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A Material Perspective of Wood, Smoke, and BBQ

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For those of us who have attempted to barbecue (BBQ), wood matters. Smoking delicious meats is effectively a chemical process that involves control over combustion of organic materials. Here, we get joint insight from a local pitmaster and a materials scientist.

The "art of cooking" requires a lifetime of dedication. Andy Husbands has pursued that path since he was a freshman in high school, when he first started working at a bakery in Needham, Massachusetts. Cooking is all he's ever wanted to do professionally, and that still holds true today. The "science of cooking" is more esoteric. Relatively few chemists and materials scientists have a passion for the molecules of meat, even though it is highly relevant to day-to-day lives. Steve Cranford has a background in molecules and materials science but is more familiar with benzene than brisket. Andy and Steve find common ground by examining the specialty of Andy's restaurants: barbecue (BBQ), e.g., slow cooking using smoke via the combustion of wood.

Andy's expertise, experience, and vision have resulted in The Smoke Shop—an American BBQ restaurant with a flagship outpost conveniently close to Cell Press headquarters (Figure 1) in Cambridge's Kendall Square and two additional locations, in Boston's Seaport District and Assembly Row in Somerville, Massachusetts. The concept behind The Smoke Shop is traditional American BBQ as seen through the lens of a northeastern chef. The Shops strive to honor the traditions of BBQ through continuous research, travels across America, and 20-plus years of competition BBQ experience (Andy is co-founder of the World Champion BBQ Team, IQUE), which has also led to a unique style of BBQ that highlights favorite dishes and techniques found throughout various regions of the country. Unbeknownst to him, through the years of building BBQ expertise, Andy was also attaining a *de facto* degree in wood combustion.

From a materials science perspective, wood is an interesting case study. Wood expresses a complex hierarchical multiscale structure that results in strength and toughness usually reserved for metals such as steel. It is one of the reasons that wood makes a great construction material. Accordingly, wood has been explored by scientists who are attempting to unlock nature's material-synthesis methods.

Although most woods have similar molecular components—primarily cellulose, lignin, and hemicellulose—the different material properties of, say, bamboo, hemlock, and oak arise from how these components are put together.[1] Arranged one way, wood is relatively flexible and weak (e.g., balsa), whereas arranged (or grown) another way, wood is stiff and strong (e.g., mahogany). Wood is undoubtedly one of the world's most interesting raw materials for industrial products and renewable energy. Many materials scientists are currently attempting to replicate wood's materials secrets synthetically to produce a tough and environmentally friendly advanced materials.[2]

The hierarchical structure of wood, however, also has influences beyond mechanical properties, such as strength. Some researchers are studying the effect of structure on optical properties.[3] Others are applying cellulose-based materials for energy storage.[4] One function of wood that seems to lack current scientific interest has literally been under the public's nose for centuries—the effect of wood structure on *taste*. Here, we focus on materials' relation to flavor, specifically the nanostructure of wood, through the perspective of BBQ, which has an intimate connection with wood and its molecular make-up.

In BBQ, the flavor of wood is transferred to meat through the *smoke*, which is produced via combustion, e.g., burning. This occurs (and is controlled) in a closed smoker. Like the environment in fume-hood stations in a chemistry lab, the environment in a smoker must be carefully controlled for temperature, air flow, exhaust, humidity, and contaminants. Each Smoke Shop location has at least one large smoker, and some have two (Figure 1). Each has the capacity to smoke 40 pork butts (400 lb) at a time. By the end of the year 2019, the three locations will have smoked a total of 150,000 lb of brisket, 150,000 lb of pork butts, 100,000 lb of ribs, and 100,000 lb of chicken. All of that meat is seasoned with proprietary rubs—about 7,000 lb each of three rubs per year. To keep the fires stoked, each of the three locations goes through about a cord of wood per week (at a minimum). How much wood is in a cord of wood? It measures 4 ft high by 4 ft wide by 8 ft long (4 × 4 × 8 ft) and has a volume of 128 ft^3. The amount of solid wood in a cord varies depending on the size of the pieces, but for firewood it averages about 85 ft^3, which is over 3,000 lb (depending on the

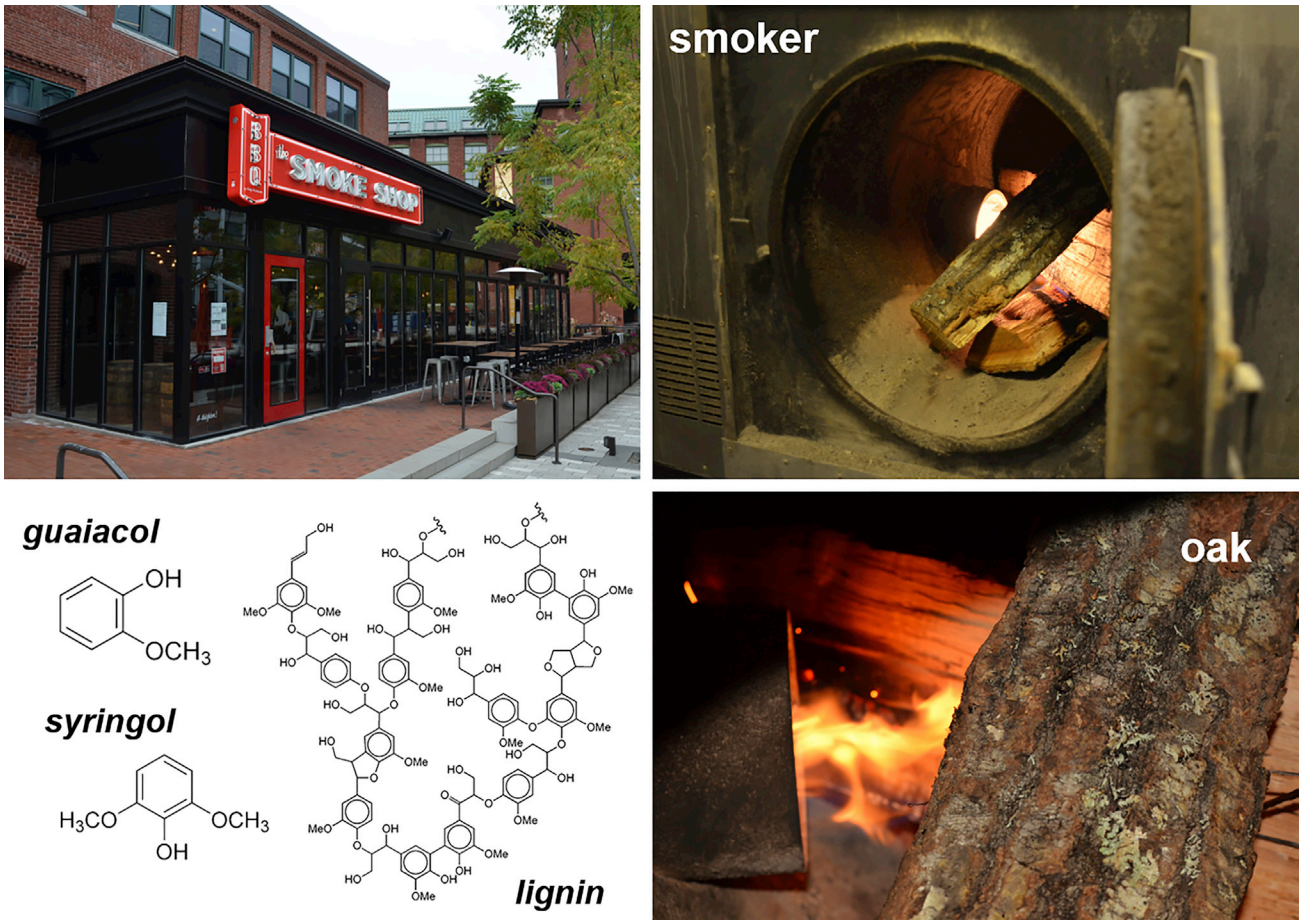

Figure 1. "Multiscale" Depiction of BBQ

A combined culinary and scientific perspective of BBQ spans all scales, from the macro (storefront of The Smoke Shop, Cambridge, MA; top left) to the equipment (burn chamber in smoker; top right) to the combustion reaction of fire and wood (in this case, oak; bottom right) to the nanoscale chemistry (the lignin components of hardwoods release the characteristic guaiacol and syringol, critical molecules for BBQ flavor; bottom left).

species and moisture content of the wood).

In terms of the chemical reaction, because wood is primarily composed of carbon (C), hydrogen (H), and oxygen (O), the output of an ideal combustion reaction would be primarily carbon dioxide (CO_2) and water (H_2O) plus some nitrogen gas and some mineral ash. However, this would result in some extremely bland BBQ! Fortunately, wood burns incompletely. Yes—the delicious taste comes from the *failure* to completely react. Partly combusted wood results in larger molecules (e.g., larger than CO_2 and H_2O molecules) in smoke, and these molecules are responsible for all the smoke flavor.

A good pitmaster thus controls the *inefficiency* of combustion, and inefficiency tastes *delicious*.

In most smokers, you add fuel and then adjust the air vents to control temperature. As it turns out, cellulose, hemicellulose, and lignin combust primarily at different temperatures. The wood finds its own equilibrium of burning components. Sometimes that equilibrium creates a light, sweet smoke flavor (primarily consisting of small molecules), and sometimes it creates a dark-gray heavy fog (containing large molecules and particulates). We note that this is a generalization—the chemical byproducts of wood combustion are not a universal constant but depend on the tree species, its age, and even its mineral composition, which can vary by soil conditions (and even the weather!). Thus, even the same species of tree can vary in flavor depending on whether it was grown in New England or the West Coast. Moreover, the moisture content heavily influences how the wood burns. The Shops ensure that its wood is cured—i.e., stored for a year to effectively "dry out" and have low and reliable moisture content. This helps it burn more consistently and cleanly.

The smoking process is highly complex with many factors, both on the meat side and the wood side. It is precisely for these reasons that BBQ is just as

much an art as it is a science. However, if we focus on the wood, we can deduce some general trends by exploring the combustion of cellulose, hemicellulose, and lignin. As each wood component is consumed by fire, various chemicals are liberated.

Cellulose is the primary component of wood, is the major chemical component of fiber walls, and contributes 40%–45% of the wood's dry weight. It is a large linear molecule with repeating D-glucose monomers. As such, cellulose is a simple sugar polymer—the name cellulose is similar to glucose and sucrose, where the suffix -ose indicates a sugar! It's not surprising then to discover caramel colors and sweet flavors abound. If cellulose is pictured like a chain, then hemicellulose is similar to it except for a few extra chain links that stick out. Hemicelluloses are varied in composition, depending on the species of tree, and aid in the cross-linking of cellulose fibers. Aside from glucose, sugar monomers in hemicelluloses can include the five-carbon sugars xylose and arabinose, the six-carbon sugars mannose and galactose, and the six-carbon deoxy sugar rhamnose. Hemicellulos compose 20%–25% of the wood. Lignin, on the other hand, is a tangled mess of interlocking chain segments and makes up about 30% of wood mass. There is no structure or regular repeated chemical units (see Figure 1). When it burns, literally hundreds of molecules can be produced—and this is where the taste of smoke emerges. Because of the chain structures of cellulose and hemicellulose, they burn at a lower temperature. At around 450°F, combusting cellulose and hemicellulose molecules are mostly acids and various gases. None are particularly desirable on food, but by 500°F most of the cellulose and hemicellulose has burned away or turned into charcoal. By 600°F, the relative abundance of cellulose and hemicellulose compounds peaks and begins to decline.

As a result of the branched, heavy-molecule structure, lignin becomes key at higher temperatures. Lignin is by far the more interesting ingredient from a culinary standpoint because of its complex structure. Bound inside lignin, a big-branched amorphous molecule, are the key precursors to smoke flavor, aroma, and color—guaiacol and syringol. Guaiacol is responsible for most of the smoky taste. Syringol, which your nose immediately identifies with fire and smoke, is more aromatic. Again, exact content is species dependent, but in general softwood lignins have only the guaiacyl type, whereas both types are included in hardwood lignins.[5,6] Thus, hardwoods are typically considered more flavor inducing than softwoods. There are also clove and vanilla-like compounds—and literally hundreds of others. Some evaporate away in hours, some in days, and others in weeks. This is one of the reasons BBQ doesn't taste the same when reheated. The molecules all arise from the combustion of lignin, which varies in structure from tree to tree.

What about the timing? How long should the meat be smoked? Clearly, it depends on the meat, wood used, temperature, etc. It is not an exact science, but the general rule of thumb at the Shop is about an hour per pound. Smoking an 18 lb brisket takes about 17–19 h on average, depending on factors that can alter cook time, including capacity, size, and how often you're going in and out of the smoker to check on the meats. The smoker does the work. As Andy likes to quip, "If you're lookin', you ain't cookin'."

Throughout the cook, temperature control should be optimized to release these desired lignin-based molecules. A good rule of thumb is that the hotter the temperature, the more complete the combustion, which results in lighter flavors—the molecules are smaller. It is a good practice to err on the side of higher-temperature combustion—a fully agitated, well-oxygenated fire running around 800°F is ideal. That being said, a fire too hot produces fewer flavor molecules, and light smoke carcinogenic molecules such as polycyclic aromatic hydrocarbons (PAHs) arise. Many desirable flavor molecules are also destroyed by the heat of a more intense fire. The best smoke flavor is generated by hardwood embers that have an average temperature between 650°F and 750°F. In competition, for Andy, temperature control is all done manually—the fire is tended with charcoal and hard woods and constantly monitored by eye and thermometers. A temperature too high could require less wood (less fuel), closing vents (less oxygen), or "burping" (releasing smoke)—there are a lot of different ways to approach it, as dictated by experience. In business, with commercial smokers, a consistent cook is achievable through a balance of technology and experience. The Shop's smokers have automatic vents and baffles, as well as auto-ignition to maintain and control temperature.

So, what else can we say about the choice of wood for smoke?

In addition to controlling the fire's oxygen level and the way new fuel is added and mixed into the embers, the pitmaster controls the choice of wood. Certainly, it is common practice to avoid long cooks with sticky resinous woods such as pine. Resin contains terpenes (which are the source of turpentine), and few guests associate oil paint with good BBQ. Cedar or redwoods, which are particularly mold and insect resistant, should also be avoided in a long cook. But in small doses, or during cold smoking, these woods strike a distinctive flavor note.

It's usually accepted that dried hardwoods with low sap, especially fruit and nut woods, are the best for BBQ. Hardwoods have compact cell structures (resulting in [1] less moisture content and [2] a more consistent

burn), and they are the best woods for cooking. Softwoods, such as pine, fir, spruce, redwood, hemlock, and cypress, are all evergreen, coniferous trees, and they have more air, have more pungent sap, and burn fast. They are not recommended for cooking.

In the end, it is the skill of the pitmaster that determines the flavor profile.

Andy's 25 years of BBQ experience span a variety of woods in trial and error. By the time the restaurant was to open, the desired woods were narrowed down. Prior to The Smoke Shop's first location, he experimented with a few different wood types and suppliers to find the exact combination that was desired. In testing various fruit woods, he found that cherry not only was easily accessible but also had a sweet, light smoke flavor that paired perfectly with the Shop's seasonings. The Shop currently uses locally sourced oak and cherry wood (Figure 1). Although the densities of cherry and oak are approximately the same magnitude, oak has 35%–40% less lignin content,[7] resulting in cleaner, more intense fire. As such, the oak is for the heat, and the cherry is for the flavor. The local sourcing results in consistency between restaurant locations, but it also means that the end result of using local sourcing will differ from oak and cherry sources in, say, California (if the Shop chooses to expand nationwide). Where exactly does the Shop source its wood? The exact flavor and how their meats are cooked is their competitive edge, so it is incredibly important to keep the wood source secret.

On the flip side, mahogany produces a strong flavor with a dense and dark smoke. Mahogany is not as dense as oak or cherry, resulting in a less consistent burn and relatively large lignin content.[8] When Andy used mahogany, the meat appeared burnt with an extremely smoky flavor that was ultimately too intense and overpowering for what he was looking for. However, some tastes might prefer the strong(er) flavors. Smoke should be like salt: used like a seasoning and used sparingly.

So we somewhat know the influence of the wood. What, scientifically, is happening to the meats as they cook? This is an entirely different material problem. One issue, for example, is the well-known "stall" when meats are cooked. The "stall" refers to a drastic decrease in cooking rate—when a brisket hits about 170°F, it takes much longer to get to around 185° than 140°F takes to get to 150°F or 160°F to 170°F (which is near linear). There is most likely some sort of phase transition, where the embedded water is released at a certain temperature (e.g., the meat "sweats"). Can this be determined before cooking? There is also the theory that if one keeps it in the stall at a constant 170°F–185°F for a longer time, then the meat becomes more tender. If so, why? Current expert chefs approach this with trial and error and get mixed results. Can materials science shed some insight on the meat aspects of BBQ? Time will tell …

To recap, the desired smoke flavor of BBQ is a result of the small molecules found in lignin in wood (among other factors), and releasing them is a simple chemical process that is optimized by controlling temperature, once you keep your stock of source materials consistent. The end result is delectable smoked brisket, ribs, pulled pork and pork belly, chicken, etc.

To complement that flavor, many BBQ aficionados turn to whiskey as the beverage of choice. Andy (and Steve) is very passionate about whiskey, specifically American whiskey. The Smoke Shops offer a selection of over 240 labels at each of the locations, a program unmatched in New England. Whiskey, like BBQ, also relies on wood to infuse flavor. However, although sometimes the aging barrels are charred, this time, no active burning is required … unless it's peat smoke for whisky. Perhaps that will be the topic for another time. Two different mediums (brisket and bourbon) can be used to infuse flavor with a common ground (wood). Both are similar and different, like a pitmaster and a materials scientist.

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