

Wood Smoke Components and Functional Properties

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Abstract

Wood smoke is an aerosol produced by pyrolysis of wood at elevated temperatures and reduced oxygen. Generated wood smoke consists of three phases: compounds in the gaseous phase, particles of liquid droplets, and solids. When condensed and given enough time for the polymerized components to settle out, the liquid fraction is called liquid smoke. There are over 400 compounds identified in wood smoke or smoke flavor from a number of sources. So far, 40 acids, 22 alcohols, 131 carbonyls, 22 esters, 46 furans, 16 lactones, and 75 phenols have been identified. The origin of the compounds in wood smoke is the polymers in the wood and the heat-induced chemical reaction between the heated polymers, gasified intermediates, and moisture. Thus, the composition of wood smoke will vary with the type of wood used in producing the smoke and the temperature and moisture content of the wood.

Wood smoke performs several functional roles in food. Whether it is applied as a gas from smoldering wood chunks or chips or as liquid smoke, it is considered a natural flavor and need not be broken down into components in the label declaration. Wood smoke is also a colorant, where the stain is immediately produced upon contact between the food surface and smoke, or the color is formed when the smoke and food components react chemically at the elevated temperature used to process the food. The preservative role of wood smoke is well known. However, although specific components have been documented to possess inhibitory activity against bacteria and fungi, wood smoke is not a stand-alone preservative. Wood smoke may be used as a component of a hurdle system for food preservation. Among the functional components of smoke, phenols and acids have shown the most antimicrobial activity, although there are data that show that carbonyls and acids can also have a wide spectrum of antibacterial activity even at low levels of phenols. Staining ability of wood smoke is associated with the acids and phenols, while reaction-developed color produced during the heating of meat can be attributed primarily to the acids and carbonyl compounds.

Introduction

Direct exposure of fish to smoke generated by a smoldering wood fire is a process that has been used since ancient

times. Before the arrival of Europeans in the New World, Native Americans had been smoking fish to preserve them for consumption on long treks or later in the season when these fishes were no longer available in the wild. For true preservative effect, smoke has been combined with water activity reduction by dehydration and salting. More recent is the use of smoke for flavor. Traditional cured meats used to be cooked in smokehouses where dehydration occurs in addition to smoke deposition. As smokehouses have become more modern, the processes of smoke flavor application and dehydration can be separated with better control of both by the processor. There have been claims about the desirability of smoke generated from certain species of wood compared to other woods, but there have been no studies of side-by-side comparison of flavor imparted by a smoke from specific woods on a smoked product.

In general, smoke is generated using wood that is readily available in a locality. Thus, smoke is generated from mesquite in the Southwest, hickory, oak, and wild cherry in the South, apple wood and maple in the Northeast, and alder, birch, and beech in the Rocky Mountain region and the Northwest. A recent trend in the smoke flavor industry is to produce liquid smoke as a byproduct of the process of making briquetted charcoal for backyard barbecues. Condensed smoke or smoke dissolved in water may be obtained by generating smoke using one type of wood or a mixture of different woods, then the liquid smoke composition is standardized depending upon the application. This review covers compounds present in smoke and the desirable smoke components for specified functional effects in the finished product.

Physical nature of wood smoke

Wood smoke produced by heating wood chunks, chips, or sawdust is a colloidal aerosol of air, water vapor, solid particles, liquid droplets, and vaporized organic compounds. The vapor phase of the organic compounds in smoke imparts the desirable flavor since rate of deposition in the food is slow and uniform. Preferably, the liquid phase is not directly deposited. This phase serves as a reservoir for generation of more of the vapor phase as the smoke temperature increases. The best smoke generators route the smoke under a curtain of flowing water to remove solid phase and liquid phase

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particles before the smoke enters the smokehouse. Solid particles are associated with soot, tar, and fly ash and are best eliminated before the smoke enters the smoke house. Tilgner (1976) suggested that liquid smoke components can also polymerize to form solid particles. Thus, depending upon the smoke temperature entering the smokehouse and the temperature of the smokehouse itself, there could be tar formation from smoke even if most of the tar has been removed prior to the smoke entering the smokehouse. The visible component of smoke consists of liquids and solids in the aerosol.

Foster and Simpson (1961) showed that the solid and liquid component of smoke do not contribute to the desirable smoke flavor. However, in the absence of analytical instruments that could measure the vapor phase organic compounds in smoke, one way to ensure that adequate

smoke components contact the product in the smokehouse is to ensure that a dense optically visible smoke is generated by the smoke generator. An alternative is to generate gaseous smoke from liquid smoke. This can be done by atomizing liquid smoke into the warm smokehouse air as the air is recirculated, or by dripping liquid smoke on a hot plate located just at the point where make-up air enters the smokehouse. These techniques ensure that there are adequate organic compounds from smoke in the smokehouse atmosphere that could be deposited on the product. Recent environmental regulations related to the release of volatile organic compounds (VOCs) into the atmosphere have curtailed the use of smoke generators in processing plants located in metropolitan areas. Smokehouses in these areas have to be equipped with an incinerator to eliminate VOCs in gas discharged from the smokehouse.

Table 1. Classes and examples of compounds predominant in wood smoke.

| Class of compound | Examples |
|-----------------------|--|
| Acids | Acetic acid |
| Alcohols | Methanol, ethanol, isopropanol, furfuryl alcohol |
| Carbonyls (aldehydes) | Acetaldehyde, isovaleraldehyde, crotonaldehyde, diacetyl |
| Carbonyls (ketones) | Acetone, methyl vinyl ketone, acetol, 2-cyclopentanone, furfural, 5-methyl furfural, cyclohexene |
| Esters | Methyl formate, methyl acetate |
| Furans | Furan, 2-methyl furan |
| Phenols | Phenol, 1,2-dimethoxybenzene, guaiacol, 4-methyl guaiacol, 4-ethyl guaiacol, eugenol, syringol, 4-methyl syringol, 4-ethyl syringol, 4-propyl syringol, vanillin |

Source: Wasserman and Fiddler 1969.

Wood smoke composition

Most of the literature on wood smoke composition is based on the components of smoke condensate generated in a controlled laboratory setting. Wasserman and Fiddler (1969) reported approximately 20 times the level of compounds in the condensate compared to that in the gaseous smoke. A number of compounds with long elution times are present in the smoke condensate but were absent in chromatograms of gaseous smoke, indicating that some polymerization of smoke components may have occurred in the liquid phase. These same authors also showed that smoke condensate improved in flavor with aging such that the 5 hour old condensate has the worst flavor while the 1 and 2 months old smoke had similar and the highest acceptability scores. The classes of compounds and specific compounds identified in wood smoke reported by Wasserman and Fiddler (1969) are shown in Table 1. These same authors also report that the concentration of the furans, phenolics, and cyclic compounds are affected by the excess oxygen supplied to the

Table 2. Composition of different woods and the chemical constituents of condensed smoke.

| Wood | Wood composition (%) | | Smoke composition (%) | | | |
|------------|----------------------|-----------------------------|-----------------------|------|----------|----------------|
| | Lignin | Cellulose and hemicellulose | Phenolic and basic | Acid | Smoke pH | Smoke point °C |
| Cherry | 13.8 | 24.1 | 46 | 18 | 2.46 | 147 |
| Red oak | 24.1 | 62 | 62 | 27 | 2.53 | 135 |
| White oak | 39.3 | 25 | 61 | 22 | 2.67 | 122 |
| Hickory | 24.1 | 43.1 | 55 | 27 | 2.71 | 103 |
| Apple | 37.9 | 27.6 | 47 | 22 | 2.72 | 103 |
| Hard maple | 55.2 | 34.4 | 45 | 18 | 2.74 | 107 |
| Chestnut | 32.1 | 25 | 34 | 44 | 2.84 | 121 |
| Mesquite | 44 | 16 | 44 | 12 | 3.02 | 164 |

Source: Chen and Maga 1993.

Table 3. Groups of compounds and percentage of chromatograph peak area in condensed smoke from a charcoal kiln.

| Class of compound | Most predominant | % of peak area |
|-------------------|--------------------------------------|----------------|
| Acid | Acetic acid | 13.9 |
| Alcohol | Methyl alcohol, acetol | 13.5 |
| Unidentified | – | 12.7 |
| Phenol | Guaiacol, 2,6,dimethoxy phenol | 9.3 |
| Ketone | 1-hydroxy, 2 butanone | 5.2 |
| Hydrocarbon | Cyclotene | 3.1 |
| Aldehyde | 4-hydroxy-3,5 dimethoxy benzaldehyde | 0.8 |

Calculated from product analytical data, Hickory Specialties Technical Center, Brentwood, Tenn.

burning wood, and that formation of phenols and cyclic compounds is favored at around 10 to 12% excess oxygen while formation of furans is favored at near zero excess oxygen.

Composition of a commercial liquid smoke preparation produced by water absorption of gaseous smoke from a charcoal kiln is shown in Table 2 (Hickory Specialties, Brentwood, Tennessee, pers. comm.). There were 61 gas chromatogram peaks reported in the sample. Twenty peaks were not identified. The percent of peak area indicate that acids, alcohols, and phenols predominate in the condensed smoke. Compared to phenol (mol. wt. 94) retention time of 26.4 min, the unidentified peaks were mostly compounds with retention times less than 20 min with molecular weights estimated to be in the 90 to 160 Dalton range.

Since the origin of chemical components of wood smoke is in the wood itself, the type of wood and the method of generation would be expected to affect smoke composition. Chen and Maga (1993) compared properties of wood smoke produced from apple, cherry, chestnut, hard maple, hickory mesquite, red oak, and white oak. Table 3 summarizes their data. No direct correlations can be made on polymer fraction in the wood and the composition of smoke generated. The wood shavings were not adjusted for moisture content so moisture is not a factor in these analyses. The smoke-point of the wood increased with decreasing concentration of combined cellulose and hemicellulose, and was higher as the lignin content increased. Concentration of acidic components in the smoke condensate did not correlate with pH of the liquid smoke. The most desirable smoke flavors are derived from phenolic compounds and compounds with a basic reaction (Maga 1987), but the concentrations of these compounds did not correlate with the lignin content of the wood. The highest concentration of phenolic and basic components in the smoke condensate were produced by red oak, white oak, and hickory while the least were produced by mesquite and chestnut.

The influence of moisture content of alder wood used to generate smoke was reported by Borys et al. (1977). Their results were presented as a regression equation of the gas

Table 4. Composition of wood smoke from 14 and 37% moisture alder wood.

| Compound | Composition (%) | |
|---------------------------------|----------------------|----------------------|
| | 37% H ₂ O | 14% H ₂ O |
| Acetic acid | 49.5 | 94.5 |
| Propionic acid | 10.1 | 1.9 |
| Butyric acid | 3.7 | 0.2 |
| Valeric acid | 2.8 | 0.2 |
| Caproic acid | 3.7 | 0.2 |
| Hydroxypropanone | 3.1 | 0.5 |
| 1-acetoxy-2-butanone | 0.8 | 0.04 |
| 2-furfural | 13.7 | 1.24 |
| 5-methyl-2-furfural | 0.7 | 0.07 |
| 2-methoxy-4-methylphenol | 2.5 | 0.09 |
| 2,6-dimethoxyphenol | 1.5 | 0 |
| 2-methoxy-4-transpropenylphenol | 1.7 | 0.07 |
| 2,6-dimethoxy-4-methylphenol | 3.1 | 0.6 |
| 2,6,dimethoxy-4-allylphenol | 1.6 | 0.2 |
| Vanillin | 1.1 | 0.03 |
| Benzo(k)fluorantene | 0.02 | 0.007 |
| Benzo(a)pyrene | 0.008 | 0.0003 |
| Pyrene | 0.4 | 0.1 |
| Chrysene | 0.05 | 0.03 |

Calculated from regression equations reported by Borys et al. 1977.

chromatogram peak areas of specific compounds, as a function of the rate of aeration of the wood during smoke generation. Table 4 shows the composition of wood smoke from wood at 14% and 37% moisture. At the low moisture content the smoke is primarily acetic acid, which constitutes 94% of the smoke. The more desirable smoke was generated from 37% moisture wood where the compounds are more widely distributed. At this moisture content the acids account for 70% of the smoke while carbonyls and phenols account for 18 and 11.5%, respectively. On the other hand, smoke generated from 14% moisture wood had only 2 and 1% respectively of carbonyls and phenols. The results of this work justify the widely used practice of wetting sawdust or wood chips used in smoke generators.

Kjallstrand and Petersson (2001) found 2,6-dinitrophenols as the compound with the highest concentration in alder smoke. 2-methoxy phenol, 2,6-anhydroglucose (furfural), 2-furaldehyde, 2-methylfuran, benzene, and methylbenzene were the other compounds with significant concentrations in the smoke. Acids, alcohols, and ketones were not reported.

A lot of variability in smoke composition is reported in the literature. Some of the sources of variation are the type and particle size of wood used, the moisture content, the rate of aeration during smoke generation, and the temperature of the wood during pyrolysis. Maga (1987) conducted a

Table 5. Compounds in wood smoke.

| Compound | Number identified | Examples |
|---------------|-------------------|---|
| Acids | 48 | Acetic, propionic, sorbic, butyric, salicylic, benzoic, pimaric |
| Alcohols | 22 | Methanol, ethanol, isopropyl, cyclohexanol, benzylalcohol |
| Carbonyls | 131 | Ethanol, acetone, methylethylketone, acetoxypropanone, 2-heptanone |
| Esters | 22 | Methylacetate, ethylbenzoate, hydroxy-2-propanone propionate |
| Furans | 46 | Furfural, benzofuran, 2-methyl-3-furfural, 2-acetyl-5-methylfuran |
| Lactones | 16 | γ -butyrolactone, methylvinyl-2-butenolide |
| Phenols | 75 | Phenol, xylenol, syringol, eugenol, resorcinol, 4-isopropylguaiacol |
| Miscellaneous | 50 | Pyrazine, pyridine, toluene, ethane-diol, pyrrole, dimethoxyethane |

A comprehensive list of the compounds is given in Maga 1987.

thorough review of the flavor chemistry of wood smoke and a brief summary of his compilation of compounds whose presence has been identified in wood smoke shown in Table 5. Not all published data on smoke composition reported by different authors have the same compounds listed. Furthermore, the concentration of the different compounds varied among these studies. Since flavor is a complex interaction between components, actual perceived flavor could vary even with the same components present if the relative concentration of the different components is different in the different smoke samples. Thus, it is important that the method for smoke generation be standardized. Consistency of smoke composition is assured by using liquid smoke where the manufacturer has standardized the product composition.

Ensuring consistency of smoke application from gaseous wood smoke

Gaseous smoke composition can only be consistent if the same smoke generator is used and the same conditions are used in the smoke generator. Modern smoking ovens use a separate unit for smoke generation and smoke application to the smoked product. This is in contrast to simple ovens where the smoke is generated from smoldering wood placed directly under the racks that hold the product. In these simple smoking ovens, it will be difficult to control smoke generation temperature, oven temperature, and humidity. When using smoke generators, uniform smoke intensity and smoke composition can be obtained by ensuring that (1) the type and particle size of wood is the same, (2) maintaining a constant moisture content by mixing a batch of wood chips adequate for the time required for the smoking process with water to the desired moisture content, (3) the orifices that

feed air to the wood in the generator are clear, (4) the wood is burning uniformly around the periphery of the burning zone before moist sawdust is added, and (5) the wood is added at rates that will maintain the same thickness of the unburned wood over the burning layer. Adding wood chips too fast will result in a thick layer of moist unburned wood over the fire zone, stifling combustion and eventually extinguishing the fire zone. On the other hand, adding the wood chips slowly will expose the fire zone, generate heat, and make the wood flame up, reducing the intensity of smoke generation. These procedures are consistent with the factors discussed above on the factors that affect the composition of wood smoke.

Smoke flavors

The term liquid smoke generally refers to the condensate of wood smoke. Smoke from a charcoal kiln is directed through a flue into an absorption tower where a liquid water film flowing countercurrent to the flow of smoke captures the smoke. The smoke solution is held for several days to permit the condensed phenolic compounds to precipitate and the solution is filtered. The process removes polymeric aromatic hydrocarbons, which are carcinogenic. Thus, the use of liquid smoke imparts both convenience and safety.

A number of wood smoke preparations are now used in the industry as a flavor. Smoke flavor is GRAS (generally regarded as safe) and is considered by both the USDA and FDA as a natural flavor. Liquid smoke can be applied as a dip or a drench to color and flavor cooked ready-to-eat meats, and added directly to other food products such as barbecue sauce, dry crispy snacks, canned baked beans, and canned fish and shellfish. In metropolitan areas where discharge of smoke to the environment is restricted, liquid smoke may be used to generate gaseous smoke.

Knowledge of the composition of smoke has helped the industry to produce smoke preparations with different flavor and functional properties. Since flavor is a result of the interactions among the various compounds in smoke, treatments that remove certain smoke components may be used to alter the flavor of smoke. Thus, vacuum evaporation may be used to remove low boiling components such as acetic acid and alcohols. Adsorbents may be used to selectively remove phenolic compounds and more importantly, remove condensed phenolics that produce a tarry precipitate in stored liquid smoke. The solubility of smoke in water can be enhanced by adding polyethylene glycol to the liquid smoke. The presence of polyethylene glycol also minimizes condensation of phenolics. Acids may be neutralized to reduce the harshness of the smoke flavor. Dekker (2003) interviewed a major liquid smoke manufacturer in the United States and discussed how liquid smoke flavors are produced and how the composition is standardized. In addition to the standard smoke condensate, products may be made from fractions of the liquid smoke produced by selectively extracting components with an appropriate solvent. For example, an oil extract of liquid smoke will contain primarily phenolics with the desirable

smoke flavor, while the harsh flavored acids and carbonyls are not transferred to the oil. The smoke flavored oil will also induce minimal color development in the product during heating because reduced levels of carbonyl compounds have been transferred to the oil from the liquid smoke.

Some applications of smoke flavor may require a solid phase material. An example of this is smoke flavored salt used on oven-baked cooked meat to simulate a grilled or broiled flavor. To produce the solid smoked flavor, liquid smoke is plated on a soluble solid carrier such as salt or maltodextrin.

Functional properties of smoke components

Flavor

It is generally recognized that the characteristic wood smoke flavor is due to phenolic compounds (Bratzler et al. 1969, Deng et al. 1974, Maga 1987). Thus, the concentration of phenols has been used to assess the intensity of the smoke flavor (Chan et al. 1975, Kjallstrand and Petersson 2001) in smoked fish or meats. However, flavor is a complex sensation that is imparted by combinations of different compounds. Thus, a single group of compounds may not necessarily completely bring out the smoke flavor. The contribution of the acids and carbonyls to flavor is important, although these compounds may be present in smaller amounts than the phenols. When liquid smoke is separated into the phenolic, carbonyl, and non-carbonyl fractions and a new liquid smoke mixture is made, the aroma quality of the mixture is best when the phenolic fraction is mixed with the appropriate amount of carbonyl and non-carbonyl fraction (Maga 1987).

Some of the phenols in smoke are similar to those in spices. An example is eugenol in cinnamon, pepper, nutmeg, marjoram, and cloves. Cinnamon contains many of the phenolic compounds present in smoke. The flavor of smoke components also depends upon the concentration. Thus, the same smoke flavor may invoke sensory responses of burnt, pungent, and cresolic at high concentration or sweet smoky at the desirable concentration. These data in the literature suggests that not all liquid smoke preparations are the same in terms of flavor and other functional properties, and that each application will benefit from a careful selection of the right smoke flavor.

Color

Color formation in smoked products is due to a combination of cold staining and heat-induced Maillard-type chemical reactions. When using liquid smoke, a cold stain is imparted by the phenolics and acids. When the product is heated, the carbonyl compounds react with the proteins in a Maillard reaction to produce the brown color. Cold smoking is the term used when raw fish is exposed to a relatively low optical density smoke at temperatures below the denaturation temperature of fish muscle (below 40°C). Cold smoked fish does not change in color because there are not enough phenols to produce a stain and the Maillard reaction does not proceed

Table 6. Smoke fractions tested for antimicrobial activity and their properties.^a

| | Smoke extract (%) | Acidity pH | Phenol content (mg/ml) | Carbonyl content (mg/ml) |
|----|-------------------|------------|------------------------|--------------------------|
| F1 | 4.5-5.9 | 2-3.0 | 0-5 | 151-200.9 |
| F2 | 0-1.4 | 6.1-7.0 | 0-5 | 101-150.9 |
| F3 | 6.0-7.4 | 2-3.0 | 0-5 | 101-150.9 |
| F4 | 3.0-4.4 | 4.1-5.0 | 20.1-25.0 | 0-50.9 |
| F5 | 6.0-7.4 | 2-3.0 | 0-5 | 101-150.9 |
| F6 | 6.0-7.4 | 2-3.0 | 0-5 | 51-100.9 |
| F7 | 1.5-2.9 | 5.1-6.0 | 0-5 | 51-100.9 |
| F8 | 0-1.4 | 6.1-7.0 | 0-5 | 101-150.9 |
| F9 | 0-1.4 | 6.1-7.0 | 0-5 | 51-100.9 |

^aAcidity as acetic acid; phenols as 2,6, dimethoxy phenol; and carbonyls as 2-butanone. Source: Milly et al. 2005. Analytical data provided by MasterTaste Inc. Zesti Smoke Division, Brentwood, Tenn.

far enough to develop the color. On the other hand, smoking at temperatures of 80 to 90°C results in excessive deposition of phenolics, formation of condensed phenolics, and excessive Maillard browning so that the product has a dull dark color with numerous small specks of dark material on the surface. The best smoked fish color is a glistening golden honey color brought about by the capture of phenolics on an oily surface and adequate Maillard reaction to generate a light brown color (Deng. et al. 1974, Chan et al. 1975). Since smoke can be labeled as a natural flavor, it is a preferred ingredient and one of the applications is a roast color accelerator with no smoke flavor at all. The smoke generated from starch or very low lignin wood is practically devoid of phenolics but is very high in carbonyls; therefore this product can be used as a browning agent.

Antimicrobial

The antimicrobial properties of smoke are well known and constitutes the primary role of smoke in food preservation. All the constituents of smoke interact to bring about the antimicrobial effect. Phenolics, acetic acid, and carbonyls individually have antimicrobial activity but their combined effect is synergistic. Thus, a mixture will be an effective antimicrobial agent at a lower level of the components than any of the individual components. Because of the differences in the composition of liquid smoke, inhibitory activity varies with different smoke preparations. Studies on antimicrobial properties of CharSol smoke preparations (Wendorff 1981) at 0.5% was bactericidal to pathogens such as *Escherichia coli*, *Staphylococcus aureus*, and *Listeria monocytogenes*. Some preparations required lower concentration than others for bactericidal activity. It was hypothesized that the enhanced bactericidal activity of some preparations was due to the higher levels of polar phenolic compounds in these preparations (Messina et al. 1988).

Table 7. Minimum inhibitory concentration (%) of nine smoke fractions shown in Table 5 on different microorganisms.

| | Gram negative bacteria ^a | <i>Listeria innocua</i> M1 | <i>Lactobacillus plantarum</i> | <i>Aspergillus niger</i> |
|----|-------------------------------------|----------------------------|--------------------------------|--------------------------|
| F1 | 1.5 | 1.5 | 0.75 | 1.5 |
| F2 | >2 | 2 | 1.5 | 2.5 |
| F3 | 2 | >2 | 2 | 2.5 |
| F4 | 3 | 2 | >10 | NT |
| F5 | 2 | 2 | 4 | NT |
| F6 | 2 | 2 | 5 | NT |
| F7 | 5 | 4 | 7 | NT |
| F8 | >2 | 2 | >2 | >5 |
| F8 | 9 | 6 | >10 | NT |

^aCocktail of *Salmonella muenster*, *Salmonella senftenberg*, *Salmonella typhimurium* and *Escherichia coli* 8677.
NT = not tested. Source: Milly et al. 2005.

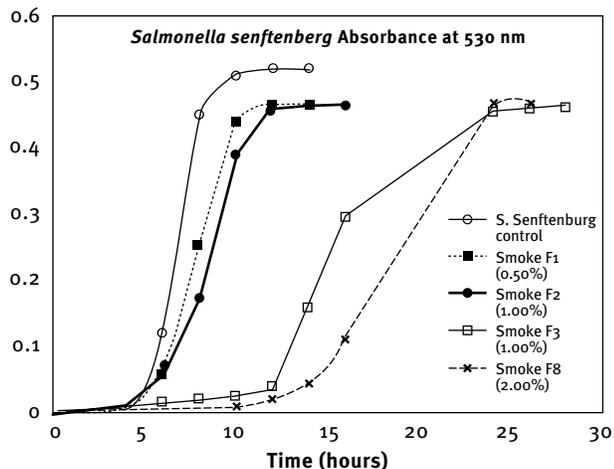


Figure 1. Growth curve of *Salmonella senftenberg* in tryptic soy broth containing liquid smoke fractions F1, F2, F3, and F8 at concentrations below the minimum inhibitory concentration (MIC).

The role of carbonyls and acids in the antimicrobial activity of liquid smoke was reported by Milly et al. 2005. Table 6 shows the composition of the liquid smoke preparations studied by Milly et al. (2005). The smoke preparations vary in acidity from 0 to 7.4% as acetic acid, and carbonyl content from 51 to 200 mg per ml as 2-butanone. Except for one preparation that had as much as 25 mg per ml of phenols as 2,6-dimethoxyphenol, the rest had 0 to 5 mg per ml of phenols. Minimum inhibitory activity was measured as the smoke concentration in a liquid growth medium that prevented growth of the test microorganism. Table 7 shows the minimum inhibitory concentration (MIC) of the different smoke fractions against several microorganisms.

The high phenol, low carbonyl, medium acidity fraction F4 had the highest MIC against *Lactobacillus plantarum*, but had similar MIC as fractions having similar acidity against *Listeria innocua* M1. The fraction with the lowest MIC on all the microorganisms tested was F1, which had medium acidity and low phenol but had the highest carbonyl concentration. The fraction F7, which also required a relatively high MIC, had low acid, phenols, and carbonyl concentration. The smoke fractions also had antifungal activity against *Aspergillus niger* (Table 7). F1 had the lowest and F8 the highest MIC against the mold. The manner in which the smoke fractions affected microbial growth is shown in Fig. 1 for *Salmonella senftenberg* applied to the growth medium at concentrations below the MIC. Below the MIC smoke extended the lag time for growth but once growth started, the organisms increased in numbers at a very rapid rate, not much different from the control. These results show that the carbonyls are a very important component of smoke, not only from the standpoint of color formation but also from the standpoint of antimicrobial activity.

Concluding remarks

Much is known about the composition of smoke and the role of these components in imparting flavor, color, and antimicrobial properties to the smoked product. However, the interaction of the components, the relative concentration of these components, and the level present in the product all affect the flavor. When using gaseous wood smoke, it is important that the conditions used in generating the smoke are maintained constant to ensure consistency of smoke functional properties. When using liquid smoke flavors, it is also necessary to optimize the type and level of smoke flavor for a given application. Antimicrobial liquid smoke preparations containing very low levels of phenols and thus low smoke flavor are now available commercially. These preparations may be used in combination with other antimicrobial treatments to improve the safety of ready-to-eat cooked meats designed to carry very low background smoke flavor.

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