Carbon Scrubbers Removing Harmful TVOCs and $PM_{2.5}$ from Barbecue Smoke

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Barbecue (BBQ) smoke contains volatile organic compounds (VOCs) and particulate matter, e.g., $PM_{2.5}$, which are health hazards. Carbon-activated scrubbers are known to remove these contaminants by adsorption. A scrubber is a system that removes harmful materials from industrial exhaust before they are released into the environment. However, techniques to differentially scrub BBQ smoke, eliminating harmful contaminants while preserving sweet-smelling compounds like syringol, have not been developed. One approach to differential scrubbing can take advantage of differences in the chemical composition and polarity of target molecules. For example, syringol is a polar molecule unlike activated carbon which is non-polar. Passive adsorption relies on favorable intermolecular interactions, where chemically similar substances will interact with one another. Non-polar carbon is therefore more effective in removing non-polar molecules. Thus, it was hypothesized that BBQ smoke can be cleaned of toxins while preserving the syringol content that people desire. It was also hypothesized that even scrubbed invisible BBQ smoke may contain some harmful VOCs. Thus, it should be possible to redesign a conventional BBQ to incorporate carbon scrubbers. In this study, a grill was modified to carry smoke via hoses to scrubbers with various concentrations of activated carbon, and then to VOC/$PM_{2.5}$ meters. Portals were constructed for olfactory sampling and smoke visibility measurements. Energy sources were either wood chips, charcoal, or propane. Up to 20 randomized trials were performed under each condition. Differential adsorption was noted. For woodchips using a 50% scrubber concentration, the percent remaining syringol was 60% compared to 6% for VOC - a 10-fold difference ($p< 0.05$ Mann-Whitney U). Compared to ambient air, invisible smoke contained some unhealthy VOC/$PM_{2.5}$ levels, and half of the $PM_{2.5}$ values were above unhealthy levels ($p<0.05$). The results of this analysis informs a proposed BBQ design divides a conventional grill into three compartments separated by carbon scrubber partitions. The outside compartments contain the energy source. Smoke passes through the scrubber partitions to reach food in the central compartment.

Keywords: carbon scrubber; barbecue smoke; volatile organic compounds; particulate matter.

Introduction

Barbecue (BBQ) smoke contains VOCs (volatile organic compounds) and particulate matter e.g., $PM_{2.5}$ that are hazardous to one's health. Breathing TVOCs (total volatile organic compounds) can irritate the eyes, nose, and throat, cause difficulty breathing and nausea, and can damage the central nervous system and other organs. Some TVOCs can cause cancer[1]. A comprehensive list of volatile compounds in the TVOC of BBQ smoke is given in Table I which includes benzene and formaldehyde. $PM_{2.5}$ can penetrate the lung tissue, and pass into the bloodstream, compromising the functioning of the heart and lungs, and exacerbating respiratory and cardiopulmonary disorders[2,3]. To appreciate what particulate matter (PM) is, Fig. 1 compares the width of a human hair to that of various PMs e.g. $PM_{2.5}$ and PM_{10}. Because of its small size $PM_{2.5}$ can deeply penetrate the lung and be more problematic. Therefore, it was chosen for study over the other sizes.

Preventive measures, such as filters or scrubbers are recommended to reduce the inhalation of VOCs[4]. Scrubbers have been used to adsorb these toxic products in laboratory and restaurant circumstances[5,6]. However, preferential scrubbing of VOCs leaving behind at least some of the sweet-smelling VOC, syringol, *has never been attempted*. Guaiacol is an organic compound that provides a pleasant taste to cooked food. Since both syringol and guaiacol are phenols, preferential preservation of one is likely to result in selective preservation of the other.

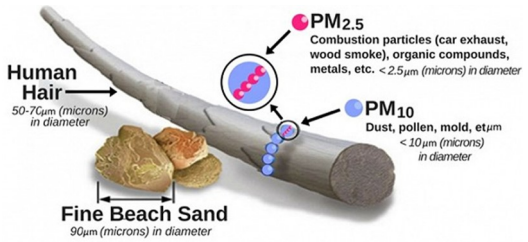

Fig. 1 Particulate matter of different sizes are contrasted to a human hair shaft

It was suspected that there is a differential adsorption of TVOCs such that some syringol, the desirable sweet smelling VOC component of BBQ might be preserved in a scrubbing process [7]. The reasoning is as follows. Syringol is a polar, highly soluble compound and occurs in both a gaseous and particulate phase. It is well known that activated carbon scrubbers are more effective at removing non-polar molecules because the activated carbon is itself non-polar [8]. For example, benzene and toluene are non-polar and would be expected to be preferentially removed over a polar substance like syringol (Fig. 2). This experiment leverages selective separation base on chemical properties to attain differential adsorption between syringol and harmful VOCs.

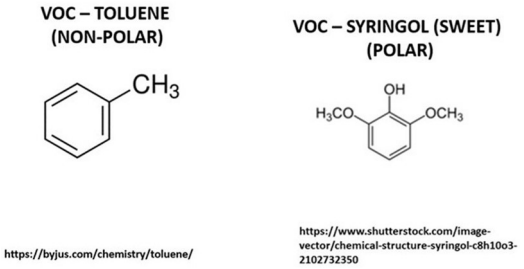

Fig. 2 As an example of a VOC toluene is non-polar molecule and would be expected to be preferentially removed over a polar substance like syringol

The proportion of VOC remaining in the smoke after filtration depends on the physio-chemical properties of the scrubber [9,10]. Different types of activated carbon scrubbers may even selectively remove $PM_{2.5}$ [11]. An ideal scrubber would selectively remove less syringol than other TVOCs so that cleaning the BBQ smoke would be safer while preserving the very reason it is so favored by the public.

The determination of TVOCs can be done with an easy to obtain inexpensive but accurate BLATN BR-smart 128s meter. Because it does not detect syringol specifically and because gas chromatography and mass spectrometry would be expensive, an olfactory test is an alternative way to measure syringol. Unlike syringol, guaiacol is difficult to measure because it would involve cooking meats and a tasting test. Because syringol and its cousin guaiacol (the taste producing VOC) are both phenols the results of one are likely to be somewhat generalizable. However, their properties do differ slightly. For example, guaiacol is more volatile (boiling point ∼205°C) compared to syringol (boiling point ∼263°C). This difference in volatility could affect their presence and concentration in BBQ smoke, influencing their interaction with carbon scrubbers.

The magnitude of TVOCs also depends upon the type of fuel used e.g. charcoal and wood chips. The latter is considered more hazardous to one's health. Both are unhealthy relative to propane which is known to exhibit the lowest TVOC levels and is approved by the EPA (2014). The initial pilot test with carbon scrubbers lowered the TVOC leaving invisible smoke. However, the TVOC levels were often not in the safe range (as recommended by the EPA). Therefore, it was hypothesized that invisible smoke may contain unhealthy levels e.g. >1.0 mg/m3 for TVOC and 35 $\mu g/m^3$ for $PM_{2.5}$. Table II indicates the various unhealthy and toxic levels for both TVOCs and $PM_{2.5}$.

If a scrubber proves to provide a differential scrubbing effect, it is not unreasonable to perform a design modification of existing barbecues. In theory, the smoke can be collected, scrubbed, and recirculated to a portion of the kettle such that it smokes the meat and heats it by conduction and convection. One 'recirculating BBQ' has been patented (United States Patent 11, 3,933,145 Harry Reich, Jan. 20, 1976, "A Recirculating Device"). However, it was done with the intention of scrubbing nothing more than the soot and did not use a high-quality activated carbon scrubber.

For all of the above reasons the following hypotheses were devised:

1. A carbon scrubber will preferentially remove more unhealthy VOCs than syringol (the sweet smelling component) thereby making BBQ smoke less hazardous to one's health while retaining some of the pleasant smell

2. Invisible BBQ smoke contains harmful TVOCs and $PM_{2.5}$s and is not safe

3. A conventional barbecue can be redesigned to incorporate a carbon scrubber

Methods

Apparatus and Substances

A conventional small Weber BBQ (with thermometer) was modified to contain an outflow hose on the top that bifurcated into 2 long (6 feet) hoses leading away from the BBQ to 2 TVOC/$PM_{2.5}$ meters (BLATN BR-smart 128s). To ensure the accuracy of the meters, three measures were taken: they were left in well-ventilated areas for extended periods of time, the auto-calibration system was run before the experiments, and there was a duration larger than one minute between individual tests to allow for the meters to reset their readings. See Fig. 3a for actual setup and 3b for closeup of meters. A proper seal was obtained at all junctions. Along the course of each hose a cork-filled portal was constructed for the olfactory test (Fig. 3c). A 3 way stop cock for potential gas sampling was placed at the terminal end of each hose. A thermometer was added to the hood. Because the meter had a maximum TVOC value of 10 mg/m^3 a few samples were taken to determine the actual TVOC value by a dilution technique.

Carbon scrubbers of different concentrations were made by filling a 24.5 x 4.3 cm plastic cylinder with easily obtainable

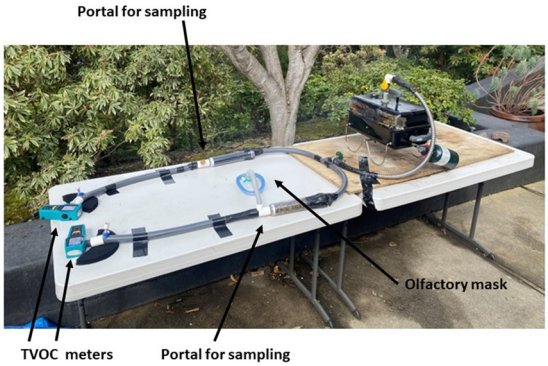

Fig. 3 Conventional BBQ grill with thermometer. A 2 cm diameter, steel lined, valve-controlled hose exited the lid. It bifurcated and extended for a distance of 6 feet. Along the course of one hose, one of 4 scrubbers was inserted. A nearby 2 cm portal for the olfaction test was provided, sealable by a cork. At the terminal end a 3-way stop cock for smoke sampling was provided. The meters were placed flush up against the ends of the hoses which fit snuggly into the entry mouths of the meters.

Fig. 4 2 TVOC/$PM_{2.5}$ meters (BLATN BR-smart 128s) located at the terminal end of the hoses.

Fig. 5 Olfaction test: 2 second evaluation of smoke for Syringol. Likert 1= odorless; 5 = strong sweet (or pleasant) smell

Australia Virgin activated carbon that is used in Vanleno carbon scrubbers (Fig. 4). A 100% scrubber contained carbon only and had a weight of 161.3 grams, volume of 355.790 cm^3, surface

Fig. 6 Investigator conducting experiment. One of three energy sources were used: woodchips, charcoal, or propane

area of 360.01 cm^2, and adsorption capacity of 30 wt.%. A 50% scrubber contained carbon in one half and glass marbles in the other with. A 25% scrubber was made similarly, and all scrubbers had proportional mass and volume to the 100% scrubber (e.g., the 50% filter had half of the volume, surface area, etc. of the 100% scrubber). The control (0% scrubber) was a plastic cylinder filled with marbles only (Fig. 1c). One hose incorporated the control (0% concentration – marbles only) and the other hose incorporated one of the 4 filters. Fuel types to create the smoke included charcoal (Kingsford original), wood chips (Weber - oak) and generic propane (Coleman Co.). Fig. 3d shows investigator using protective gloves to ignite the BBQ.

Participants

10 adult volunteers were asked to smell samples of the smoke emitting from a portal on the exiting hose. When the cork was removed, they had about 2 seconds to smell the emission. They were asked to rank the sweetness from 1-5 (using a Likert scale; 1 = odorless; 5 = strong sweet/smoky smell). They were not told what scrubber was involved and the brief exposure to smoke was harmless compared to what one normally is exposed to when operating a barbecue. All participants were also given breaks in between trials so as to not overwhelm them with the BBQ smoke.

The health of the participants was taken seriously. They were only exposed to relatively small amounts of smoke and for short intervals of time – seconds. Although part of this manuscript explains the danger of barbecue smoke, the olfaction tests are very brief compared to the amount of time used when conventionally operating a barbecue. Furthermore, the safety measures taken were approved by the research protocol

Fig. 7 Carbon scrubbers of different concentrations were made by filling a 24.5 x 4.3 cm plastic cylinder with easily obtainable Australia Virgin activated carbon. A 100% scrubber contained carbon only. Marbles added to the cylinders controlled the scrubber concentration. Note the portal at the end of each scrubber.
Source: Ruler image:https://ready-set-start.com/products/wooden-ruler

committee of the Alameda County Science and Engineering Fair where this science project received 3rd prize.

Protocols

Four sets of 5 trials were run for each of the charcoal and wood chip fuel conditions and the four scrubber conditions (100%; 50%; 75%; 25%) for a total of 160 trials whose sets were randomized. One set of 5 trials was run for the propane condition using each carbon concentration for an additional 20 trials. A 0% concentration scrubber acted as the control. The BBQ was ignited using one of the three fuels keeping the temperature between 200 - 350 degrees F. (commonly used when barbecuing). One of the four scrubbers was incorporated into one hose. The other hose always incorporated the control.

The meters were calibrated to ensure reliability and accuracy. To obtain a measurement, the meters were first allowed to drift to near zero values of ambient air and plateau for several seconds. A particular condition was then introduced, and a value was obtained when it plateaued and remained stable for several seconds.

To overcome possible minor variability between the meters, they were switched between the hoses periodically. TVOC values that exceeded the meter's limit of 10.0 were recorded as 10.0, which occurred in a few cases.

When the TVOC value plateaued in response to the arrived smoke, the 2 second olfaction test was performed. Smoke emanating from the portal was then estimated against a black background using a Likert scale of 1-5 (1 = clear, invisible 5 = maximally dense). TVOC and $PM_{2.5}$ values of normal ambient air were obtained by simply noting the meter results just prior to sending the smoke through the hoses.

A Likert scale was used as it was the most efficient way found and because equipment like opacity meters were not in the range of the budget allocated to this project. Both a white and black background were initially tested when measuring the thickness of the smoke, but the black background was found to be best for what is predominantly white smoke.

Results

Toxic emissions from unscrubbed BBQ smoke

First it is important to note the extent of TVOC and $PM_{2.5}$ production by different energy sources (woodchip, charcoal, propane) when there is no scrubber (0% concentration). Fig. 5 indicates that both woodchips and charcoal release the highest and toxic concentrations of TVOC and $PM_{2.5}$ far beyond the unhealthy and toxic levels and all values beyond the maximum recordable values (10.00) of the meters.

In stark contrast the median values $PM_{2.5}$ for propane was found to be below the unhealthy limit. The TVOC was values were slight above the toxic limit with a median of 3.7. No statistically significant differences were seen between the woodchip and charcoal groups for the high values of either TVOC or $PM_{2.5}$. However, propane was significantly lower for both TVOC and $PM_{2.5}$ (Mann-Whitney U, $p < 0.01$).

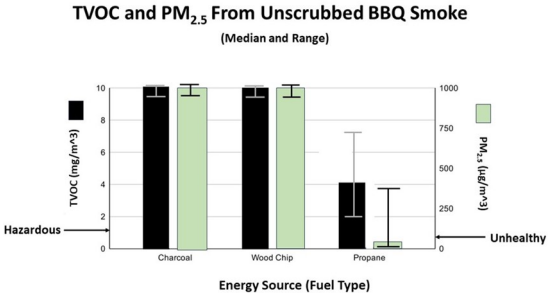

Fig. 8 TVOC and $PM_{2.5}$ levels for unscrubbed (0 % concentration) energy sources: woodchips, charcoal and propane. Only propane is significantly lower ($p<0.01$ Mann-Whitney U) and even below EPA recommendations for TVOC.

Selective adsorption of TVOC and Syringol

TVOC and $PM_{2.5}$ values before and after scrubbing were all recorded for both TVOC and syringol groups. A separate graph could have been made for that data but by itself would not indicate what needs to be known, i.e., the difference in adsorption between the two groups. That is particularly true in this experiment because the units of measurement are not the same (mg3 vs. Likert no.). However, by choosing units that reflect the extent of adsorption i.e., 'percent remaining,' then it becomes possible to compare the two groups.

The much higher smoke producing woodchip group was analyzed first. Fig. 6 indicates the percent remaining TVOC and syringol as a function of the scrubber concentration. Without a scrubber (0 %) virtually all of the TVOC remained, and no differential could be demonstrated. However, as the concentration of the scrubber increased a noticeable differential occurred. For example, at 50% concentration the percent remaining syringol was approximately 60% in contrast to a remaining TVOC of 6%. That is a 10-fold difference. The results were statistically significant using the Mann-Whitney U test giving $p<0.05$. The charcoal group also exhibited a similar differential result, but the effect was considerably less and not statistically significant.

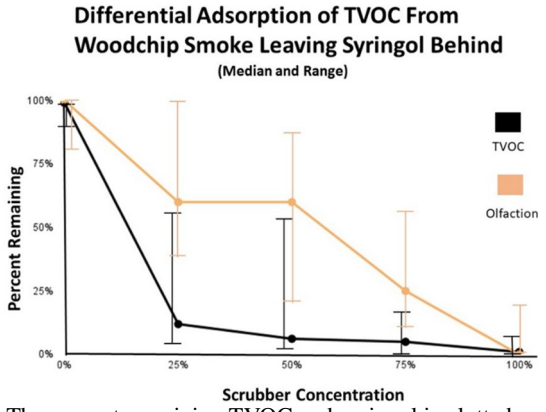

Fig. 9 The percent remaining TVOC and syringol is plotted as a function of the scrubber concentration. When there is no scrubber (0%) or maximal scrubber (100%) there is no differential. At 50%, however, approximately 60% of the syringol remained compared to 6% of the TVOC, significant at $p< 0.05$ Mann-Whitney U).

Unhealthy values in invisible smoke

Smoke visibility from the wood chip group were tabulated as follows: Values of TVOC and $PM_{2.5}$ from the invisible smoke (Likert = 1) of 25, 50, 75 and 100% scrubbers were combined. This was then compared to the TVOC and $PM_{2.5}$ values of adjacent normal ambient air which are basically the meter values before smoke was passed through the hoses. All abnormal TVOC and $PM_{2.5}$ scores from the invisible smoke trials are noted in the mean/individual data point bar graph of Fig. 7. The results showed that invisible smoke contained a significant amount of TVOCs, half of them higher than that of ambient air. The $PM_{2.5}$ results revealed that about half were above the unhealthy level (35) and half were in the hazardous range (>250). Statistical analysis was performed with Mann-Whitney U and found to be significant at $p < 0.5$ for both TVOC and $PM_{2.5}$ groups. Notably, all of the invisible smoke results were clearly below the corresponding unscrubbed (0% scrubber) smoke (Likert = 5) which were almost all greater than the maximum of 10.00 (the hazardous level).

To be clear, it is possible to examine the invisible smoke of individual scrubbers and not combine the group for data analysis. So doing would allow scrubber concentration to become a variable. However, as can be seen in Fig. 7, there are not enough data points. More trials would be needed and the result would not alter the conclusion that invisible scrubbed smoke is potentially harmful.

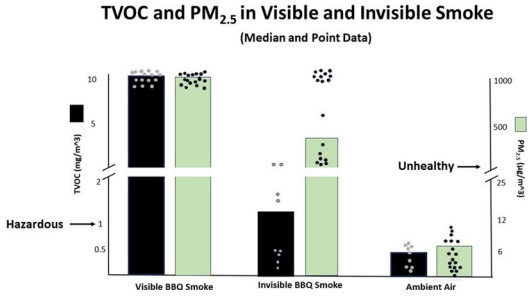

Fig. 10 Invisible smoke despite scrubbing contains a few levels of unacceptable TVOC and $PM_{2.5}$ values. This is noted in contrast to normal adjacent ambient air ($p< 0.5$ Mann-Whitney U). However, the values are far better than visible smoke (Likert =5) of unscrubbed smoke.

Proposed 'scrubber BBQ' Design

A drawing (design) was created to modify a conventional BBQ grill such that it incorporates carbon scrubbers. As seen in Fig. 8, the grill is divided into 3 compartments separated by carbon scrubber partitions. The outside compartments provide the energy source, e.g. wood chips. The smoke filters through the carbon partition to reach food in the central compartment. Heating of the food is primarily by convection (and some conduction) through the partitions. The outer hoods should be kept closed for the most part. The central hood allows access to insert and remove food. A size variable vent on the central hood allows the scrubbed smoke to exit.

Discussion

It is no surprise that activated carbon provides a good scrubber for both TVOCs and $PM_{2.5}$ [5,6]. It was also no surprise that wood chips are notorious for high TVOC and PM 2.5 levels in contrast to charcoal and the much safer propane [12]. The sometimes-hazardous values noted with propane are at odds with UEPA (2014) observation that propane does not contain hazardous levels. The occasional high results observed here are undoubtedly due to the fact that the BBQ was not wiped out between trials which would leave traces of woodchip and charcoal ashes that could easily evoke some high TVOC values.

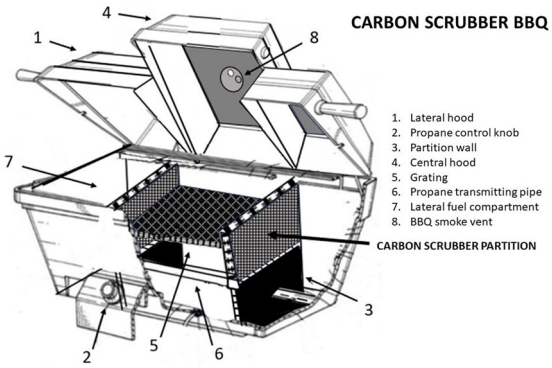

Fig. 11 Proposed design for "scrubber BBQ." Energy source e.g. wood chips in lateral compartments provides heat by convection and conduction. The scrubbed smoke enters the central compartment where the food is located before exiting through the variable size vent in the middle lid.

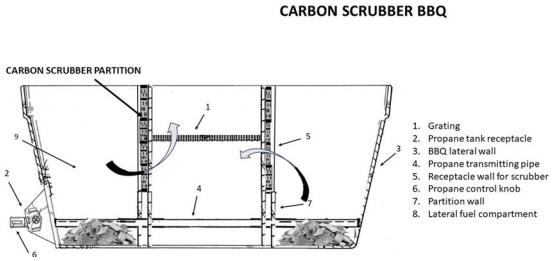

Fig. 12 Side view of "scrubber BBQ" with partitioned wall scrubbers. Smoke from lateral compartments passes through the activated carbon to reach food in central compartment and then exit through vent in middle lid.

No studies had been performed to determine the differential adsorption of TVOCs in general by comparison to the VOC, syringol. Therefore, it was a pleasant surprise that the carbon scrubber could preferentially (selectively) remove a greater percentage of the TVOCs and $PM_{2.5}$ than the syringol organic compound. That was strictly the result of serendipity. The TVOC/PM2.5 meters are fortunately easy to obtain, inexpensive and provided accurate data. Although the olfaction test is admittedly a somewhat inaccurate estimate of syringol it must be taken seriously. A more complicated mass spectroscopy measurement of syringol would have been ideal but too costly.

Because syringol (the sweet-smelling component of BBQ smoke) and guaiacol are both phenols it is reasonable to predict that similar results would be obtained for guaiacol (the enjoyable taste providing component of BBQ smoke). Such an experiment is possible but because it involves the actual tasting of cooked meat the experiment would be onerous in comparison to a simple smell test. The significance of being able to selectively remove much more TVOCs and $PM_{2.5}$s than syringol is that it allows the user of a BBQ who insists on one that emits smoke is that it is possible with the right scrubber concentration to reduce the health hazards considerably while leaving some of the sweet smell that prompts the BBQ in the first place.

It is true that results from scientific equipment are being compared to the results from human perception including its inherent variability. However, the data obtained from using the olfactory detector of the brain are valid, just much less accurate. The legitimate concern is how to mitigate the inherent variability that biological sensors possess. For that, statistical analysis is relied upon. Thus, the data obtained here are as accurate as possible and usable without resorting to unaffordable gas chromatography.

To achieve the best possible objective data from human perceptual results the Likert scale is most helpful. It is commonly used in research questionnaires. It is the most widely used approach to scaling responses in survey research, such that the term is often used interchangeably with 'rating scale.' Clearly, the 1-5 rating results are not as accurate as using gas chromatography, but because the ratings are all relative to what the participant experienced in the control group, they can be tested statistically and provide valid conclusions.

Clearly, the adsorption capacity of scrubbers, in general, diminishes over time and may impact their effectiveness. However, the Vanleno scrubber which provided the activated carbon in this experiment is said by the manufacturer to be useful for 1-3 months. Because the scrubbers in this experiment were employed for less than 50 hours each, it would appear that the factor of diminishing effectiveness over time is not very significant here. If it was a significant factor the scrubbers would not work as well and statistically significant results would not be achieved.

Of great interest and importance was the finding that invisible smoke exhibits unsafe levels of TVOC and $PM_{2.5}$. This should be used as a friendly warning to the public that if BBQ smoke is to be used at all, it should be recognized that just because the smoke clears and is no longer seen that does not mean it is safe.

The recommended design variation of one of the conventional BBQ grills would require little effort. Partitions for the carbon scrubbers would be required and period exchange of scrubber plates would be necessary. However, the concept that the flow of unhealthy smoke can be diverted to the scrubbers for healthier if not totally safe smoke, but still somewhat sweet smoke seems to be a reasonable option.

Conclusion

Several conclusions can be drawn from the above experiment:

1. TVOC and $PM_{2.5}$ values in BBQ smoke were highest for wood chips followed by charcoal and least for propane.

2. Certain scrubber concentrations selectively remove substantially more TVOCs and $PM_{2.5}$s than syringol

thereby reducing the health hazard while retaining a pleasant smell.

3. Invisible BBQ smoke is not safe. It contains some high TVOC and $PM_{2.5}$ levels that are hazardous to health. Ideally, a smoke-scrubbed BBQ is best for health reasons.

4. The proposed modification of a conventional BBQ grill with carbon scrubber partitions should be easy to construct and test.

Future Research

If it is possible to acquire a mass spectrometer that can assay syringol, a second experiment for next year's Alameda County Science and Engineering Fair would be ideal in which the exact values of the sweet substance that prompts barbecuing can be measured. Another project for the fair next year would be to test the proposed "cleaner (scrubbed) BBQ" (Fig. 8) on approximately 100 willing participants to see, if indeed, 1) the principle of selective adsorption of TVOCs and $PM_{2.5}$s can persist in the grill scenario and 2) if there is enough retention of sweet smelling syringol to make it worthwhile for the BBQ user.

Acknowledgements

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APPENDIX

- **Benzene:** Known carcinogen
- **Toluene:** Linked to respiratory issues.
- **Formaldehyde:** Irritant and carcinogen.
- **Acrolein:** Causes eye and respiratory irritation.
- **Styrene:** Associated with nervous system effects.
- **Xylene:** Can affect the central nervous system.

Level of Health Concern	VOCs (mg/m^3)
No irritation or discomfort	<0.3
Irritation and discomfort	0.3–0.5
Exposure effect and headache	0.5–1.0
Toxic effects may occur	>1.0

Table 1: Source : Environmental Analytical Services Inc. (2020).

AQI categories	$PM_{2.5}$ concentration ($\mu g/m^3$)
Good	0-12
Moderate	12.1-35.4
Unhealthy for sensitive groups	35.5-55.4
Unhealthy	55.5-150.4
Very unhealthy	150.5-250.4
Hazardous	250.5-500.4

Table 2: United States Environment Protection Agency (2014).