect was found as delignified wood provided structural and thermal insulation properties, PCM showed high thermal storage capacity and thermal reliability and long afterglow luminescence materials improved both energy storage and consumption by absorbing UV and visible light. Moreover, in the process of energy conversion, this product also showed light emitting properties that can have potential application for decoration, emergency lighting and building energy conservation purposes.

Aerogels made from wood

By removing both lignin and hemicelluloses with chemical treatment then freeze-drying, it is also possible to produce aerogels [5]. The obtained product is light, has low thermal conductivity and shows higher mechanical strength than other insulation materials (e.g., polyurethane; rockwool and fiberglass) [6]. Since wood is an anisotropic material, it ensures a faster thermal dissipation in one direction and therefore increasing the insulation in the other, as shown in Figure 2.

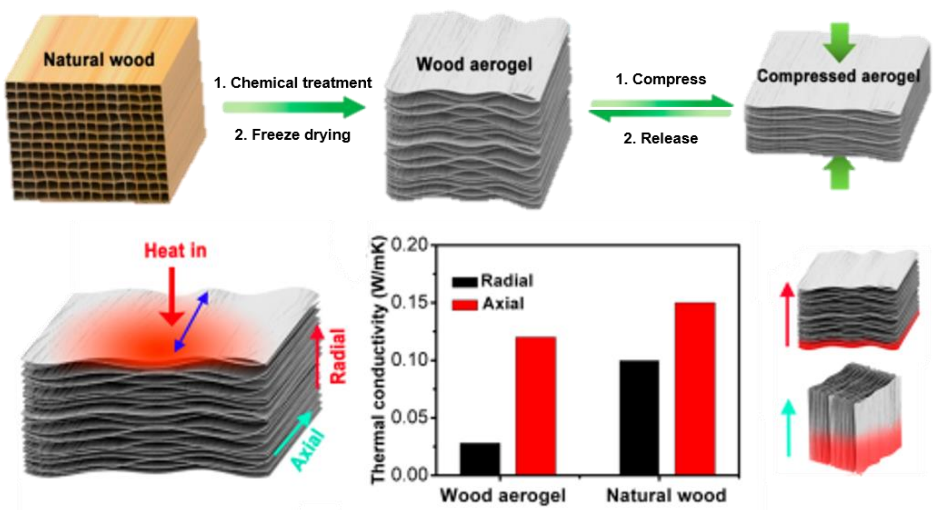


Figure 2. Wood aerogels (modified from reference [5])

Nanowood for flexible electronics

Wood can also be used to fabricate thin films as substrates for flexible electronics, which can be functionalized and then applied in smart packaging, sensors and wearable devices [7]. These films are produced by removing lignin and hemicelluloses from wood, and the product obtained will appear as a white solid. The treated wood is then compressed between two polyethylene terephthalate (PET) membranes. As both materials have similar refractive index, transparent wood films are obtained. A conductive ink is then printed on this substrate to make an electronic circuit. The conductive ink used can also be bio-based on lignin carbon nanofibers. These fabricated electronics can be recycled by reusing the fibers in paper-making processes. So, if we want to improve the sustainability of our electronic devices, nanowood is an option to consider!

Making batteries from nanowood

For the development of wood-based batteries, researchers were inspired by the porous structure of wood, which ensures the transport of water and nutrients in trees [8]. The presence of pores sized from microns to nanometers, plays an important role for the high performance of the batteries by providing independent channels for oxygen, ions and electrons. Therefore, wood gives us a one-step solution for avoiding obstacles that may occur during the charging/discharging cycle of the battery (e.g., insoluble Li_2O_2 solids that could reduce the transmission of oxygen and lithium ions). Other than lithium-oxygen batteries, wood have been investigated for the use in the development of lithium-CO_2 batteries and an all-wood supercapacitor.

Wood-based solar steam generators

Similar as for the batteries, the micropores of wood can play an important role for the high performance of solar steam generators [8,9]. Therefore, researchers took advantage of the natural structure of wood for the water transport and carbonized the top layer of wood to also have a good conversion of light to heat. In the reverse-tree design, water is either transported across the vessels of wood or by the smaller pores (see Figure 3). To further improve the performance of these systems, researchers have removed lignin from wood to reduce its thermal conductivity. These wood-based solar steam generators can be used for seawater desalination and steam power generation, which could contribute to the global efforts for resolving energy and clean water shortage crisis.

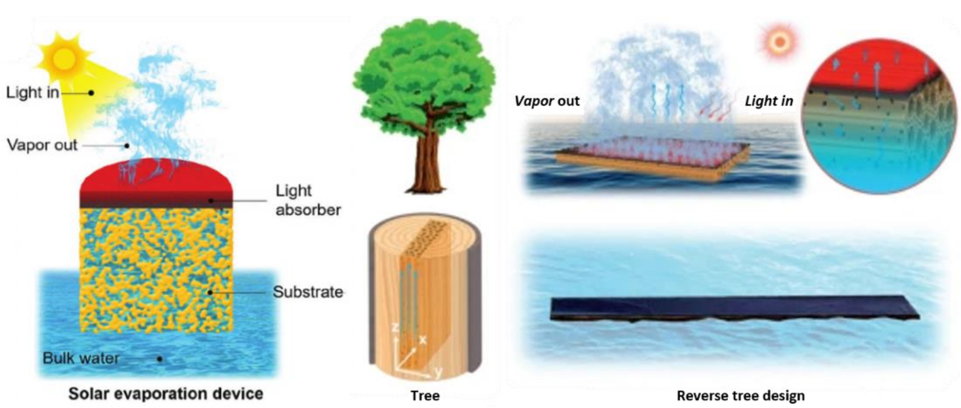


Figure 3. Wood-based solar steam generator [8,9].

Engineered wood for membrane distillation

Nanowood membrane was also used for membrane distillation (MD) which is a technology used for extracting freshwater from high-salinity and contaminated sources such as seawater or wastewater [9]. To make the nanowood membrane, lignin and hemicellulose are removed. The surface is then treated to increase the hydrophobicity and to allow only the vapor to pass through. The porous structure of wood ensures a high vapor permeability and low heat loss because of the low thermal conductivity.

Conclusion

The new technologies need to start compensating for the environmental damage caused by decades of industrial production. Thus, bio-based materials became a hot topic for sustainable technology. Wood is a bio-based material with high mechanical performance and a unique appearance, which makes it interesting for both construction and interior products. Its structure is porous and can be treated or combined with other products, such as long afterglow luminescence particles, to enhance its properties and to be used in many applications. Recently, nanowood was manufactured as a light and biodegradable material with potential applications in sustainable energy development, wastewater treatment, electronic devices, sensors and more. This article showed many ways in which wood can be used and adapted to new technologies, to harness its potential and help us on the path to a more sustainable future.

References

[1] M. Plötze, P. Niemz, Porosity and pore size distribution of different wood types as determined by mercury intrusion porosimetry, Eur. J. Wood Prod. 69 (2011) 649–657. https://doi.org/10/bk56bv.

[2] R. YOUNG, Historical developments in wood chemistry, Türkiye Ormancılık Dergisi. 9 (2008) 1–15.

[3] M.H. Ramage, H. Burridge, M. Busse-Wicher, G. Fereday, T. Reynolds, D.U. Shah, G. Wu, L. Yu, P. Fleming, D. Densley-Tingley, J. Allwood, P. Dupree, P.F. Linden, O. Scherman, The wood from the trees: The use of timber in construction, Renewable and Sustainable Energy Reviews. 68 (2017) 333–359. https://doi.org/10/f9mhqg.

[4] H. Yang, W. Chao, S. Wang, Q. Yu, G. Cao, T. Yang, F. Liu, X. Di, J. Li, C. Wang, G. Li, Self-luminous wood composite for both thermal and light energy storage, Energy Storage Materials. 18 (2019) 15–22. https://doi.org/10/ghk7rg.

[5] J. Song, C. Chen, Z. Yang, Y. Kuang, T. Li, Y. Li, H. Huang, I. Kierzewski, B. Liu, S. He, T. Gao, S.U. Yuruker, A. Gong, B. Yang, L. Hu, Highly Compressible, Anisotropic Aerogel with Aligned Cellulose Nanofibers, ACS Nano. 12 (2018) 140–147. https://doi.org/10/gf8tmr.

[6] C. Chen, Y. Kuang, S. Zhu, I. Burgert, T. Keplinger, A. Gong, T. Li, L. Berglund, S.J. Eichhorn, L. Hu, Structure–property–function relationships of natural and engineered wood, Nat Rev Mater. 5 (2020) 642–666. https://doi.org/10.1038/s41578-020-0195-z.

[7] Q. Fu, Y. Chen, M. Sorieul, Wood-Based Flexible Electronics, ACS Nano. 14 (2020) 3528–3538. https://doi.org/10/ghk7rc.

[8] Z. Zhu, G. Xiao, J. Chen, S. Fu, Wood nanotechnology: a more promising solution toward energy issues: a mini-review, Cellulose. 27 (2020) 8513–8526. https://doi.org/10/ghk7vk.

[9] X. Chen, X. Zhu, S. He, L. Hu, Z.J. Ren, Advanced Nanowood Materials for the Water–Energy Nexus, Advanced Materials. n/a (n.d.) 2001240. https://doi.org/10/ghk7vm.