Guide for selecting tree species for making xylem filters

Overview

Gymnosperm xylem exhibits great morphological variability across and within species, and even within the same tree. A description of how the filter performance (*i.e.*, permeance and rejection) may vary with the structural characteristics of the xylem is provided in the subsequent slides.

This excel file 'Geographic availability, structural and degradation characteristics, and pricing of gymnosperms' below lists these characteristics in detail[1,2,11–14,3–10] and also provides information on geographic availability, pricing, and decay resistance for a wide range of gymnosperms.

Dependence between filter flow rate & choice of tree species

In general, for a given xylem structure without significant pit aspiration, the flow rate is expected to be proportional to sapwood area and driving pressure, and inversely proportional to filter thickness. In the absence of fouling, the flow rate through a xylem filter depends on:

1. ***Fraction of xylem-containing sapwood present in the filter cross-section:*** Flow rate increases with sapwood area. Inclusion of impermeable heartwood in filters (*e.g.*, when a filter is made from a branch cross-section) can reduce the sapwood area available for filtration. Sections of branches used for filtration tend to have less effective area for filtration due to the impermeable heartwood present in the center. Filters made exclusively from the sapwood in trunks have their entire area available for filtration but are limited in size by the width of the sapwood in the trunk. Some tree species, like ponderosa pine (*Pinus ponderosa*), ocote pine (*Pinus oocarpa*), Douglas fir (*Pseudotsuga menziesii*), pond pine (*Pinus serotina*), red pine (*Pinus resinosa*), spruce pine (*Pinus glabra*), Virginia pine (*Pinus virginiana*), and sitka/yellow/western/silver spruce (*Picea sitchensis*) have a wider sapwood and are well-suited for creating large area filters[15].
2. ***Tracheid and pit membrane properties:*** Wider and longer tracheids can yield higher flow rates[2]. A high fraction of the tracheid wall area covered by pit membranes and higher pit membrane porosity increase fluidic conductivity. The tracheid conductivity for some tree species is provided in Supplementary Data 1. The tracheid length plays a key role in determining filter thickness. Filters should ideally comprise not more than 2-3 tracheids along their thickness to minimize flow resistance without compromising rejection ability. Tracheid lengths could vary significantly within a tree. For example, tracheids in trunks are typically longer than those in stems, and tracheid length also decreases with tree height. However, tracheid lengths are typically less than 5.6 mm[16].

Dependence between rejection performance & choice of tree species

The rejection of the pit membranes depends on the following parameters:

1. ***Pore size of pit membranes:*** Smaller pores have better rejection performance. The pit membrane pore size varies considerably across and within a plant. The pores in latewood (summerwood) are typically smaller than those in earlywood (spring wood)[17]. Intra-species variability is most prevalent amongst pines[17], where reported pore size measurements vary from 200-400 nm[5,6,17]. The pit membranes in ancient gymnosperms (belonging to genus *Cycas* and *Welwitschia*), *Ginkgo*, and cedars (which belong to genus *Thuja* in the cypress family), are very dense and are expected to be capable of excellent rejection[17].
2. ***Resin canals/ducts:*** Resin canals/ducts are cylindrical intercellular spaces in the xylem oriented in the axial (longitudinal) direction[18]. Their inner surface is lined by epithelial cells, which secrete resins for defense against pests and pathogens[19]. If not filled with resin, these canals could act as leakage pathways in xylem filters and hence, attention should be paid to their presence. They could be several centimeters in length and are typically longer in the trunks than branches[20,21]. Resin canals are generally present in *Picea* (spruce), *Larix* (larch), *Pseudotsuga* (Douglas fir), and *Pinus* (pine); those in pines being numerous, large and evenly spaced while the ones in spruces, larches, and firs are few, small, and evenly spaced[22,23]. These canals are generally absent in *Abies* (fir), *Tsuga* (hemlock), *Pseudolarix* (golden larch), *Cedrus* (cedar), *Taxus* (yew, caution: yews are toxic), *Juniperus* (juniper), *Cupressus* (cypress) and *Ginkgo* (ginkgo) unless formed in response to external stimuli or stress[22,24,25].

Dependence between need for dry preservation & choice of tree species

Filters made from tree species whose pit membranes are more resistant to cavitation may be less susceptible to drying-induced loss of performance during operation. Prior studies suggest that the resistance to cavitation depends on tracheid properties, the thickness or the rigidity of the torus, and ratio of the torus diameter to that of the cell wall aperture[1]. Junipers and cypress-pines tend to have high resistance to cavitation[1].

Safety

Selection of tree species for filter fabrication should be preceded by a thorough investigation of the potential toxic effects of its sap and methods to eliminate them (if any).

- Sap of some trees is consumed by humans[29,30], and sapwood occurs naturally in surface waters.
- Plants belonging to genus *Pinus* (pine), *Tsuga* (hemlock), and *Picea* (spruce) have been characterized as non-toxic[31,32], though the needles of *Pinus ponderosa* (ponderosa pine) and *Pinus contorta* (lodgepole pine) and can be toxic to cattle during gestation[33,34].
- The oil extract of genus *Juniperus* (juniper) are commonly used in cosmetics[32]. Plants that are known to be non-toxic include Norfolk pine (Australia hemlocks).
- All parts of plants belonging to genus *Taxus* (yews) and *Cycas* (cycads) are known to be poisonous[35].
- *Abies balsamia* (balsam fir) is known to be a skin irritant, and the seeds of *Ginkgo biloba* (ginkgo) are known to be poisonous[35].

Confirming that the sapwood is nontoxic is essential for use of the filters for filtering drinking water for human consumption. In addition, appropriate safety certifications and approvals may be procured before distributing the filters for human use. International NSF/ANSI standards are commonly employed to certify point-of-use drinking water filters. Although not required, the following certifications could be useful before marketing the product:

a. NSF/ANSI 53: This standard is used to certify health-related microbiological contaminant reduction claims.
b. NSF/ANSI 42: This standard is used to certify the chemical and material safety of filters. We note that drinking water standards typically do not have health-related constraints on natural organic matter in water (although there are constraints related to aesthetics, such as color).

In the future, it may be useful to develop certifications specifically for xylem filters.

Additional factors to consider

In addition to aforementioned factors, the following notes could be helpful for filter manufacture:

1. **Selection of branches:** Branches that do not have leaves undergo inactivation of the xylem through a process called compartmentalization[26] and have lower permeance. Junctions (where branches connect to one another) have a bent xylem vasculature and a lower hydraulic conductivity[27]. The wood from such branches and junctions should preferably not be used for manufacturing filters. Further, branches or trunks that show signs of decay (black marks, spots, etc.) should also be avoided.

2. **Standardization of filter size:** Xylem filters made from branches suffer from variability in shape and size, presenting challenges for designing compatible filter holders that can house these filters and enable their practical use. Coring out fixed-diameter circular discs from branches could enable standardization; but such a process can result in wastage of the xylem-containing sapwood present in the periphery while preserving the impermeable heartwood in the center, thereby reducing the effective area available for filtration. Standardized filters with a high fraction of sapwood area can be manufactured by cutting rectangular or circular sections from the peripheral sapwood in tree trunks. Certain species like Ponderosa pine, which have wider sapwood in the trunk cross-section, are more suited for the creation of such filters[15]. It is to be noted that the length of xylem conduits could vary across trunks and branches; as a result, the filter thickness may need to be adjusted to maintain rejection performance[28]. 0.375-inch thick filters made from branches of Eastern White Pine showed 98.8±1.2% rejection of 1 μm microspheres. However, 0.5-inch thick filters made from partly-dried trunks (procured after two weeks of felling) also showed comparable rejection (98.57±0.86%), whereas 0.75-inch thick filters showed a rejection of 99.21%±0.73%.

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