Scientific Correspondence

Why is ramie the strongest yet stiffest of bast fibres?

Ramie (Boehmeria nivea (L.) Gaudich.), commonly known as white ramie or Chinese grass, is a perennial (6–20 years) herbaceous flowering plant of the family Urticaceae. It is native to east Asia and grown mostly in tropical and subtropical regions of the world, such as Brazil, China, India, Philippines, South Korea, Taiwan, Thailand and the Lao PDR. Another less commercially important species B. nivea (L.) Gaudich. var. tenacissima (Gaudich.) Miq., which is indigenous to the Malay Peninsula, is known as green ramie or rhea. Both the species are mainly distinguished by the colour of the lower leaf surface, in addition to other morphological features. A white ramie plant (Figure 1) produces a large number of unbranched stems (stalks) from underground rhizomes, grows to a height of about 2.0–3.0 m with a diameter of 12–20 mm, yields about 8–20 t/ha green biomass and develops bast (phloem) fibres, with an average fibre yield of 1.5 t/ha (ref. 4). It is one of the oldest textile fibres used to make mummy clothes in Egypt about 5000–7000 years ago. Ramie fibre is characterized by white colour and a silky lustre. Fibre strands measure up to 190 cm in length, with the longest individual cells that are as long as 40 cm (ref. 4), that is, about 7–13 times longer than cotton seed trichomes (fibres). The length and breadth of typical hexagonal or oval shaped fibre cells are 40–250 mm and 16–126 μm respectively. Unlike the other bast fibre crops, ramie phloem is distinguished by excess amounts of colloidal substances, such as gums and pectins, and therefore, degumming is the process employed to extract spinable ramie fibre from the phloem tissue.

Ramie is the strongest bast fibre and one of the strongest natural fibres comparable to cotton and silk; like cotton, it exhibits even greater strength when wet. In contrast to jute and kenaf (mesta) but similar to flax and sunhemp, ramie fibre is prosenchyomatous in origin, which develops from the procambium as elements of the protophloem by cell division followed by extensive cell elongation. Since the fibre is not differentiated by the secondary activity of the cambium, it is regarded as primary in origin. This distinguishes ramie fibre from that of jute and kenaf (mesta), which are protophloic and predominantly (90%) secondary in origin. Although a typical ligno-cellulosic bast fibre, ramie fibre contains a very high proportion of pure cellulose. It is even better than flax and hemp fibres in terms of fibre (filament) strength, the length and breadth (L:B) ratio of ultimate fibre cells and fibre (filament) finesse (Table 1)11. The L:B ratio, whose high value indicates better fibre quality, of ramie is even greater than that of cotton (1050–3000)4. These intrinsic fibre properties account for high durability, pliability, uniformity and absorbency of ramie fabrics, as compared to those woven from the other bast fibres. However, ramie is stiff and brittle with low elasticity. Why is that? It's why blends are more common than pure ramie, with the most typical being a blend of 55% ramie and 45% cotton.

What makes ramie the strongest but the stiffest bast fibre? For natural fibres, such as cotton, flax, jute, kenaf (mesta), ramie including forest trees, the secondary cell wall is more important than primary cell wall. A mature cotton fibre (trichome) is composed of a single cell wall biopolymer (cellulose) that accounts for about 95% of the dry weight, and unlike typical secondary cell walls, it does not contain lignin. In comparison, the secondary walls of bast fibres are chemically characterized by cellulose, hemicellulose and lignin. The biopolymer lignin essentially provides mechanical support, but there is enough evidence to support that it does not account for fibre strength; with 27 times low lignin content in ultimate fibre cells, ramie is stronger than jute (Tables 1 and 2). This is also supported by observations that lignin-deficient mutants of both the cultivated jute species (Corchorus capsularis L. and C. olitorius L.) have fibre strength similar to their corresponding parents. Interestingly, those lignin-deficient jute mutants have normal cellulose structure, indicating that it is not the lignin but the α-cellulose that provides strength to the jute fibre. Based on this line of evidence, a higher α-cellulose content together with β-cellulose in ramie than in the other bast fibres (Table 2) may be responsible for its superior fibre strength. However, as compared to other bast fibres, ramie has low elasticity and resilience despite the fact that it contains not only the highest percentage of cellulose, but also a very high proportion of pure cellulose. The degree of crystallinity of ramie (native cellulose I), as determined by X-ray methods, is generally 70%, with 74% and 54% crystallinity in the dry and moist states respectively. Most interestingly, for native ramie fibres, the unit cell in the crystallites is identical to that of cotton.

Cellulose is an unbranched glucan polymer of β1,4-linked glucose, with a polymeric repeating unit known as cellulose. Several of these glucan chains, each of which may consist of about 2000 to more than 25,000 glucose residues, are arranged as a crystalline, parallel array under covalent association (H bond) to form a cellulose (cellulose I) microfibril. For cotton cellulose, the degrees of polymerization (gluean chain length) in primary and secondary cell walls are 2000–6000 and 13,000–14,000 respectively. Of the bast and leaf fibres, ramie (3300–5800) appears to have the highest degree of polymerization, whereas jute (1920–4700) has the lowest. The levelling-off degree of polymerization (LODP) values (of hydrocellulose after treatment with 1 M HCl at 55°C) for ramie (300 glucose units) are even much higher than that of cotton (175 glucose units), suggesting a higher ratio of crystalline: amorphous regions vis-à-vis less periodic interruption of the crystalline regions by the amorphous regions in the ramie cellulose. The cellulose micro-

Figure 1. A 30-day-old white-ramie (Boehmeria nivea (L.) Gaudich.) crop in an one-year-old plantation.
fibril is considered as a single thin and long crystalline entity, with highly anisotropic physical properties. Its size varies from as small as 36 (ref. 23) to as large as 1200 (ref. 31, in giant marine alga Valonia macrophysa) glucan chains and width in the range of 2–5 nm (ref. 32). However, the morphology of the cellulose microfibrils is still obscure because of their small size and the tendency to tightly associate with each other in the cell wall. In cotton, a single cellulose microfibril is thought to include 60–70 glucan chains, with an average of 2300 cellulose beams making up a fibril. Although no such calculations for microfibrillar/fibrillar units are available in bast fibres, there are variations in the diameter of microfibrillar crystallites of jute (28 Å), flax (28 Å) and ramie (43 Å), in comparison to cotton (55 Å). Interestingly, the width of the cellulose microfibrillar unit in ramie has been reported to be as thick as 11 nm (ref. 32), far exceeding the width of the basic microfibrillar unit (2–5 nm) of higher plant cellulose. This indicates the crystallite complexity of native microfibrils in ramie fibres, which requires a thorough investigation at a high vertical resolution, particularly by atomic force microscopy (AFM) of microfibrils suitably dispersed on a flat surface.

In contrast to cellulose, hemicellulose is a branched polymer, with a backbone of β-1,4-linked pyranosyl residues, such as glucose, mannose and xylose. Because of structural homology, hemicellulose(s) forms a non-covalent association with cellulose microfibrils in plant cell walls. Xyloglucan is the main hemicellulosic biopolymer in the primary cell walls. However, xylans, such as arabinoxylans, glucuronoxylans and glucuronara-binoxylans that are essentially based on a β-1,4-linked xylosyl backbone are the major hemicelluloses in the secondary cell wall, and are thus the most important constituents of plant fibres. Cellulose is synthesized in the plasmalemma by cellulose synthase (CesA), whereas hemicelluloses are synthesized within the Golgi bodies by Golgi-resident genes including Ces-like (CesL) genes that belong to the CesA super-family. Modulation of cellulose or hemicellulose biosyntheses (content) results in altered cellulose–hemicellulose interactions (actions) that are increasingly being considered as one of the most important determinants of fibre properties. In Acetobacter xylinus, cellulose alone acts as a matrix of fibrils (stiff), but its composites when cross-linked with the hemicellulose xyloglucan have lower stiffness and greater extensibility, indicating that cellulose–hemicellulose networks provide inherent strength and extensibility to plant cell walls. Hemicelluloses cause the native bacterial cellulose to lose its crystallinity.

Amongst the bast and leaf fibres discussed here, the hemicellulose content is the least (3.6–4.4%) in flax, ramie and sunhemp, and the highest (14.8–17.9%) in jute, kenaf (mesta) and sisal (Table 2). Interestingly, the former three fibres are qualitatively superior to the latter irrespective of their ontogeny development (Table 1). In jute, major hemicelluloses are xylan (8.0–12.5%), galactan (2–4%), glucoronic acid (3.0–4.0%) and traces of araban and rhamnose. Although very little is known about the structure and composition of the secondary walls of the bast fibres in relation to hemicelluloses, it is logical to assume that they regulate intrinsic fibre properties by interacting with fibre-specific celluloses. The cellulose and hemicellulose (C:H) ratio may be an indicator of differential biosynthesis of and interactions between cellulose and hemicelluloses (given here). It is the highest for ramie (23.6) followed by sunhemp (21.7) and flax (18.2), whereas it is between 3.6 and 4.1 for the other fibres (Table 2). A high C:H ratio in ramie may favour a high degree of cellulose crystallinity, and this may perhaps be one of the reasons for being the strongest but the stiffest bast fibre. In other words, ramie fibre is low in elasticity due to the less amorphous state of the cellulose biopolymer in its secondary wall. Similarly, a low C:H ratio may result in a low degree of cellulose crystallinity vis-à-vis reduced fibre strength in jute and kenaf (mesta), although these bast fibres are typically characterized by low cellulose content (Table 2), which may have a serious implication for conditioning their intrinsic cell wall properties.

Table 1. Characteristics of ultimate fibre cells and fibre quality in important natural fibre crop species. Except for cotton and sisal that produce seed (trichome) and leaf (sclerenchyma) fibres respectively, the other species produce bast (phloem) fibres

<table>
<thead>
<tr>
<th>Trait</th>
<th>Cotton</th>
<th>Jute</th>
<th>H. C. mesta</th>
<th>H. S. mesta</th>
<th>Sisal</th>
<th>Sunhemp</th>
<th>Flax</th>
<th>Ramie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre strength (g tex⁻¹)</td>
<td>30.0³</td>
<td>47.5</td>
<td>45.0</td>
<td>40.0</td>
<td>45.0</td>
<td>40.0</td>
<td>55.0</td>
<td>65.0</td>
</tr>
<tr>
<td>Length : breadth</td>
<td>2500⁵</td>
<td>110</td>
<td>140</td>
<td>100</td>
<td>150</td>
<td>450</td>
<td>1700</td>
<td>3500</td>
</tr>
<tr>
<td>Fibre fineness (tex)¹,⁷,¹³</td>
<td>0.2⁶</td>
<td>4.5</td>
<td>5.5</td>
<td>5.5</td>
<td>35.0</td>
<td>17.0</td>
<td>6.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

²H. C., Hibiscus cannabinus; H. S., H. sabdariffa.
³Values represent averages over different economically important cotton species, viz., Gossypium arboreum, G. barbadense and G. hirsutum.

Table 2. Biopolymer content (% weight) in important natural fibre crop species other than cotton. Except for sisal that produces leaf (sclerenchyma) fibre, the other species produce bast (phloem) fibres

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Jute</th>
<th>H. C. mesta</th>
<th>H. S. mesta</th>
<th>Sisal</th>
<th>Sunhemp</th>
<th>Flax</th>
<th>Ramie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose: hemicellulose</td>
<td>3.8</td>
<td>4.1</td>
<td>4.0</td>
<td>3.6</td>
<td>21.7</td>
<td>18.2</td>
<td>23.6</td>
</tr>
</tbody>
</table>

⁷Same as in Table 1.
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Hemicelluloses appear to be the key to modifying the inherent properties of bast fibres. Characterizing the hemicellulose types and identifying genes involved in their biosynthetic pathways may allow targeted manipulation of the hemicellulose content in bast fibres. Using comparative genomics, a major quantitative trait locus (QTL) for (1:3:1:4)-β-D-glucans (hemicellulose) content in barley grains has been linked to the rice OsSfi genes and then expressed in Arabidopsis thaliana. This elegant experiment not only substantiated the involvement of OsSfi genes in hemicellulose biosynthesis, but reinforced the importance of QTL mapping of hemicellulose content in identifying its genomic location in relation to that of cellulose content. A high hemicellulose content in ramie is likely to increase its elasticity/resilience or to reduce its stiffness/brittleness. On the contrary, a low hemicellulose content may increase the fibre strength and improve other inherent fibre characteristics, especially fibre fineness, in jute and kenaf (mesta). QTL or association mapping of hemicellulose (e.g. xylan) content in important bast fibre crops, particularly in jute and kenaf (mesta), would enable marker-assisted selection (MAS) of breeding lines with low hemicellulose content. To date, however, there has been no published research reporting the modulation of the hemicellulose content for improving the bast fibres, and thus research in this direction is worth pursing.


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