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Control of Fecal Malodor by Adsorption onto Biochar

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CONTROL OF FECAL MALODOR BY ADSORPTION ONTO BIOCHAR

By

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This thesis entitled:
Biochar Adsorption for Control of Fecal Malodor
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Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Stetina, Kathleen (M.S. Civil Engineering, Department of Civil, Environmental, and Architectural Engineering)
Control of Fecal Malodor by Adsorption onto Biochar
Thesis directed by Professor Karl G. Linden

Abstract

The provision of sanitation services has been accelerated as part of the Sustainable Development Goals with increasing focus on the need for solutions within the fecal sludge management services supply chain. One common constraint in the sanitation value chain is malodor nuisance associated with fecal sludge. Finding cost-effective ways to minimize end user malodor nuisance from latrines is critical. Adsorption of malodor onto biochar was hypothesized as one possible technology intervention to malodor nuisance. Adsorption studies were conducted as part of a project funded by the Bill & Melinda Gates Foundation to control and mitigate malodors derived from human waste. Biochars derived from bamboo wood, pine wood, and human feces, and NORIT ROZ 3 activated carbon were used to evaluate adsorption of malodor. A reconstitution of fecal malodors was used, comprised of four compounds including carboxylic acids, sulfur and nitrogen containing compounds shown to be responsible for human fecal odor. Both batch and flow-through adsorption tests were performed. Odor was quantified using ascending concentration series method of dynamic threshold olfactometry by an odor panel, and a hydrogen sulfide (H_2S) meter. Breakthrough capacities of the adsorbents for both odor reduction (odor units per g of adsorbent) and H_2S reduction (mg/g of adsorbent) were determined for the equilibrium odor levels represented by the adsorption studies for batch and flow-through methods. Complete odor removal was never achieved; generally, 40-50% of odor could be removed by adsorption. Results showed that all biochars exhibited comparable adsorptive characteristics to each other and modified activated carbon. All experiments were performed at a high relative humidity, as would be typical in many latrine settings. Results indicated significant fouling by water vapor during continuous flow operation that generally decreased odor capacity of the chars by an order of magnitude. Specific compounds representing adsorption challenges were identified. Overall, the results provide baseline engineering data to apply and size biochar filters for adsorption as a malodor control method in various latrine settings.

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BET	Brunauer–Emmett–Teller
BVs	Bed Volumes
C_e	Equilibrium Concentration
CSOs	Civil Society Organizations
DI	Deionized
D/T	Dilution-to-Threshold
FSM	Fecal Sludge Management
GAC	Granular Activated Carbon
GC-MS	Gas Chromatography-Mass Spectrometry
H_2S	Hydrogen Sulfide
K_{oa}	Air-octanol Partition Coefficient
K_{ow}	Octanol-water Partition Coefficient
MFC	Mass Flow Controller
ODT	Odor Detection Threshold
ORS	Odor Reconstitution Solution
O.U.	Odor Units
q_c	Adsorption Capacity
RH	Relative Humidity
RTT	Reinvent the Toilet
SDGs	Sustainable Development Goals
SuSanA	Sustainable Sanitation Alliance
TLUD	Top-lit updraft gasifier
VIP	Ventilated Improved Pit
VOC	Volatile Organic Compound
VOSC	Volatile Organic Sulfur Compound

CHAPTER ONE: INTRODUCTION

1.1 Fecal Sludge Management and the Global Sanitation Crisis

The introduction of safe sanitation is one of the most influential interventions to improve human health. When not managed appropriately, human waste poses one of the most acute and serious risks to human and environmental health. Nevertheless, access to safe sanitation remains one of the most pressing global challenges. 2.4 billion, approximately one in three of our global neighbors, do not use forms of improved sanitation [1]. Approximately 30% of these people live in urban areas [1], which presents a unique set of challenges associated with lack of available land for latrine pits. In urban settings that are not connected to sewerage networks, there is generally greater need to treat and/or transport human waste after it is safely collected. This collection, transportation, and treatment of human waste represents the field of fecal sludge management (FSM). FSM is associated with a supply chain of services to safely treat the sludge and carry it away from users. A wide array of service chain models exist to meet this need, that range in involvement of users, private sector players, governments, and civil society organizations (CSOs).

The Sustainable Development Goals (SDGs) have set a lofty goal (SDG 6.2) to achieve "adequate and equitable access to sanitation and hygiene for all" by 2030 [2]. In the scramble to mobilize resources and find scalable solutions to this goal, fecal sludge management professionals find themselves navigating a complex web of economic, social, institutional, and technical challenges; safe management of waste is not simple nor cheap. While there are significant barriers to achieving SDG 6.2, there is room for technological innovation to affordably improve the FSM services supply chain.

1.1.1 The *Reinvent the Toilet* Program

The Bill & Melinda Gates Foundation *Reinvent the Toilet* (RTT) program has advanced the design of latrine systems that safely transform human waste into a usable or harmless form. Many of the RTT designs are based upon the heating or combustion of human waste, which is known to emit malodors. Ultimately, most latrine systems will emit malodor associated with human waste, which could be a barrier to system success. As one example, the pyrolysis of human waste into biochar is one successful method of transforming

pathogenic human waste into a useful resource, and is known to emit significant malodor that should be treated [3]. Technologies that can help minimize or eliminate malodor could positively contribute towards wider adaption of safer sanitation systems. This research was part of project OPP1119852 of the Bill & Melinda Gates Foundation.

1.2 Malodor

1.2.1 Malodor Nuisance

FSM is a smelly business. Yet, evidence of this has been largely anecdotal and ignored. While this may be justified due to seemingly more pressing issues in the evolving field, odor remains a defining and unavoidable characteristic of FSM. Anecdotally, a literature search for latrine malodor studies in poverty settings produces few results. Quantitatively, a survey performed via the Sustainable Sanitation Alliance (SuSanA) defined malodor nuisance as a widespread and notable barrier in global sanitation efforts; as part of this project, research at Duke University and the University of Colorado Boulder developed this survey to assess locations, causes, intensity and impacts of malodor along the chain of FSM [4]. The survey received responses from 258 sanitation solution providers, researchers, and users from a range of developing countries. Key highlights that serve as motivation for this research include:

- 94% of respondents felt that malodor is an important barrier to latrine adoption (Figure 1)
- Malodor is considered unpleasant or very bad at several stages of FSM practices, and is worst when untreated waste is released (Figure 2)
- Malodor can have many several negative impacts on users, including attracting files or other bugs, enduring unpleasant odor, or use of open defecation or a different latrine (Figure 3)
- There has not been adequate progress made to address latrine malodor issues (Figure 4)

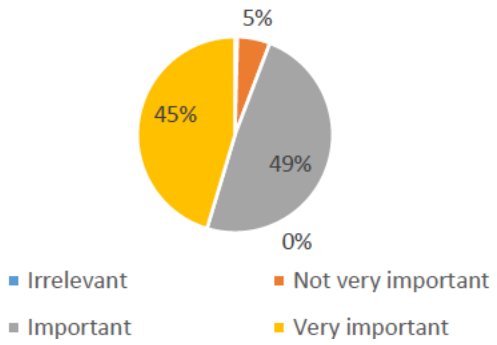


Figure 1: How important is malodor as a barrier to latrine/toilet adoption? Results from a SuSanA survey. [4]

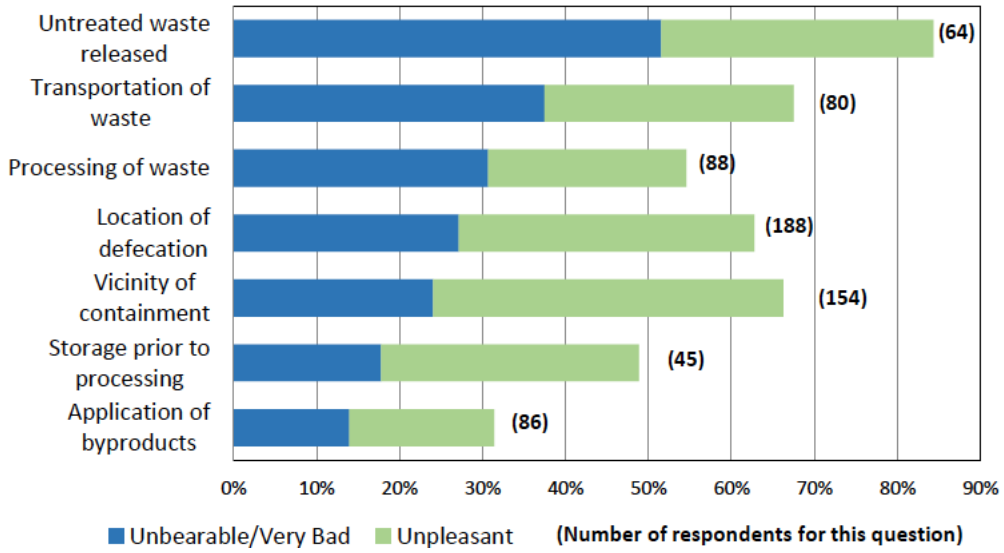


Figure 2: Malodor nuisance rating by FSM component [4]

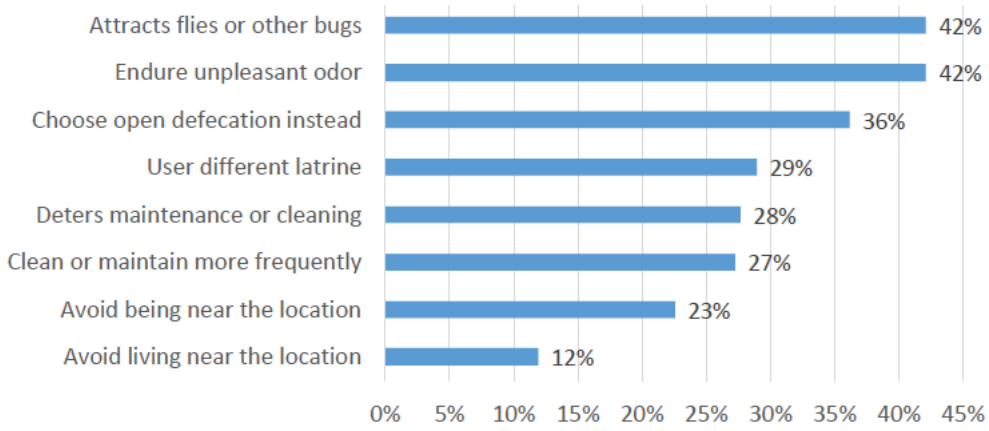


Figure 3: Malodor impacts on latrine users [4]

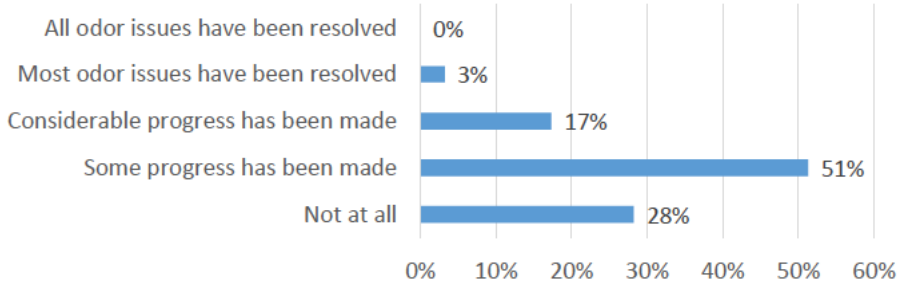


Figure 4: To what extent are odor issues currently being addressed? [4]

These results serve as motivation for this research; along the chain of FSM, malodor nuisance in a latrine setting is the most severe. Furthermore, malodor nuisance and its impacts can be severe for users, and on top of that negatively affect latrine adoption. Finally, this is an important issue that needs to receive more attention in order to find good solutions.

1.2.2 Typical latrine malodorants

It is important to understand the the odorants that are responsible for latrine malodor so that an odor control can target the behavior or these molecules in air. Specifically, important parameters for the development of a control technology includes the type of odorant, concentration, and flowrate [5]. Since the 19th century butyric acid, indole, p-cresol, and skatole have been known as significant odorants associated with human waste[6]. The presence of sulfur compounds in human waste facilities is also well known. Particularly, methyl mercaptan and hydrogen sulfide (H_2S) are the most significant sulfur compounds [7] [8]. Table 1 summarizes the typical qualities and sources of these malodors of interest in latrine settings.

A study out of the Research and Development Division of Firmenich in Geneva, Switzerland quantitatively measured odorant molecules present in the headspace above twelve latrines in India, South Africa and Kenya using gas chromatography-mass spectrometry (GC-MS). Primary odor compounds found were consistent with literature, and included hydrogen sulfide, butyric acid, methyl mercaptan, p-cresol, indole, and skatole [9]. Results were somewhat consistent between the twelve ventilated pit, ventilated improved pit (VIP), or urine-diverting (UD) latrines. Hydrogen sulfide and methyl mercaptan were the most

significant contributors to latrine malodor and a smell of sewage [9], but are also highly volatile and unstable compounds. In latrines that were not well-ventilated, less volatile compounds like p-cresol, butyric acid, and indole become more important [9].

Table 1: Odor descriptors, typical sources, odor detection thresholds, and expected concentrations in latrines for malodorants of interest

Malodorant	Odor Quality	Sources	ODT
Hydrogen sulfide	Rotten eggs [10]	Human and animal waste, petroleum and natural gas, volcanic gases, hot springs, industrial activities [10]	4 ppb [11]
Methyl mercaptan	Sharp but disagreeable, like garlic or rotten cabbage [12]	Decayed organic matter, animal feces, oil refineries, pulp mills [12]	4×10^{-5} μg/L [9]
Indole	Almost floral and pleasant in low concentrations, unpleasant and like feces in high concentrations [13]	Jasmine, insect control, tobacco smoke [13]	6×10^{-5} μg/L [9]
Butyric acid	Unpleasant, rancid, obnoxious [14]	Animal fats, plant oils, fermentation product [14]	9×10^{-4} μg/L [9]
p-Cresol	Sweet, tarry [15] Animal, barn-like	Widely distributed in nature, excreted in urine, human and animal tissue and fluids, solvents, pesticides, vehicle exhaust, wood and trash burning, tobacco smoke [15]	2×10^{-5} μg/L [9]
Skatole	Fecal [16]	Feces, beetroot, nectandra wood, fragrance industry, food additive [16]	5×10^{-6} μg/L [9]

1.3 Adsorption by Carbonaceous Adsorbents

1.2.1 Activated Carbon

One treatment technology that is widely used in air quality applications is adsorption of contaminants by activated carbon. Activated carbon uses physical and chemical adsorption processes to clean the odor solution that comes in contact with it. Physical adsorption results from dispersive interactions of the sorbate with the sorbent surface. Physical adsorption has low binding energy and is reversible. Chemical adsorption results from a reaction between the sorbent and sorbate, and therefore is high in energy and usually non-reversible [17].

Activated carbon is a highly effective adsorbent and commonly used for treatment of odor emissions with sulfur compounds in sewage-based wastewater treatments facilities [18][19]. Physical adsorption generally is enhanced by using a carbonaceous sorbent with high specific surface area (750-1500 m^2/g), and a significant portion of total pore volume in the micropore range (less than 2.5 nm diameter) [20]. However, other factors include total pore volume of the activated carbon and surface chemistry, and some studies have shown that the combination of micropore and mesopore volumes are more effective for hydrogen sulfide removal [21][22].

There is significant literature that details adsorption of sulfur compounds like hydrogen sulfide and methyl mercaptan. Physical adsorption capacity of hydrogen sulfide of typical carbons is ~0.01 g H_2S/cm^3 of carbon [23]. However, chemical adsorption of a sulfur compound like H_2S can increase capacity of carbon [23]. Chemical adsorption of methyl mercaptan can present an even higher adsorptive capacity than H_2S [23]. However, in combination with H_2S, methyl mercaptan can have a lower adsorption adsorptive capacity [24]. Generally, activated carbon provides a high adsorption capacity towards sulfur compounds and volatile organic sulfur compounds (VOSCs) compared to nitrogen-containing volatile organic compounds (VOCs) [25]. Of the malodorants in interest for this work, indole and skatole can be classified as nitrogen-containing VOCs.

1.3.2 Biochar

Biomass-based biochars can present a low-cost alternative to activated carbon to remove pollutants from air or water. Biochar is the product of pyrolysis of organic matter. The pyrolysis process is thermal decomposition of organic matter at high temperatures and in absence of oxygen. Biochar production represents a beneficial, widely available, and potentially economic use of agricultural waste. Biochar has been studied for use as an adsorbent of contaminants in water and air, a fuel source as an alternative to charcoal, and as a soil amendment to increase crop yields [26] and for carbon sequestration [27].

For this work, biochar was evaluated as an adsorbent and deodorant. As with activated carbon, biochar's surface properties and chemistry can dictate adsorptive characteristics and effectiveness. The two primary characteristics in biochar production to affect surface properties and chemistry is biochar feedstock type and pyrolysis temperature. In general, as pyrolysis temperature increases, surface area and pore distribution of resulting biochar increase, resulting in an increase of adsorption effectiveness. Asada et al. found that indole and skatole were better adsorbed onto bamboo biochar pyrolyzed at 1000° C compared to pyrolysis temperatures of 500° C and 700° C [28].

1.4 Research Background and Motivation

Generally, odor emissions from various types of sewage-based wastewater treatment (WWT) settings is understood and specific characterization of these odor types and sources has been well-studied. Chappuis et al. has begun to characterize specific malodors in specific latrine settings in India and parts of Africa [9]. A Duke / University of Colorado study has begun to understand the level of malodor nuisance along the chain of FSM services and anecdotal impacts [4]. There has not been clear, or peer-reviewed, characterization of malodors along the chain of FSM services, nor a clear understanding of the specific importance of malodor nuisance in regards sanitation-related development efforts.

Adsorption of VOSCs and other sulfur compounds by activated carbon in a variety of industries has been well studied. Adsorption of odor emissions containing sulfur compounds by activated carbon from sewage-based WWT settings has been well studied. Increasingly, adsorption by biochars for various applications is becoming well-studied. To some extent, adsorption of malodor specifically by biochars have been included in this. Adsorption by activated carbon or biochar of malodor in latrine settings is not understood.

Based on demonstrated adsorption of malodors in related settings, adsorption onto carbonaceous adsorbents could be a solution to malodor control in latrines. In addition, biochar could have comparable effectiveness in these settings to well-understood activated carbon adsorbents.

1.5 Research Objectives

The objectives of this research were designed to address needs surrounding malodor nuisance in latrines and fill gaps in literature. A primary, secondary, and related objective were developed, which are called Objective 1, Objective 2, and Objective 3 for this purposes of this thesis. Objectives are summarized in Table 2.

Table 2: Summary of research objectives

Objective	Importance	Description	Details
Objective 1	Primary	Preliminarily assess adsorption as a means of malodor control of newly identified malodor compounds present in latrines in India and parts of Africa.	Effectiveness of biochar adsorbents will be compared to that of activated carbon for each of malodors in singularity and in combination.
Objective 2	Secondary	Determine adsorption characteristics of selected malodors onto selected carbons.	Adsorption characteristics include: preliminary adsorption isotherms, adsorption kinetics, and breakthrough curves.
Objective 3	Related	Relate the determined adsorption characteristics with the physicochemical properties of the selected carbons and malodorants.	Quantify adsorption properties of biochars in a latrine setting, and propose adsorption mechanisms when possible.

Results of this work compare the adsorption four malodors in singularity and in combination onto a modified activated carbon and three biochars of various feedstocks and pyrolysis temperatures. The four malodors studied are indole, p-cresol, butyric acid, and H_2S. The carbon adsorbents studied are NORIT ROZ 3 modified activated carbon, fecal char, bamboo char, and pine char.

CHAPTER TWO: RESEARCH

2.1 Methods

2.1.1 Latrine Malodor Synthesis

For laboratory bench-scale tests of latrine malodor adsorption by activated carbon and biochar, a source of odorous air was needed. Odor solutions were synthesized in a fume hood by dilution then evaporation (for those in liquid or solid form) of chemicals of interest. Five air steams that were created then treated were designed to represent various latrine malodors in singularity and in mixture, at constant concentrations.

Selection of malodorants

From the six primary malodors identified by Chappuis et al. [9], four were selected for this research. These include H_2S, butyric acid, indole, and p-cresol. An odor reconstitution solution (ORS) was created as a mixture of the three non-sulfur-containing malodors: butyric acid, indole, and p-cresol. Methyl mercaptan and skatole were not used for simplicity sake and because the four selected compounds created a sufficiently representative odor profile. H_2S was decided to be representative of adsorption of the sulfur compounds, and the relative adsorptive characteristics of H_2S and methyl mercaptan are well studied in literature [24] [23]. Skatole, specifically, was not selected because of a prohibitively low solubility in water, and because Chappuis et al. [9] consistently measured skatole at the lowest concentrations of the six odorants measured.

Physicochemical properties must be well understood in order to relate adsorption behaviors to physicochemical properties of selected malodors (Objective 3). Known properties of the four selected malodors are summarized in Table 3. Of particular importance to adsorption is the air-octanol partition coefficient, (K_{ao}) which is an indicator of a compound's likelihood to partition between the gas phase and the organic dissolved phase, such as soil or or carbonaceous adsorbent. K_{ao} is calculated using Equation 1. While K_{ao} is a defined property unique to a compound and may be experimentally determined, there is a lack of reported values in literature. Nevertheless, a calculation of K_{ao}, based on its theoretical relationship to better known values of octanol-water partition coefficients (K_{ow}) and Henry's Law Constants (H), produces an acceptable value [29].

Equation 1: Air-octanol partition coefficient

$$K_{ao} = \frac{K_{ow}RT}{H},$$

where K_{ow} is the octanol-water partition coefficient unique to the compound,
R is the gas constant, in atm-m^3/mol-K,
T is the temperature, in Kelvin (K), and
H is Henry's Law Constant unique to that compound, in atm-m^3/mol.

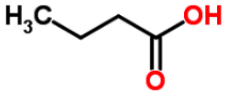
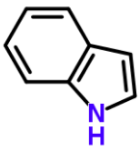
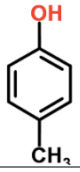
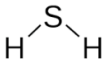
The air-water partition coefficient (K_{aw}), a measure of a compounds likelihood to partition between the aqueous phase and gas phase, is important for malodor compounds because all adsorption experiments were performed at significant relative humidity, to mimic a latrine setting. K_{aw} is calculated according to Equation 2.

Equation 2: Air-water partition coefficient

$$K_{aw} = \frac{K_{ow}}{K_{ao}} = \frac{H}{RT},$$

where K_{aw} is the air-water partition coefficient unique to the compound.

Table 3: Known physicochemical properties of butyric acid, indole, p-cresol and H_2S

Property	Butyric Acid	Indole	p-Cresol	Hydrogen Sulfide
Chemical Formula	$C_4H_8O_2$	C_8H_7N	C_7H_8O	H_2S
Structure				
Molecular weight (g/mol)	88.11	117.15	108.13	34.09
Boiling point	164° C	253° C	202° C	-60° C
Melting point	-7.9° C	52° C	35° C	-85° C
pKa at 25° C	4.8	-2.4 (basic)	10.3	pKa1 = 7.4 pKa2 = 11.96
Log K_{ow}*	0.79	2.14	1.94	2.1
Henry's Constant	$5.35x10^{-7}$ atm-m^3/mole	$5.3x10^{-7}$ atm-m^3/mole	$1.0x10^{-6}$ atm-m^3/mole	0.0098 atm-m^3/mole
Vapor Pressure	1.65 mm Hg	0.0122 mm Hg	0.11 mm Hg	$1.36x10^4$ mmHg
Solubility in water at 25° C	$6x10^4$ mg/L	3560 mg/L, or in hot water	$2.15x10^4$ mg/L	2.257 m^3/m^3-water
Log K_{aw}**	-4.66	-4.66	-4.38	-0.393
Log K_{ao}**	5.45	6.80	6.32	2.49

Unless noted otherwise, properties all referenced are information from the substance's page in the HSDB database in TOXNET [30]
**Log K_{ow} values from Hansch et al. [31] for organic compounds and from Cuevasanta et al. [32]for H_2S*
*** Log K_{ao} and K_{aw} values calculated as explained in above section*

Tested malodor solutions

Five odorous odor solutions of various malodorants and concentrations were designed for a representative sample of typical latrine malodors. These five odor solutions are summarized in Table 4. For the purposes of this thesis, the five odor solutions will be referred to by the malodor(s) present in the odor solution. The concentrations of butyric acid, p-cresol, and indole in the ORS mixture were set at concentrations determined directly by the recent findings of Chappuis et al. [9]. All target concentrations are above reported ODT levels for these compounds, as summarized in Table 1. The odor solutions of the individual compounds were set at the total concentration of malodor compounds in the ORS mixture for purposes of

consistency of equilibrium odor concentrations. H_2S deviated slightly from the findings of Chappuis et al. (which was approximately 72 ppb H_2S) due to restrictions in achievable H_2S levels based on system flowrates and H_2S source concentrations. Actual delivered concentration was calculated to be 223 ppb (see *Synthesis of odor solutions* section below).

Table 4: Summary of malodorants and their concentrations that were synthesized and treated during adsorption experiments

Odor solution	Malodors present	Target Concentration	Units
ORS	Butyric Acid	5×10^{-3}	µg/L
	p-Cresol	3×10^{-3}	µg/L
	Indole	3×10^{-4}	µg/L
	Total ORS	8.3×10^{-3}	µg/L
ORS+H_2S	Butyric Acid	5×10^{-3}	µg/L
	p-Cresol	3×10^{-3}	µg/L
	Indole	3×10^{-4}	µg/L
	Total ORS	8.3×10^{-3}	µg/L
	H_2S	223	ppb
Butyric Acid	Butyric Acid	8.3×10^{-3}	µg/L
p-Cresol	p-Cresol	8.3×10^{-3}	µg/L
Indole	Indole	8.3×10^{-3}	µg/L

Synthesis of odor solutions

Figure 5 shows a schematic of the odor synthesis process followed by the flow-through experimental set up. A picture of the actual set up inside a fume hood is shown in Figure 22 in *Appendix C: Photos of Laboratory Set Ups*. For each odor solution, these three relevant compounds were diluted in deionized (DI) water to reach a desired concentration in proportion to the target concentrations of each odor solution. Indole, however, was obtained in form of solid crystals and has a melting point of 52° C. Therefore, indole was dissolved in hot water. In order to keep butyric acid speciation consistent, pH for all odor solutions was kept around 3 by adding a few drops of hydrochloric acid to each solution. All compounds were maintained at concentrations in water below their solubility limits (See Table 3). Figure 5 explains how diluted liquid solutions of malodor compounds were synthesized and combined with H_2S, when applicable, within a fume hood. All tubing was comprised of non-odor-sorbing Norprene Food Tubing (Masterflex, Vernon Hills, IL). Compressed air flowed through an Alicat MCP Moderate Mass Flow Controller (Alicat

Scientific, Tuscan, AZ) at a constant rate, passed through a granular activated carbon (GAC) cartridge filter to ensure cleanliness and remove any residual odor, and enter a closed 4 L vaporization chamber made from a mason jar. A KDS 230 110 VAC Syringe Pump (KD Scientific, Holliston, MA) pumped a constant rate of the dilute liquid solution of malodor compounds from a 150 ml plastic syringe through a 16.5 gage needle and into the vaporization chamber and onto a surface of glass beads. The syringe was refilled approximately every 24 hours, as needed. Flow-through experiments were paused during the time of syringe refill (approximately fifteen minutes). The glass beads were contained in a small beaker and suspended in the vaporization chamber. The glass beads were heated by a 200 watt, 240 volt swaged cartridge heater (Grainger, Lake Forest, IL) that entered the vaporization chamber also and was controlled by a PID temperature controller. The PID temperature controller communicated with a temperature sensor that was placed inside the vaporization chamber, placed in space several centimeters away from the glass bead surface. For the odor solution with H_2S, 246 ppm H_2S was delivered from a gas cylinder at a constant rate of 59 ml/min, the minimum allowable based on the mass flow controller (MFC) technology, which resulted in a calculated H_2S concentration of 223 ppb. The LabVIEW VI program controlled a voltage set point for a driver, that delivered the desired voltage to a 1000 SCCM H_2S MFC (MKS Instruments, Andover, MA) that controlled flow from an H_2S cylinder.

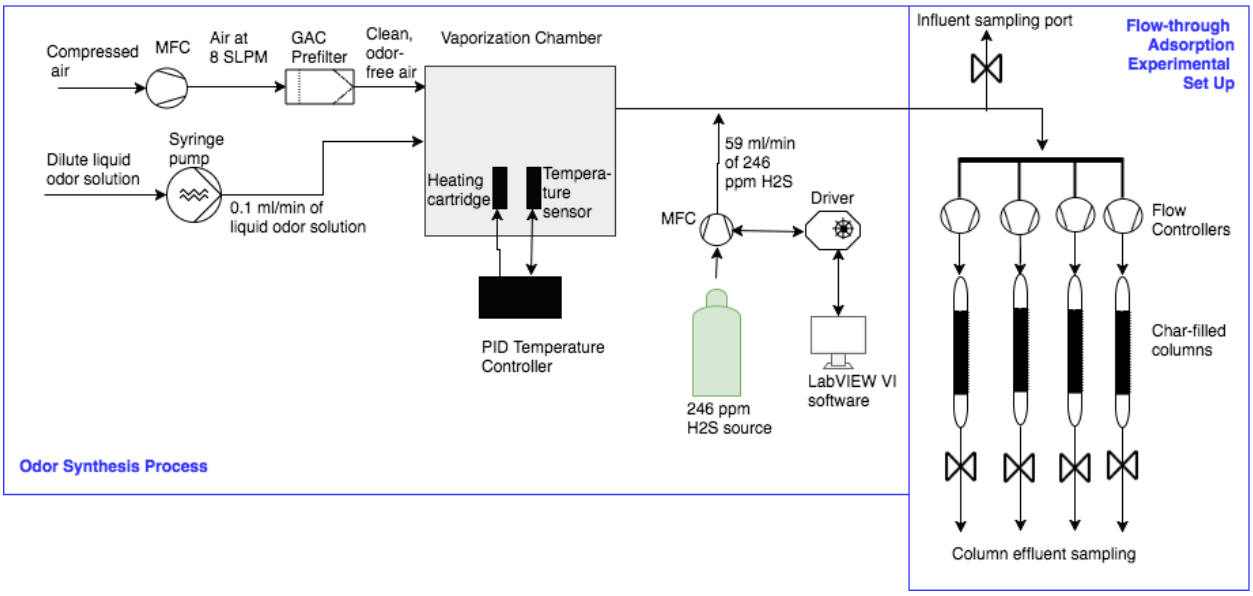


Figure 5: Schematic of experimental set up: odor synthesis process and flow-through adsorption

Flow rates of the dilute liquid odor solutions and of cleaned compressed air were maintained for consistency in water loading rate and relative humidity (RH). Odor levels were varied by the types and concentrations of liquid malodor compounds being applied. These parameters of the odor synthesis process are summarized for each set of experiments in Table 5. A "set" refers to both a batch and a flow-through experiment performed for each odor solution (See *Section 2.1.4 Batch Experiments* and *Section 2.1.5 Flow-through* Experiments). For the odor solution of ORS+H_2S, ORS was synthesized identically to the ORS odor solution, then H_2S was delivered from a gas cylinder at a constant rate to result in a target H_2S concentration of 223 ppb. The average measured H_2S concentration was 235 ppb, which indicates that actual H_2S concentrations reflected the targeted value well.

Table 5: Parameters of liquid odor synthesis process

Odor solution	Quantity of malodor compound diluted in 100 ml DI water (g)	Dilution factor	Final concentration in dilute liquid odor solutions (µg/L)	Pump rate of dilute liquid odor solutions (ml/min)	Flow rate of clean air (SLPM)	Target Concentration in air stream (µg/L)
ORS	Butyric Acid: 0.2	5,000	400	0.1	8	0.005
	p-Cresol: 0.12	5,000	240	0.1	8	0.003
	Indole: 0.012	5,000	24	0.1	8	0.0003
Butyric Acid	1.0	15,000	660	0.1	8	0.0083
p-Cresol	1.0	15,000	660	0.1	8	0.0083
Indole	1.0	15,000	660	0.1	8	0.0083

2.1.2 Odor Measurement

Odor is the least well understood of the five senses, and perhaps the most mysterious to measure. Odor measurement is an incomplete field, and is even regarded as an art, rather than a science by many [33]. Nevertheless, odor measurement is becoming increasingly understood and well recognized methods exist for a variety of measurement techniques [33][34]. In general, odor measurements fall into the two categories of sensory and analytical, and it can be difficult to link the two [33]. While some laboratories may be able to analytically quantify relatively high concentrations of certain odor-causing compounds using GC-MS, the sensory measurement of olfactometry was chosen as the primary method for this research due to prohibitive issues in detection limits of the selected compounds using GC-MS. Additionally, olfactometry measures human perception of malodor, and the goal of this research is to reduce malodor nuisance, which could be a called a measurement of human perception. Olfactometry is a method of odor measurement to quantify an odorous air sample in terms of human perception by dilution with clean air below the odor detection threshold (ODT) until detection is reached. The dilution-to-threshold (D/T) represents is the lowest dilution at which an odor can either be detected or recognized.

Olfactometry

Odor was measured by an SM-100 Olfactometer (Scentroid/IDES, Ontario, Canada). A picture of the olfactometer is shown in Figure 21 in *Appendix C: Photos of Laboratory Set Ups*. All measurements of treated and untreated odorous air in this research were sampled using olfactometry by an odor panel. In determining detection thresholds with the olfactometer, odor panelists began by being presented with clean, odor-free air by the olfactometer, which was incrementally adjusted to increasingly lower dilutions of the odorous sample in clean air. This is termed the ascending concentration series method of dynamic threshold olfactometry [34]. A panelist records when an odor is first detected odor in a forced Yes/No choice situation in accordance with standard methods for olfactometry VDI 3882 and EN 13725 [35] [36]. The position of detection correlates to a D/T, which equates directly to a pseudo-dimension of odor called *odor units per cubic meter* (O.U./m^3). In creation of this unit, the choice of a cubic meter was arbitrary and must be handled with care [33]. The odor level in O.U./m^3 for each reading was calculated as the geometric mean between the dilution of detection and the previous dilution.

The limitations associated with olfactometry measurement, used as the primary method of measurement throughout this research, include variability between odor panelists and the non-linearity and misunderstood nature of human olfactory senses. Methods to minimize variability between panelists are discussed in the *Odor Panel* immediately section below. Methods to account for variability between panelists are discussed in the *Calculations* section. However, a person's response to odor is subjective, and it is expected that human responses to odor will vary between people, depending on the odor and the concentration [37]

In the olfactometer, two dilution plates with different dilution ranges were used (plate A and plate 3) depending on the odor solution being treated. Table 6 shows the D/T range for the different plates with which the SM-100 Olfactometer is compatible. The values in Table 6 refer to the dilution of the sample with clean air at the position for which odor is first detected. Because steps between positions are discrete, the actual D/T value associated with a sample reading may be anywhere between the dilution level of the

detected position and the dilution level of the previous position. Therefore, D/T value for each reading was calculated as the geometric mean between the dilutions of the position at which odor was detected and the previous position.

Table 6: D/T values for the various plates of SM – 100 plates (H, A, 3, 2 and 1). As position increases, the extent of sample dilution with air decreases. Table supplied by SM-100 vendor (Scentroid/IDES, Ontario, Canada).

	Plate A		Plate 3	
Position	**Dilution Level**	**D/T result based on geometric mean of position's and previous position's dilution level**	**Dilution Level**	**D/T result based on geometric mean of position's and previous position's dilution level**
1	*678*	*-*	*656*	*-*
2	*319*	*499*	*328*	*492*
3	*176*	*248*	*219*	*274*
4	*98*	*137*	*164*	*192*
5	*62*	*80*	*131*	*148*
6	*35*	*49*	*109*	*120*
7	*24*	*30*	*94*	*102*
8	*17*	*21*	*82*	*88*
9	*13*	*15*	*73*	*78*
10	*10*	*12*	*66*	*70*
11	*8*	*9*	*60*	*63*
12	*7*	*8*	*55*	*58*
13	*6*	*7*	*51*	*53*
14	*5*	*6*	*47*	*49*
15	*4*	*5*	*44*	*46*

One dilution plate was used for a single experiment throughout the sampling period. The odor solutions of singular compounds had relatively lower initial and treated odor levels, and therefore plate A was used

in these sets of experiments to reach the finest resolution possible in D/T results. The odor solutions with ORS had higher starting odor levels had relatively higher initial and treated odor levels, and therefore plate 3 was used in these sets of experiments to reach the finest resolution possible in D/T results. The ranges of possible dilution of the odor samples and detected D/T values are shown in Table 7, for reference.

Table 7: Possible ranges of positions and D/T values associated with measurements from adsorption experiments of each air steam

Odor solution	Plate used in olfactometer	Range of dilution of plate	Range of positions detected (1-15 possible)	Range of D/T detected
ORS	3	44 - 656	3 - 13	274 - 53
H_2S+ ORS	3	44 - 656	2 - 14	492 - 49
Butyric Acid	A	4 - 678	4 - 14	6 - 137
p-Cresol	A	4 - 678	4 - 15	5 - 137
Indole	A	4 - 678	6 - 15	5 - 49

Odor Panel

An odor panel used olfactometry to determine the D/T for each sample of odorous air. A minimum of four people and up to six people participated in each set of adsorption experiments. In literature, generally between 4-10 panelists are used, with 8 being common [33]. For each of five odor solutions, the same odor panel sampled all treated and control samples of treated air. A total of 11 panelists participated in all adsorption experiments, and were assigned letters between A–K for anonymous identifiers. Table 8 shows which panelists participated in each experiment.

The odor panel, their olfactometry measurements, and the method of presentation conformed with standard methods according to VDI 3882 and EN 13725 [35] [36]. All panelists were trained. Panelists were instructed to avoid caffeine and spicy foods before olfactometry measurements. Measurements were carried out in a distraction-free environment. Panelists were instructed to not participate during times of obviously inhibited olfactory senses (i.e. when congested). In order to avoid odor fatigue, panelists were required to take olfactometry measurements for no more than one hour, after which an extended break was

required before continuing to take measurements. Panelists' results were screened for adequate olfactory sensitivity during each period of olfactometry measurement using an odor bag of particularly high odor concentrations, called a "screening odorant bag." In olfactometry literature, it is typical for a kind of screening with a reference gas to remove individuals outside a set deviation from panelist means [33][38][39][40]. For this study, the screening odorant was the same odorant or or combination of odorants used for the odor solution of that set of experiments. The concentration of the screening odorant was targeted at a concentration five times higher than the target concentration of malodors for that air experiment's odor solution (See Table 4 for target concentrations of each odor solution). An exception is for H_2S, which was only increased by a factor of 2 from the original target concentration. A 60 L odor bag was filled with the 5x-concentrated screening odorant. Panelists' results were screened for adequate olfactory sensitivity by measuring the screening odorant bag before and after all other olfactometry measurements during that testing period. Generally, a set of experiments would produce 40 odor bags for each panelist to test, and generally 10 bags were sampled during a single testing period. Therefore, panelists would complete a set of experiments in approximately 4 testing periods, and would measure the screening odorant bag approximately 10 times. An acceptable range of D/T detection levels were determined based on the average and standard deviation of all panelists' measurements [38][39]. Acceptable detection ranges for each set of experiments is shown in Table 8. In cases in which a panelist's screening odorant bag measurement falls outside the acceptable detection range, all of that panelist's results for that testing period were removed, as their olfactory sensitivity may have been compromised. Throughout the course of olfactometry measurements for all adsorption experiments, a total of 91 testing periods were performed by all panelists. Out of the 91 testing periods, there were 8 instances in which results from a testing period were removed due to the screening odor bag process. Relatedly, throughout the course of olfactometry measurements, four panelists out of 15 were deemed to have inadequate olfactory sensitivity to participate in the odor panel. These panelists were deemed inadequate by an inability to detect odor in the screening odorant bag after training, on several occasions.

Table 8: Odor panelists that participated in each set of adsorption experiments and the screening odor and concentration

Odor solution	Size of odor panel	Panelist participation	Screening odorant	Target concentration of screening odorant (µg/L)	Acceptable detection positions of screening odorant bag
ORS	4	A, D, E, F, G	ORS	Butyric: 2.5×10^{-2} p-Cresol: 1.5×10^{-2} Indole: 1.5×10^{-3}	2 – 4 (plate 3)
H_2S+ ORS	6	A, D, I, J, K, L	H_2S+ORS	Butyric: 2.5×10^{-2} p-Cresol: 1.5×10^{-2} Indole: 1.5×10^{3} H_2S: 400 ppb	3 – 6 (plate 3)
Butyric Acid	5	A, C, D, E, G	Butyric Acid	4.2×10^{-2}	5 – 7 (plate A)
p-Cresol	4	A, B, C, H	p-Cresol	4.2×10^{-2}	7 – 10 (plate A)
Indole	5	A, B, I, J, K	Indole	4.2×10^{-2}	7 – 10 (plate A)

H2S Meter

H_2S was measured with a Jerome 621 Gold Film Hydrogen Sulfide Analyzer (Arizona Instrument LLC, Chandler, AZ) and for odor level using the olfactometer. Input and output H_2S were measured for each time sample, for each flow-through column and batch odor bag. Because of the H_2S meter's old age, it was calibrated by measuring four bags of varying, known H_2S concentrations. A linear trend line was found to relate all measurements with an R^2 value of 0.99. The resulting calibration curve was used to adjust all H_2S measurements.

2.1.3 Selected Carbon Adsorbents

The activated carbon selected for adsorption experiments NORIT ROZ 3, ground to pass US 50 mesh size. NORIT ROZ 3 is an activated, peat-based, carbon, impregnated with minimum 2% potassium iodide [41]. It has a high degree of macro and mesopores [41]. Human fecal char made at 900° C were also used for the experiments. Wood chars made from pine and bamboo, made at 300° C and 900° C respectively, were also used initially. All biochars were ground to a size passing US 50 mesh size, and which represented a particle

diameter of 0.3 – 0.59 mm. Literature indicates that 0.3-0.4 mm is an ideal biochar particle diameter for gas-phase adsorption of hydrogen sulfide onto biochar [42].

Relevant char properties such as physical and chemical surface characteristics and packed bed density were found. Average pH of each biochar was measured to understand the surface chemistry of the chars. pH measurements were performed by Elizabeth Travis, M.S., of the Linden Lab at the University of Colorado Boulder. To measure pH, approximately 0.75 g of each sample was added to 15 mL of deionized water. This solution was placed on a shaker at 200 rpm for twenty-four hours before filtration by a syringe and 2-micron filter. The pH of the filtrate was then measured using a pH probe. A Brunauer–Emmett–Teller (BET) surface analysis was performed for the three biochars by Dave Rutherford at the USGS Lab in Denver, Colorado. In the BET analysis, surface area, pore volume, and pore size distribution were determined from nitrogen isotherms via a method that uses a five-point N_2 gas adsorption technique (ASAP 2020, Micrometrics) in which the relative pressure was run up to 0.98 atm. Analysis was performed by Dave Rutherford at the Unites States Geological Survey Laboratory in Denver, Colorado. Packed bed density was measured for each column in each flow-through experiment. The packed bed density reported for each char in this report was determined by averaging all measured packed bed densities for each that char throughout all experiments. Packed bed density was rather consistent through experiments; standard deviation between the values averaged values reported here was a nominal 1.5 to 2.1%. All characteristics, including feedstock and pyrolysis temperature and method, are summarized in Table 11 in *Section 2.2.1 Physical properties of chars.*

2.1.4 Batch Experiments

A batch adsorption test was performed for each odor solution, for each carbon. Approximately 20 mg of char was added to aluminum weighing boats and put in the bag (duct tape used to fix it) before sealing the bag. A mass flow controller was then used to deliver to the odor bags 30 L of odorous air from the odor

synthesis process (see Figure 5 in *Section 2.1.1 Latrine Malodor Synthesis*). The odor bags, serving as batch reactors for the adsorption process, reacted for a minimum of 48 hours before olfactometry measurements were taken by the odor panel. This time frame was determined by kinetic experiments (see *Section 2.2.1 Physical properties of chars.* The kinetic experiments were performed with varying doses of char and 30 L of odor solutions of malodor mixtures to conservatively show time to equilibrium for multiple conditions.

Odor bags

Odor bags were made from rolls of Nalophan bag (Scentroid/IDES, Ontario, Canada). Nalophan is a non-odor-sorbing plastic with a low odor background. One end of the bags was carefully folded against a piece of stainless steel tube (1/4-inch diameter) and sealed by using two zip ties. The open end of the bag was then folded against a piece of hollow stainless steel tube (1/4-inch outer diameter) and sealed by two zip ties. Norprene food tubing was attached to the stainless steel tube and the flow of air was turned on or off by pinching the tubing using a clip. All odor samples were collected in an odor bag and measured by the odor panel within 72 hours of collection. A picture of an odor bag is shown in Figure 20 in *Appendix C: Photos of Laboratory Set Ups.*

Calculations

To review, in performing calculations with olfactometry results, and specifically with the pseudo-dimension of O.U./m^3, great care must be taken [34]. All calculations including odor levels in units of O.U./m^3 followed the protocol described here. Additionally, each position on the olfactometer correlated to a unique D/T, and steps between positions were discrete and non-linear; a step between positions one and two represented a larger difference in D/T than did a step between positions ten and eleven. To be precise, for typical plate A positions recorded in adsorption experiment, the D/T value of a given position was on average 72.5% that of the previous position's D/T value, but the following position's D/T value was on average 76.6% that of the recorded position's D/T value. For typical plate 3 positions recorded in

adsorption experiment, the D/T value of a given position was on average 85.2% that of the previous position's D/T value, but the following position's D/T value was on average 87.5% that of the recorded position's D/T value. This meant that variability between panelists could be modeled as a normal distribution in the "position space," but in the "D/T space" the distribution was an unknown non-normal distribution. Therefore, any calculations including olfactometry measurements were performed in the "position space," then manually converted to a D/T value by interpolation of Table 6. This somewhat convoluted reasoning for working the "position space" perhaps is best explained by a simple, fictitious example summarized in Table 9. In the example, four panelists detect odor at positions 4, 6, 5, and 4 in plate A. The resulting odor level is averaged and upper and lower bound for error found by standard deviations first in the "position space" with manual conversion to D/T, and second in the "D/T space." The results for all calculations are notably different. The "position space" method is the statistically accurate method of performing calculations with olfactometer readings.

Table 9: A simple, fictitious example to explain error associated with calculations performed in the "position space" versus the "D/T space"

Panelist	A	B	C	D
Position recorded in plate A	4	6	5	4
Dilution level of position (D/T)	98	35	62	98
Corresponding D/T value based on geometric mean with previous position (O.U/m^3)	137	49	80	137
Average D/T value with upper and lower bounds based on standard error by calculation in the "position space" followed by manual conversion to D/T (O.U/m^3)		*Lower: 62* *Average: 94* *Upper: 160*		
Average D/T value with upper and lower bounds based on standard error by calculation in the "D/T space" (O.U/m^3)		*Lower: 57* *Average: 101* *Upper: 138*		

In summary, all calculations of a olfactometer reading output were performed in the "position space" and manually converted to a D/T value in O.U/m^3 before further calculations. In all equations of this report,

the variable "*position_D/T_conversion*" indicates this step. All important calculations and plots included in this report were performed in RStudio.

The adsorption capacity (q_c) of the chars was calculated according to Equation 3. Adsorption capacity is a primary property that provide information on adsorption characteristics and char's ability to adsorb odor. Q_c was calculated for each odor panelist's results for each batch experiment, then all calculated q_c values for a batch experiment were averaged to calculate the final, reported q_c value.

Equation 3: Adsorption capacity, q_c, for batch experiments

$$q_c = \frac{\left(Position_{control} - Position_{sample}\right) * position\_D/T\_conversion * V_{air}}{mass_{char}} ;$$

where $Position_{control}$ is the olfactometer position at which the panelist detected odor in the untreated batch control odor bag,
where $Position_{sample}$ is the olfactometer position at which the panelist detected odor in the treated batch odor bag,
V_{air} is the volume of odorous in the treated batch odor bag in m^3, and
m_c is the mass of char used to treat the batch odor bag, in g.

Confidence intervals for q_c in batch experiments were calculated according to Equation 6, Equation 7, Equation 8, and Equation 9 in *Section 2.1.5 Flow-through Experiments* with a $n_t = 1$, assumed by modeling the batch reactor as a single time step in the method of calculating confidence intervals over several time steps.

In understanding adsorption characteristics, q_c must be used intimately with the appropriate equilibrium concentration, C_e, in that experiment. For batch experiments, C_e was defined as the odor level of the treated batch odor bag, as determined by averaging the odor panelist's results as described in *Section 2.1.2 Odor Measurement*. The error associated with C_e values for the batch experiments was calculated as the standard deviation of odor panelist results. Although other sources of error may have influenced experiments, it is

expected that variability in the odor panel is, very significantly, the primary source of error and therefore the only consideration in most error calculations of this report.

The odor removal percent in batch experiment was calculated according to Equation 4. The odor removal percent was calculated for each odor panelist's results for each batch experiment, then all calculated odor removal percent values for a batch experiment were averaged to calculate the final, reported value. The error associated with odor removal percent values for the batch experiments was calculated as the standard deviation of odor panelist results.

Equation 4: Odor removal percent calculation for batch experiments

$$Odor\ removal\ percent = \frac{1 - Position_{sample}}{Position_{control}} * position\_D/T\_conversion * 100\%$$

2.1.5 Flow-through Experiments

A batch adsorption experiments was performed for each odor solution, for each char. The odor solution, after synthesis was directed to four glass adsorption tubes of 6 mm inner diameter containing char packed to a height of 30 cm. A Dwyer VFA Flowmeter (Dwyer Instruments, Michigan City, IN) controlled the flow rate of odorous air into the packed char columns. A flow rate of 189 ml/min was used, which was made to be above the flow rate of the H_2S meter used (150 ml/min) and set to a constant contact time of 2.7 seconds, as determined by kinetics experiments. Synthesized odor that did not pass through the char columns was wasted to a fume hood, along with column effluent. Column operating conditions are summarized in Table 10. The schematic in Figure 5 illustrates the flow-through experimental set up. A picture of the actual set up inside a fume hood is shown in Figure 22 in *Appendix C: Photos of Laboratory Set Ups.*

The kinetics experiment was performed until identical conditions as subsequent flow-through experiments, except that activated carbon was used in all columns, and flow rate was varied instead. Flow rate of odorous air through the columns was varied in order to vary contact time at 0.5, 1.7, and 3.6 seconds. The range of typical contact times for flow-through adsorption columns is 1-10 seconds. Logistical barriers in experimental set up (resolution of flow controllers into columns, and time needed to collect adequate quantity of samples from the column effluent) prohibited a contact time above 3.6 seconds.

Table 10: Column operating parameters

Operating Condition	Value	Units
Contact time	2.7	seconds
Bed volume	8.5	cc
Aspect ratio	50	
Average bed density	0.425	g/cc
Char size: column diameter ratio	15	
Relative Humidity	64%	
Water loading rate	2.37	g-water/g-char

Calculations

The adsorption capacity (q_c) of the chars was calculated according to Equation 5. This equation describes mathematically approximated integration of the area between column influent and effluent values over time until breakthrough (see in *Appendix A: Breakthrough Curves*), divided by the mass of char in the packed column. Q_c was calculated for each odor panelist's results for a flow-through experiment's results, then all calculated q_c values for a batch experiment were averaged to calculate the final, reported q_c value.

Equation 5: Adsorption capacity, q_c, for flow-through experiments

$$q_c = \frac{\sum_{i-1}^{n}\left(Position_{control,i} - Position_{sample,i}\right) * position\_D/T\_conversion * V_{air,i}}{m_c} \ ;$$

where $Position_{control,i}$ is the olfactometer position at which the panelist detected odor in the influent odor bag for the i^{th} time step,
where $Position_{sample}$ is the olfactometer position at which the panelist detected odor in the effluent odor bag for the i^{th} time step,
$V_{air,i}$ is the volume of air assume to flow through the column over the time step of interest according to the midpoint numerical approximation method of integration, in m^3, and
m_c is the mass of char in the packed column, in g.

A confidence interval was calculated for each integrated q_c value according to Equation 6, Equation 7, Equation 8, and Equation 9. This process outlines finding the sample variance, standard error, margin of error, and finally confidence interval for all q_c calculations.

Equation 6: Sample variance of flow-through experiment results, for all odor panelists, over all time steps

$$s^2 = Var\left(\sum_{i=1}^{n_t} Position_i\right) = \sum_{i=1}^{n_t} Var(Position_i) + 2 \sum_{i=1,j=1}^{i=n_t,j=n_p} Cov(Position_i, Position_j) \ ;$$

where n_t is the number of time steps,
n_p is the number of panelists, and
$Position_{i,j}$ is the D/T result for all odor panelists (i), over all time steps (j).

Equation 7: Standard error for q_c of flow-through experiments

$$SE = \sqrt{\frac{s^2}{n_q}} \ ;$$

where SE is the standard error, and
n_q is the number of time steps times the number of panelists.

Equation 8: Margin of error for q_c of flow-through experiments

$$ME = t_{(1-\alpha),(n_q-1)} * SE\ ;$$

where ME is the margin of error, and
*$\propto$ is the p-value for a confidence level of (1-$\propto$)*100%.*

Equation 9: Confidence interval for q_c

$$[Confidence\ interval\ \rightarrow\ (q_c - ME)] * position\_D/T\_conversion \leq q_c \leq [(q_c + ME) * position\_D/T\_conversion]$$

For flow-through experiments, C_e was defined as the average odor level of the column influent, as determined by averaging the odor panelist's results as described in *Section 2.1.2 Odor Measurement*. The error associated with C_e values for the batch experiments was calculated as the standard deviation of odor panelist results for all column influent measurements.

Use rate was calculated according to Equation 10. Use rate is a simple way to interpret one result of a breakthrough curve; it tells us what quantity char can treat a quantity of air until saturation.

Equation 10: Use rate for flow-through experiments

$$Use\ rate = \frac{m_c}{breakthrough * BV}\ ;$$

where m_c is the mass of char in the packed column, in g,
breakthrough is the number of BVs treated until saturation is achieved, as defined by Figure 9, and
BV is the volume of the column's packed bed, in m^3.

2.2 Results

2.2.1 Physical properties of chars

The BET surface analysis of the biochars, along with published properties of the manufactured activated carbon, are summarized in Table 11. Also included in Table 11 are surface pH and pyrolysis information. Pine char had a notable surface area and pore volume, at one to two orders of magnitude lower than the

other chars. Activated carbon had a total pore volume an order of magnitude higher than fecal char and bamboo char. Bamboo char had a very high fraction of total pore volume in micropores, and pine char's micropore volume fraction was very low. While surface pH is unknown for the activated carbon, fecal char had the most basic surface.

Table 11: Char properties for activated carbon, fecal char, bamboo char, and pine char used in adsorption experiments

Property	Activated carbon (NORIT ROZ 3)*	Fecal Char	Bamboo Char	Pine Char
Feedstock	Peat	Human feces	Bamboo	Pine
Pyrolysis Temperature	-	900° C	900° C	300° C
Pyrolysis Technology	-	Furnace	Furnace	Furnace
pH**	-	11.28	9.96	9.59
Surface Area (m^3/g)	-	89.9	146	0.7
Pore Volume (cc/g)	0.84	0.081	0.091	0.001
Micropore Volume Fraction	0.38	0.26	0.87	0.07
Mesopore Volume Fraction	0.13	0.68	0.12	0.67
Macropore Volume Fraction	0.49	0.06	0.01	0.26
Micropore Volume (cc/g)	0.32	0.021	0.079	0.000070
Mesopore Volume (cc/g)	0.11	0.055	0.011	0.00067
Macropore Volume (cc/g)	0.41	0.0049	0.00091	0.00026
Density of packed bed (g/cc)***	0.39	0.47	0.35	0.49

Blank cells indicate that value is unknown
** Pore volumes for activated carbon from Boppart, 1996 [41]*
***Surface pH values for biochars from Travis, 2014 [3]*
**** Packed bed density calculated from results of this research, as explained in Section 1.3.2 Biochar*

2.2.2 Batch experiments

Batch Kinetics

The batch adsorption kinetics experiments were performed to determine how much time should be allowed for adsorption to reach equilibrium. The kinetic experiments were performed with varying doses of char

and 30 L of odor solutions to conservatively show time to equilibrium for multiple conditions. It was assumed that kinetics for adsorption of singular malodor compounds, with smaller char doses, would require the same or shorter time to reach equilibrium. Results for all experiments that adsorption of 30 L of odorous air reached equilibrium after 48 hours, as shown in Figure 6. This result informed following batch adsorption experiments in that a minimum of 48 hours was allowed for adsorption before olfactometry measurements were taken to determine odor removal. Furthermore, odor levels did not significantly degrade in the odor bags between 48 hours to 72+ hours.

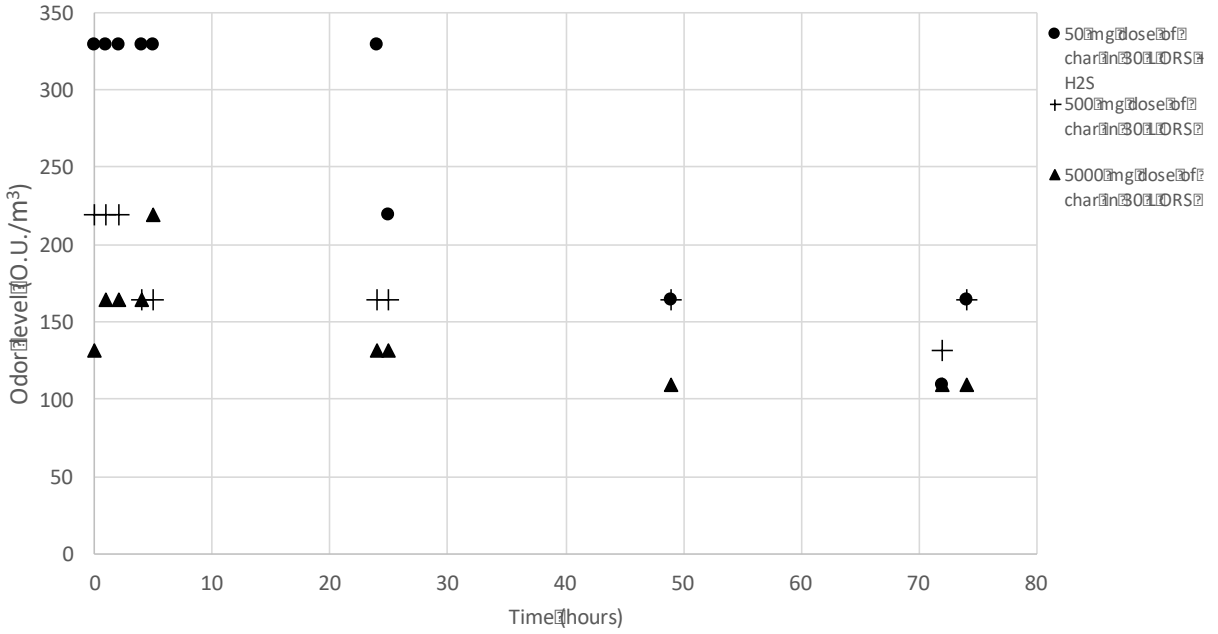


Figure 6: Batch adsorption kinetics experiments.

Percent removal

The batch experiments were considered to show the maximum removal capacity of each char to remove each malodor because a known amount of char was given time to reach adequate equilibrium with a known amount of odor. Results are shown in Figure 7. A high removal percent indicates better adsorption by the char, and better result towards the goal of removing malodor with biochar. All removal percentages ranged between 20% to approximately 60%, with the median at 42%. ORS and ORS+H_2S experienced the highest removals. Of the individual non-sulfur malodors, butyric acid generally experienced higher removals. Consistently, pine char has the worst odor removal ability. There was significant error associated with

these results due to variability in odor panelists' results. Based on the variability, the removal rates that possibly were close to non-detectable were bamboo char's ability to remove indole, and fecal and pine char's ability to remove p-cresol.

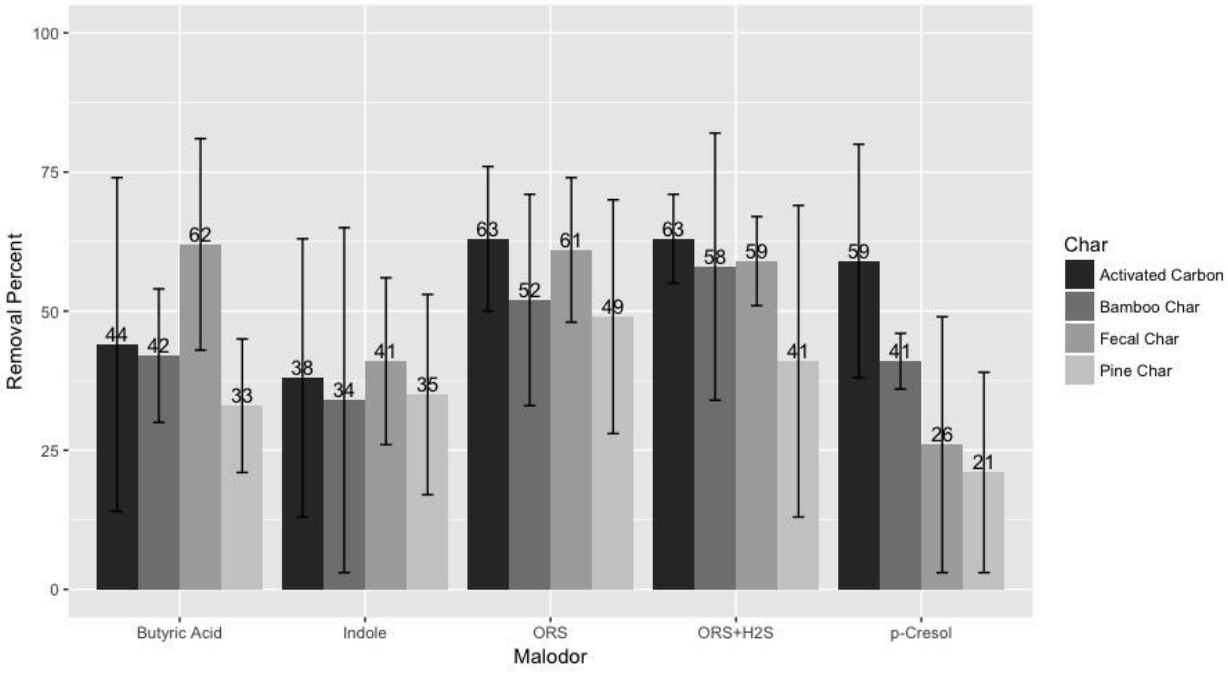


Figure 7: Percent removal of malodor by olfactometry measurements of D/T. Error bars represent standard error of odor panel data.

Table 12 shows the starting and lowest treated odor levels achieved by adsorption in the batch experiments and dynamic experiments. The non-sulfur malodors in mixture (ORS) led to an odor detection threshold an order of magnitude higher than in singularity, indicating the synergistic quality of some human fecal malodors. However, there was not a large difference in odor detection threshold when H_2S was added to the mixture, which could indicate an antagonistic quality of H_2S odor with the others.

The initial odor levels are important to provide insight to the relationship between concentration of odor molecules, and odor level perceived by the odor panel olfactometry; despite equal initial concentrations of odor compounds, different compounds in singularity and in mixture were detected at different levels by the odor panel. This speaks to the nonlinearity of human olfactory senses, and indicates that odor in mixture have would lead to worse malodor nuisance, as in case of a latrine. A noteworthy limitation of this research

is the low odor levels for the butyric acid, indole and p-cresol odor solutions through experiments. These low detection levels create a more significant challenge because there is more variability in human olfactory senses at such low concentrations [37].

Table 12: Average initial and treated odor concentrations for all tested odor solutions

	Batch experiments		***Flow-through experiments***	
Odor Solution	***Initial D/T level***	***Lowest treated D/T level***	***Initial D/T level***	***Lowest treated D/T level***
ORS	*173*	*73*	*110*	*58*
ORS+H2S	*181*	*49*	*-*	*-*
Butyric Acid	*15*	*7*	*34*	*8*
Indole	*23*	*12*	*18*	*7*
p-Cresol	*15*	*7*	*23*	*7*

Note: Odor panel did not measure odor levels for flow-through experiments of ORS+H2S adsorption

2.2.3 Flow-through Columns

Continuous-flow kinetics

In order to determine an appropriate contact time, a kinetics experiment was performed with three columns of activated carbon to treat an air stream of the ORS odor solution, as described in *Section 2.1.5 Flow-through* Experiments. Figure 8 shows the results of this kinetics experiment, which indicate noticeable differences in the three studied contact times; 0.5 seconds was inadequate to allow for adsorption processes, 1.7 seconds broke through up to twice as fast as 3.6 seconds. It would be helpful to see how, or if, this time to breakthrough would change at longer contact times. For this research, 3.6 seconds was the absolute maximum achievable based on time and flow restrictions in the experimental set up. These results led to a decision for a 2.7, which was seen as near 3.6 seconds, but significantly more reliable in collection of adequate sample quantity. However, this decision represents a major limitation of this study; at 2.7 seconds, complete odor removal was not achieved, indicating the possibility of an inadequate time to allow for full mass transfer. If the contact time could be increased beyond 3.6 seconds and breakthrough curves were plotted on Figure 8, they may have achieved a continually lower initial breakthrough until zero

breakthrough, or until increased contact time resulted in constant initial breakthrough. The result that initial breakthrough of odor level lowered between the 1.7 s and 3.6 s contact times indicates that the chosen contact time of 2.7 s still resulted in mass transfer rate limitations such that maximum adsorption was not achieved; therefore, the minimum contact time to avoid limitation by mass transfer rate remains unknown. The implications of this may been seen in the results shown in Figure 9, as explained in the following section, *Breakthrough*.

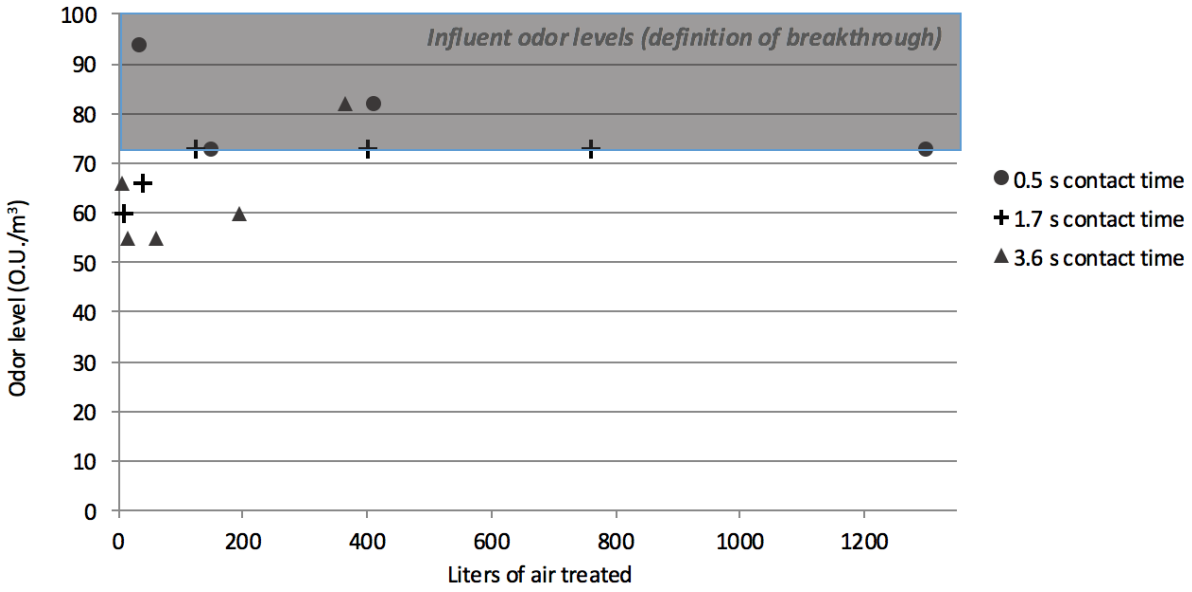


Figure 8: Flow-through kinetic experiment results. The grey box represents influent odor levels, and therefore definition of saturation.

Breakthrough

Results of the flow-through experiments were plotted as breakthrough curves in three separate manners:

- First, by plotting direct D/T results of the odor panel versus bed volumes (BVs) for all columns and the influent (Figure 16 in *Appendix A: Breakthrough Curves*).
- Second, by plotting normalized D/T results of the odor panel (C_e/C_o) versus BVs for all columns (Figure 9). This method was perhaps the most straightforward to understand, and is therefore reported in the body of this report.
- Third, by plotting normalized D/T results of the odor panel (C_e/C_o) versus BVs for all columns and the influent, defined by C_0/C_{avg} (Figure 17 in *Appendix A: Breakthrough Curves*).

Figure 9 shows that for all chars and odor solutions, there is initially breakthrough around 50%. This is inconsistent with an expected breakthrough curve, as initially there is normally no breakthrough of an adsorbent. This is likely due in part to the residual odor of the chars being picked up by the odor panel. However, the fact that the ORS curve had initial breakthrough significantly above the residual odor level of the char indicates that there likely must be another, or additional, explanation for immediate breakthrough around 50%. One likely explanation is that the contact time through the columns was too short to allow for full removal (see reasoning in *Continuous-flow kinetics,* above). Another possible explanation is the non-linearity of the human olfactory senses; it is possible that if a miniscule concentration of a malodor broke through, an odor panelist would detect this odor at a similar level to a higher concentration. However, the linearity or lack of in olfactory odor detection is unknown for these particular odorants. Nevertheless, at particularly low odor concentrations such as those exhibited by the treated odor solutions of singular compounds, it has been shown in literature that, indeed, olfactory senses are not linear [37]. However, the linearity, or lack of, in olfactory odor detection is unknown for these odorants.

p-Cresol experienced the highest variability, particularly for adsorption by the three biochars. This may be explained by the low adsorptive capacity of these chars, as shown in the batch adsorption experiments (see *Section 2.2.2 Batch experiments*). If not much is being removed, there may be higher variability in the odor panel's results due to nonlinearity and low odor levels.

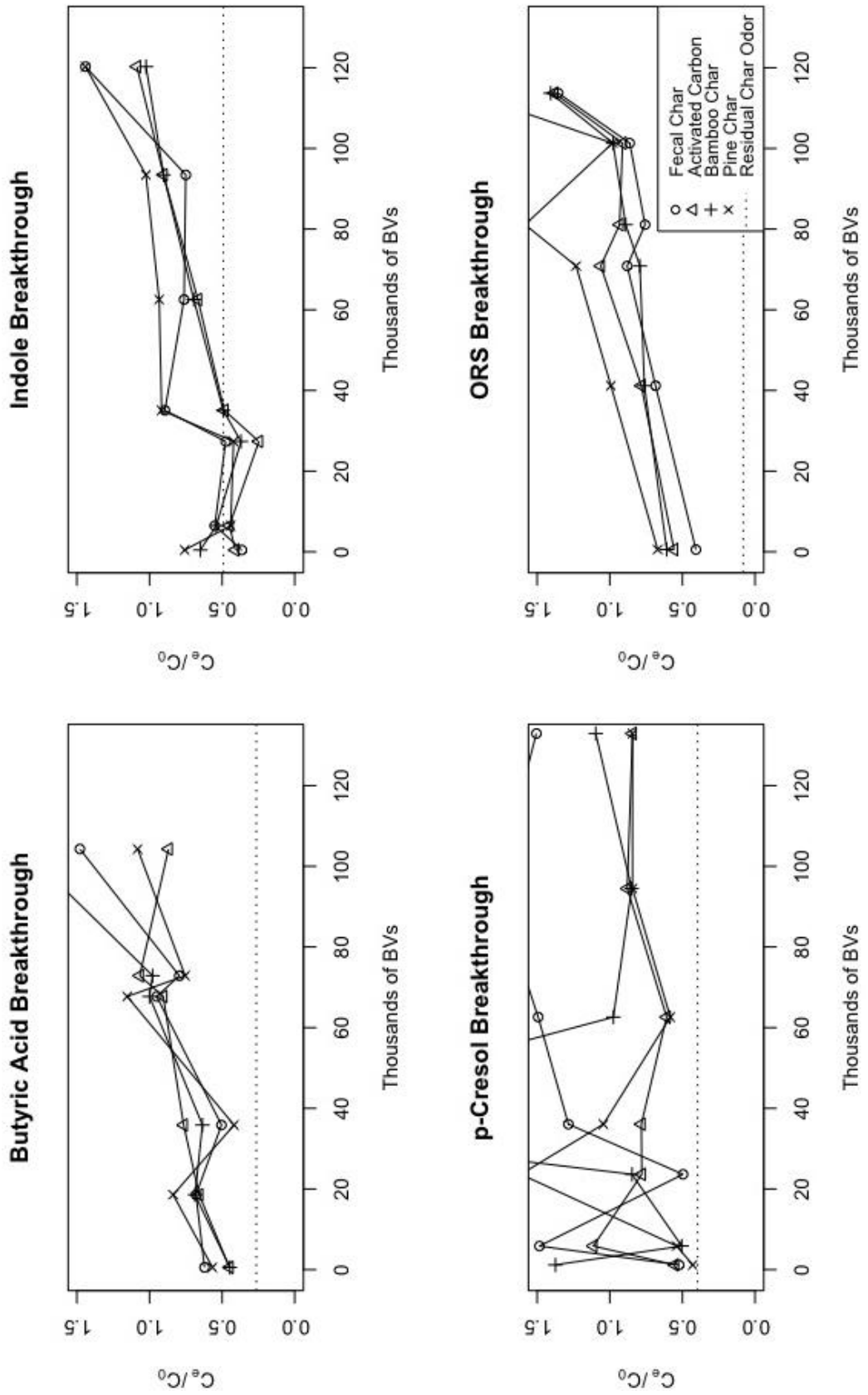


Figure 9: Breakthrough curves of flow-through adsorption experiments for all odor solutions treated by all char types, normalized by (variable) influent odor levels. Theoretical definition of breakthrough, or full saturation, is 1.0. However, due to error in odor panel results, breakthrough may be defined at C_e/C_0 value of between 0.85 - 1.0 or above. Theoretically, values of C_e/C_0 cannot exceed 1.0. However, to due variability of influent levels over time, and error odor panel results, exceedances of C_e/C_0 over 1.0 are recorded.

In measurement of breakthrough in ORS+H_2S experiments, the odor panel was not used and therefore ODT and q_c in units of O.U./m^3 was not found. Instead, only H_2S was measured with an H_2S meter, and results are shown Figure 10 below and in Figure 18 in *Appendix A: Breakthrough Curves.* H_2S breakthrough occurs immediately given the resolution of the sampling frequency. Activated carbon treated the most H_2S until saturation. Fecal char and activated carbon treated much more H_2S until saturation compared to the other two biochars, and did not breakthrough until after a dramatic 250,000 BVs. This is about twice as many BVs of treatment compared to flow-through adsorption experiments of other malodors, and there was no immediate breakthrough as in other experiments. Pine char, as in other adsorption experiments, exhibited the poorest adsorption of malodor.

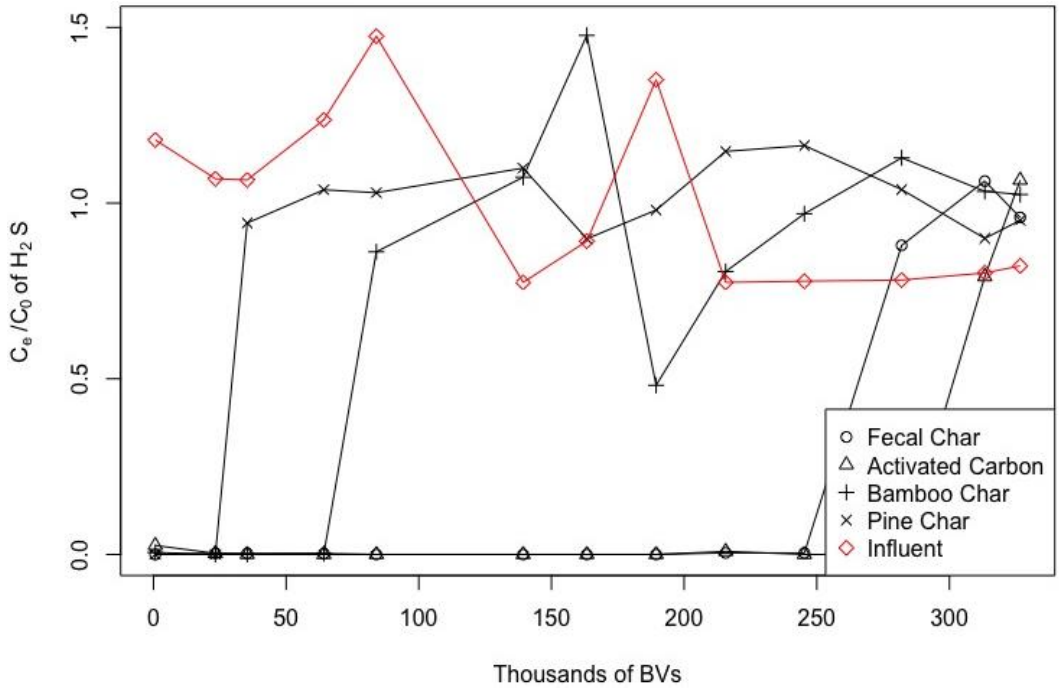


Figure 10: Breakthrough curves for H_2S in flow-through adsorption experiments of ORS+H_2S treated by all char types (normalized by variable influent odor levels). The normalized variable influent odor curved is also shown in red, which is defined by $C_0/C_{0,avg}$. Definition of saturation is when C_e/C_0 passes 1.0.

<u>*Use Rate*</u>

Use rate was calculated and results shown in Figure 11. Use rate is a simple way to interpret one result of a breakthrough curve; it tells us what quantity char can treat a quantity of air until saturation. However, it does not indicate to what level odor was treated until saturation was achieved. Results are consistent with batch experiments in that pine char consistent shows worst capacity for odor removal (highest use rate),

while the other three chars are comparable with activated carbon generally showing best results. The high error associated with adsorption of the p-Cresol odor solution is consistent with the high variability in its breakthrough curves (see Figure 9). Char use was most effect for removal of ORS+H_2S, followed by indole and ORS.

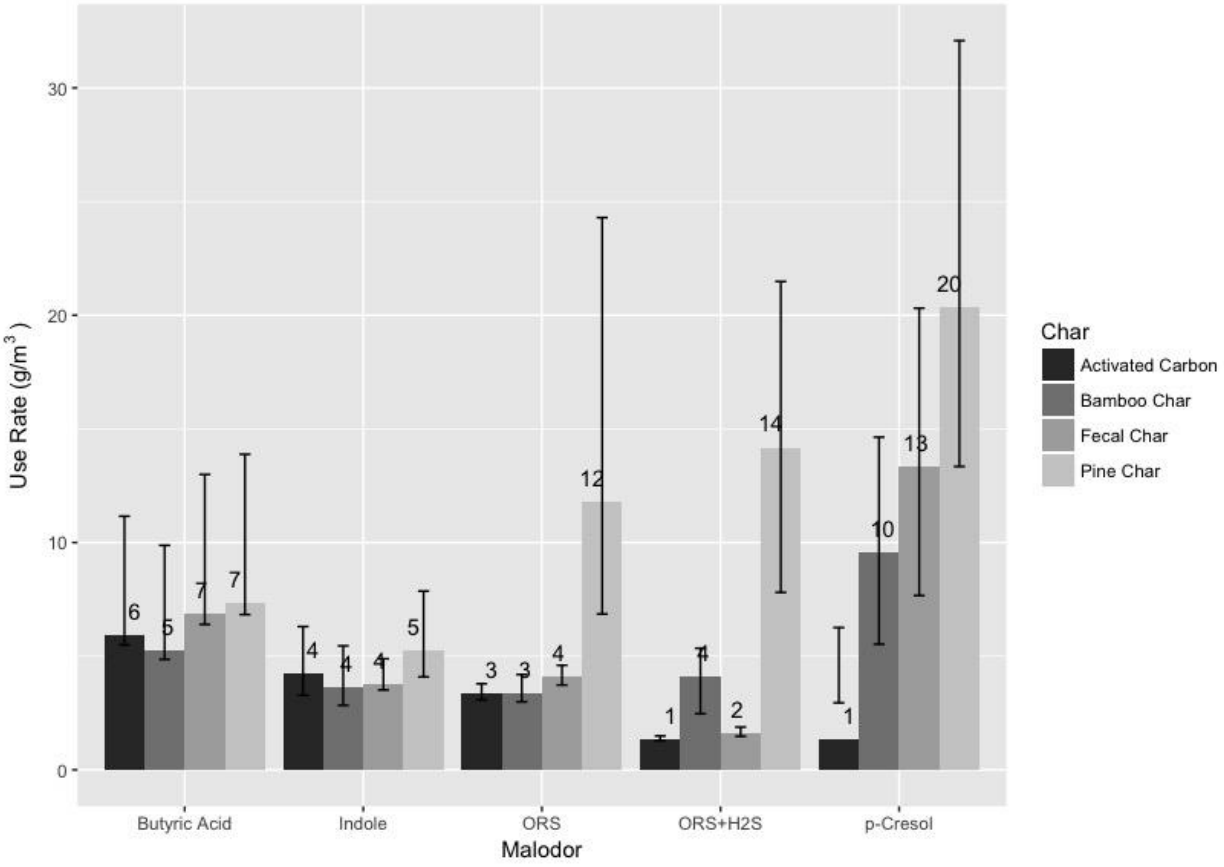


Figure 11: Use rate of each char in treatment of each odor solution. Use rates are based on time to breakthrough in flow-through experiments. F bars represent error in the determination of the time to breakthrough; upper error was calculated assuming breakthrough as the previous data point on the breakthrough curve, and lower error was calculated assuming breakthrough as the following data point on the breakthrough curve. Therefore, the percent error on the chart corresponds directly to the resolution of sampling frequency.

2.2.4 Adsorption Isotherms

Adsorption capacity, q_c, with 90% confidence intervals, and C_e values, with standard error were calculated for each batch and flow-through experiment. A plot of q_c versus C_e represents an isotherm. Each char's adsorption of each odor solution produced one measured value of q_c at an equilibrium concentration, and therefore one point on that context's adsorption isotherm. Since a batch and flow-through experiment were performed for each char and odor solution combination, two points for each experiment type were plotted

on the same plot, but each representative of that experiment type's adsorption. These plots with isotherm data are shown in

on a log-log scale, and in Figure 19 in *Appendix B: Adsorption Isotherm Plots* on a linear scale. In understanding this data, it is vital to delineate fundamental differences between the batch and flow-through data points; these two points do not belong on the same isotherm because the parameters for adsorption were different, and could even have led to different adsorption mechanisms based of forced (flow-through) versus passive (batch) adsorption. Instead, the data points should be understood as a single data point on each isotherm, but are placed on the same plot for comparison's sake. Each data point is expected to be a point on a linear curve with a positive slope.

shows that flow-through capacities were consistently lower than batch capacities, despite operating at a higher C_e. The relationship of two data points on each plot indicates that like the flow-through isotherm lies below the batch isotherm. This leads to the conclusion that batch experiments led to to notably better adsorption than flow-through experiments. Hypotheses for this includes inadequate contact time in the column that leads to faster breakthrough, and column fouling by water vapor. Columns and bags were operating at a RH of 64%. For most GAC adsorbents, water adsorption is significant when RH is above about 40% [43]. When this happens, capillary condensation occurs in the column, meaning water vapor condense in the micropores and complete for adsorption sites, which could significantly reduce adsorptive capacity for odors. However, a high humidity such as this leads to greater water vapor loading onto the char over a longer time of operation. The water vapor loading rate depended upon column density and time to breakthrough, but the average column contained 3.60 g of char and the average time to breakthrough was 80.3 BVs, which led to an average water loading rate of 2.37 g-water/g-char ± 0.67 g-water/g-char. Crittenden et al. [44] developed isotherms for water vapor loading onto several activated carbons. Although NORIT ROZ 3 was not included, the operating RH of 64.4% for these experiments led to significant adsorption by the activated carbons studied, up to 0.5 g-water/g-carbon. At 64.4%, all activated carbons

had already experience to portion of the isotherm of rapidly increasing adsorption, and neared a maximum value. Based on this significant water vapor loading rate by a high RH, and known competition of water vapor with other adsorbates, it is likely that fouling by water vapor occurred in the columns. High humidity is a likelihood in many latrine settings, and the implications of fouling by water vapor are discussed in more depth in the discussion of this report. In addition to fouling, there may have been further inhibition by inadequate contact time (see reasoning in *Continuous-flow kinetics,* above), but even mass transfer rate limitations likely would not account for inhibition that resulted in an order of magnitude lower capacity.

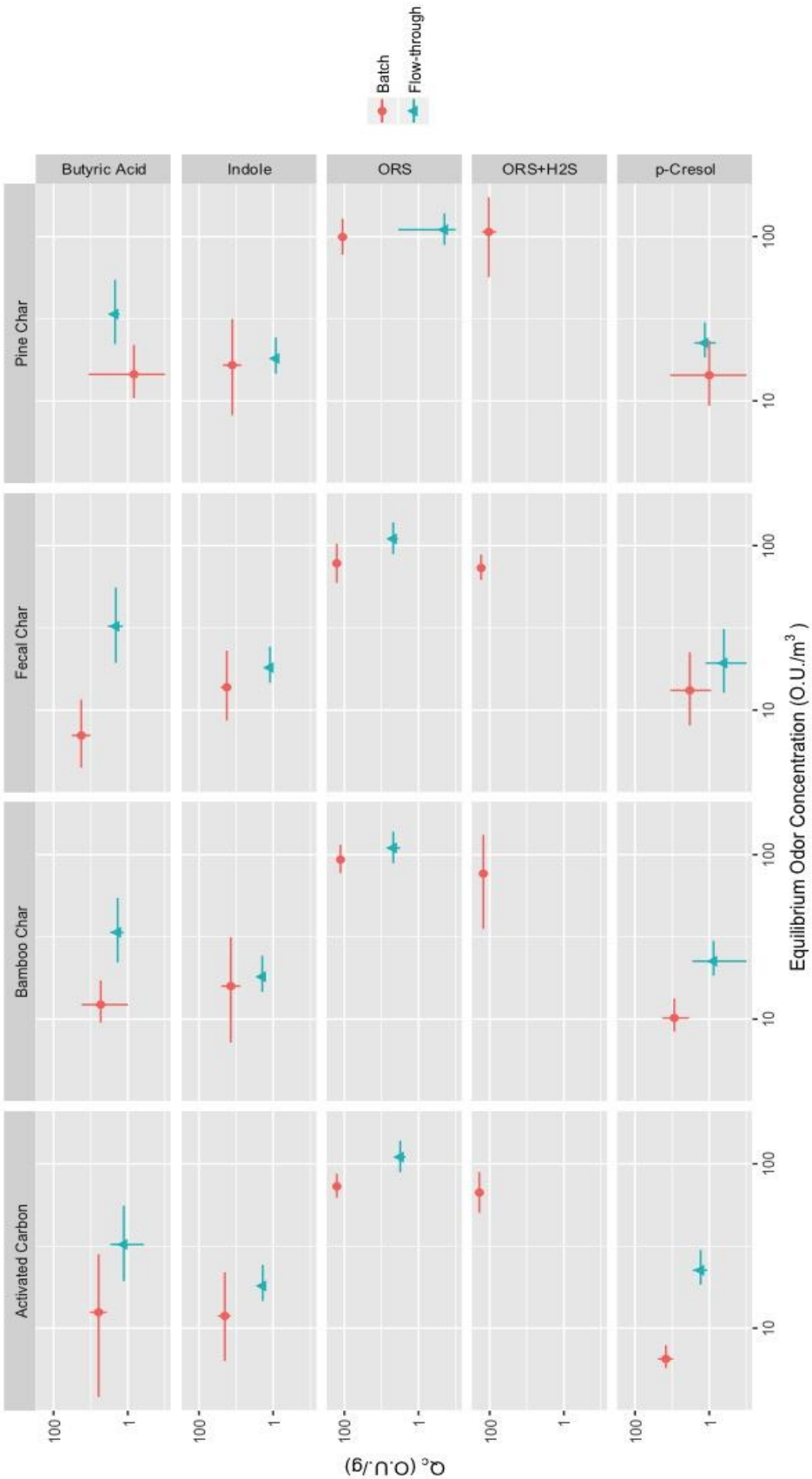


Figure 12: Adsorption experiment data plotted on isotherms plots for all four chars' adsorption of the odor solutions on a log-log scale. Each isotherm plot has two points on it: one for the batch adsorption experiment, and one for the flow-through adsorption experiment. On a log-log plot such as this, a typical isotherm should be a straight line with a positive slope. ODT was not measured for ORS+H_2S for flow-through experiments

An isotherm plot was not created for ORS+H_2S experiments in terms of q_c in units of mg-H_2S/g-char because batch adsorption experiments did not result in a defined q_c value because all H_2S was adsorbed in all experiments. Additionally, the flow-through adsorption experiments operated at the same equilibrium concentration. Therefore, the adsorptive capacity found for H_2S adsorption capacity in mixture with other odor compounds is summarized for all chars in Table 13. The capacity found for activated carbon is consistent with both typical values for chemical and physical adsorption of H_2S: Bandosz et al. [45] found chemical adsorption capacity that ranged from 5-295 mg-H_2S/mg-char and Turk et al. [23] found physical adsorption capacity that was around 10 mg-H_2S/cm^3-char, or ~30 mg-H_2S/g-NORIT ROZ 3 activated carbon. The capacities found for fecal char and bamboo char are similar to values found by Travis, 2014 [3] of 37.6 and 4.97 mg-H_2S/mg-char, respectively. The first trial for ORS+H_2S flow-through adsorption experiment experienced a sudden, unplanned interruption in operation, after which pine char had experienced H_2S breakthrough but no other chars had. When the columns were restarted several days later, pine char continued to adsorb all H_2S for until a similar quantity of BVs were treated. This unexpected result leads to two hypotheses. First, that H_2S in the pine char column had been reversed, and all H_2S volatized into the headspace surrounding the column. Reversible adsorption would be indicative of a physical adsorption process of H_2S. A second hypothesis is that during the break in intermittent operation, adsorption of water vapor was reversed and also volatized into the headspace surrounding the column. In a sense, this would indicate regeneration of the char by allowing it to "dry out."

Table 13: Adsorptive capacities for H_2S adsorption in flow-through ORS+H_2S adsorption experiments

	Activated carbon	**Fecal Char**	**Bamboo Char**	**Pine Char**	**Units**
Calculated q_c	28.5 ± 2.8	25.6 ± 3.3	7.6 ± 1.8	3.2 ± 1.1	mg-H_2S/mg-char
C_e	298 ± 74	298 ± 74	298 ± 74	298 ± 74	ppb H_2S

Error associated with reported q_c values represent the error in the course sampling frequency over time in the flow-through experiments. Error associated with reported C_e values represent the standard deviation of variable influent H_2S levels over the course of the experiment.

2.3 Discussion

2.3.1 Adsorption ability

The adsorption capacities from the batch experiments were used to understand the theoretical ability of activated carbon and biochar to adsorb latrine odor. The batch results were used in this capacity, and the flow-through results were ignored for three reasons. First, batch tests were more reliable because they did not experience significant fouling like flow-through tests did. Second, batch tests represented a theoretical maximum for adsorption because of reactor configuration. Third, batch tests were more comparable between odor solutions because C_e for all odor solutions with singular compounds were very close, but were more varied in flow-through experiments.

Figure 13 displays a simple view of the adsorption capacities found from all static experiments, for sake of a quick comparison. For the odor solutions of singular malodors, adsorptive capacity ranged between from non-detectable up to 20.1 ± 10.4 O.U./g, depending on the char and the malodor, at an average C_e of 11.5 ± 4.2 O.U. For the mixtures of malodors, capacity averaged an order of magnitude higher, at 146 ± 29 O.U./g, at an average C_e of 83 ± 14 O.U. These results represent a significant reduction of odor for a small amount of char.

However, in all scenarios, 40-50% of odor was usually removed, with a minimal removal close to 20% and a maximum removal above 60% (see Figure 7). This also represents a significant reduction in odor levels. While the quantity of malodor molecules removed is unknown, methods of this research result in a measurement of reduction of odor detection by humans. A potential reduction in the level of malodor nuisance of a latrine by half, using adsorption onto biochar, could represent a significant benefit from a simple technology.

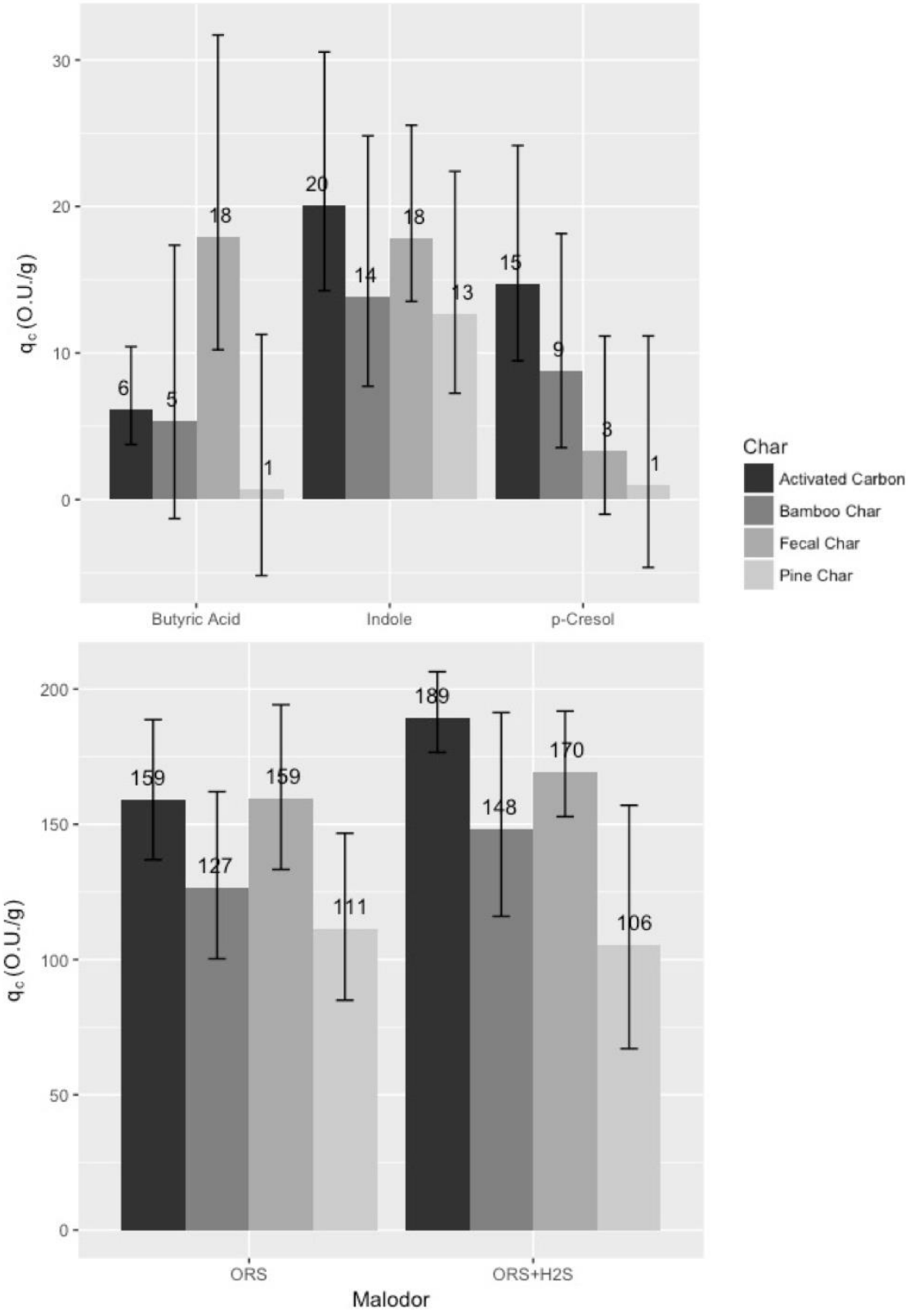


Figure 13: Adsorptive capacity, q_c, for all static experiment tests. Error bars represent the standard error associated with odor panel variability.

Ignoring some failures of adsorption by pine char, and some failures of adsorption of p-cresol, all malodors tested were able to be adsorbed by all chars. In continuous-flow operation, saturation was not achieved until an impressive average of 80,300 BVs, and some biochars achieved well over 100,000 BVs. Despite differences in adsorption characteristics and adsorptive inefficiencies during continuous-flow operation, all chars adsorbed odor somewhat comparably to a leading modified activated carbon for gas-phase adsorption.

2.3.2 Influence of char and malodor properties

When comparing the chars' adsorption characteristics, results from the p-Cresol odor solution will be largely ignored due its relatively low capacity and resulting high variability; at such low values, it is difficult to delineate differences. In evaluation of the adsorption of each odor solution, errors bars between all chars overlap and adsorption capacities were similar, for the most part. Therefore, a primary result of this work is that all char are acceptable adsorbents. Nevertheless, pine char had consistently the lowest adsorptive capacity. Pine char also had starkly worse surface characteristics for adsorption; pore volume was an order of magnitude lower than other chars, and surface area was 2-3 orders of magnitude lower than other chars (see Table 11). This presents a likely explanation for pine char's poor performance compared to other chars.

Because the rest of the chars exhibit more acceptable surface area and pore volume, their performance is compared to each other in regard to adsorption of each malodor. In indole adsorption, performance between chars is so similar that a definitive conclusion about ideal pore structure is difficult. However, indole has the largest K_{ao} (see Table 3), which is likely indicative of its overall notably better adsorption than butyric acid and p-cresol. Similarly, adsorption of p-cresol was non-definitive in comparison between biochars due to the process's high variability and low adsorption. In adsorption of butyric acid, fecal char outperforms activated carbon and bamboo char. Based on the differences in pore volume fractions between chars, this could indicate an affinity of butyric acid for adsorption in mesopore sites; while activated carbon has the largest volume in each type of pore, the mesopore volume in fecal char is the only pore volume of

a biochar that is on par with that of activated carbon (see Table 11). The importance of mesopore volume in adsorption is further supported by the evidence of fouling by water vapor; water likely filled the micropore sites, so that adsorption of malodors primarily occurred in the mesopore. Otherwise, the consistently high adsorption by activated carbon followed by fecal char is likely a result of activated carbon's highest surface area and pore volume.

H_2S has the largest K_{aw} (see Table 3) but smallest K_{ow}, and experienced very good adsorption in relation to other malodors. The high K_{aw} may indicate that more of this malodor partitioned into the aqueous dissolved phase in the presence of humidity before adsorption. Additionally, the low K_{ow} but high adsorption may be explained by a hypothesis that H_2S was not physically adsorbed to the extent that other malodors were, but instead was chemically adsorbed. For hydrogen sulfide, the likely mechanism for this process is catalytic oxidation of H_2S to elemental sulfur. In this process, after water is adsorbed onto the carbon's surface, H_2S and oxygen dissolve into the water. Within the water-filled pores, oxygen radicals react with hydrogen sulfide ions to form elemental sulfur and water [46].

2.3.3 Importance of Humidity

This research shows that humidity can have a significant inhibitory effect to odor adsorption by char. For all experiments, the difference between the flow-through and batch q_c was calculated. The median was 89%, meaning the flow-through q_c was typically 11% that of the batch q_c, or an order of magnitude lower, despite a higher equilibrium concentration.

This is of particular importance to FSM settings, as generally a latrine pit, depending upon quality of ventilation, would have very high humidity. In addition, many developing countries experience temperate, humid climates. While fouling by humidity may have detrimental effects to filter performance, simple regeneration may also be possible by allowing physical sorption of char vapor to reverse and desorb, then

evaporate. To understand the implications of humidity better, and possible regeneration or reversal of water vapor adsorption, these variables should be included in future field trials.

CHAPTER THREE: IMPLICATIONS

3.1 General Conclusions

This research has served as a proof-of-concept that biochar can effectively adsorb latrine malodor and can perform as a comparable alternative to modified activated carbon. Furthermore, it was shown that an array of biochars could adsorb odor successfully, which indicates that type of biochar used in a specific context is flexible; a latrine user or owner could access biochar made from the most convenient local organic waste materials, pyrolyzed in the most convenient local technology. Odor control by adsorption using biochar has potential to provide a radically simple, economic and widely available technology with potential impact in the global sanitation crisis.

3.2 Possible filter designs and biochar requirements

The use rates and efficiencies from this research are useful to develop preliminary filter designs for fecal odor adsorption in latrines, and inform estimates of filter lifetime for these designs. Three possible designs in varying settings, and varying adsorption technologies, are described here. All designs are based upon a superstructure volume of 1.8 m^3 [47] and the assumption that the superstructure is full of odorous air at odor concentrations used for this research. The parameters of design and resulting biochar requirements are summarized for all three designs in Table 14.

An important note is that all designs are based upon use of the fecal char used in this study. Adsorption characteristics and performance are based upon fecal char's results in this study. In comparison to the activated carbon's performance determined in this research, activated carbon would perform about 25% better; the use rate of 4 g/m^3-air for fecal char is used for the following design work, while activated carbon achieved a use rate of `3 g/m^3-air (Figure 11).

3.2.1 Biochar cartridge filter for odor treatment of VIP latrine exhaust

Ventilated improved pit (VIP) latrines are common in developing country settings, and is designed with an air exhaust pipe which may lend well to a cartridge filter before to treat exhaust odor. A typical VIP latrine

is shown in Figure 14. The careful design for ventilation in a VIP latrine is already aimed to combat malodor issues, which is a major advantage of the design. Nevertheless, many VIP latrines around the world do not ventilate properly enough to have acceptable odor; for example, the Chappuis et al. study [9] included several VIPs with malodor issues in their measurements that founded the odor treatment studied in this research. Typically, a VIP latrine is recommended to be designed for 6 air changes per hour (ACH) for acceptable odor control [48][47]. However, this range can vary; 10-20 ACHs will lead to ideal odor conditions [47], and some guidelines are set at 2 ACH [49], which may be inadequate for odor control. This preliminary design will assume 2 ACH, to address under-performed VIP latrines.

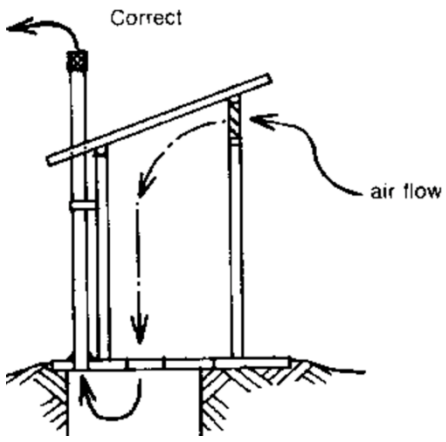


Figure 14: Schematic of air flow through a VIP latrine and out of the the exhaust vent. Image courtesy of WHO, 1992 [50].

Exhaust gas from a typical VIP may be treated as follows: A biochar cartridge filter, designed similarly to a typical GAC cartridge filter, is placed inside the upper end of the exhaust pipe (so that it may be more easily accessed for replacement) but not at the end so that the wind outside, (which is the primary driver for air flow [47]) still draws air through the ventilation path. Filter diameter may be adjusted according to existing exhaust pipe diameter, but a typical recommended diameter of 150 mm is used. Assuming a char use rate of 4 g/m^3 (Figure 11) and the typical values described above, the biochar filter would last about 5 days, which would represent a need for a staggering 31 kg of biochar each month. All relevant design

parameters and resulting filter lifetimes are described in Table 14. The filter could be containing inside PVC pipe or whatever material makes up the vent pipe, for ease of integration.

Nevertheless, this design represents a conservative estimate because it assumes a constant odor loading rate. In actuality, there may be variable odor loading rates when a cartridge is installed and successfully treating odor; initially after use odor loading may increase, then decrease after further treatment.

Advantages of the biochar cartridge filter for odor treatment of VIP latrine exhaust include the simplicity to adapt into an, existing common type of latrine with known odor issues. Disadvantages include the significant, potentially prohibitive, biochar quantity requirements.

3.2.2 Biochar cartridge filter for active adsorption in a latrine superstructure

Beyond VIP latrines, many latrine types experience malodor nuisance. Still, biochar can also as a filter to latrines without a built-in stream of odorous air. One possible design is a cartridge filter like previously described, but under different operating conditions. A cartridge filter must be designed in a location to allow for adequate mass transfer for adsorption to occur; there needs to be a forced air stream through the filter in order to remove odor. A similar, simple cartridge filter could be designed according to the specifications in Table 14, and contained in an affordable, locally available material such as PVC pipe. The cartridge filter should be sealed within the ceiling of the superstructure, and a small, solar powered fan secured on the outside of the biochar cartridge. A small fan like that displayed in Figure 15 could, with some degree of simplicity be sealed into the superstructure ceiling to pull air into a PVC pipe housing the char. The ventilation should be placed across from a doorway, in design to draw air to treat from the superstructure rather than the pit. A fan like the one in Figure 15 would have minimal energy requirements to be supported by a small solar panel outside the latrine.

Figure 15: Possible vacuum pump for active adsorption biochar filter. Image courtesy of Ventilene [51]

In this design for a normal latrine superstructure, the volume of odorous air can be assumed to be less than a VIP, assuming the flow rate of ventilated air through the structure is less. This preliminary design assumes use of a family latrine about 10 times per day, and the need to treat the superstructure's volume of air after each use assuming the pit is covered. This would result in about 0.5 ACH, with around a 20% factor of safety. Assuming a char use rate of 4 g/m^3 (Figure 11) and the typical values described above, the biochar filter would need to be replaced every 14 days. All relevant design parameters and resulting filter lifetimes are described in Table 14.

Table 14: Design parameters proposed cartridge biochar filters for active adsorption of VIP exhaust and superstructure fecal odor

Design parameter	Cartridge filter for VIP exhaust	Superstructure active adsorption cartridge filter	Units	Source
Char use rate	4	4	g/m^3	*This report*
Volume of superstructure	1.8	1.8	m^3	*Mara and Ryan [47]*
Air changes per hour	2	0.5	*ACH*	*ASHRAE [49]*
Filter diameter	0.20	0.15	*m*	*Mihelcic et al. [48]m*
Ratio of filter:particle size diameters	15	15		*Set from typical values*
Average diameter of GAC/PAC particles	13	10	*mm*	
Flow rate through column	3.6	0.9	m^3/hr	
Contact time	10	10	*seconds*	*Set from typical values*
Bed depth	0.32	0.14	*m*	
Aspect ratio	1.6	0.9		*Set from typical values*
Bed density	469	469	kg/m^3	*This report*
Mass of biochar inside filter	4.68	1.17	*kg*	
Filter lifetime	4.5	14	*days*	
Biochar requirement	31	2.6	*kg-char/ month*	

Similarly to the cartridge filter for VIP exhaust described above, this design represents a conservative estimate because it assumes constant odor loading rate, despite a likely reality that the modeled odor loading represents an estimate for a maximum concentration of malodors that decreases soon after treatment. Because these kinetics are not known, the maximum was assumed for these design calculations.

Advantages of the biochar cartridge filter for active adsorption of odor in a latrine superstructure include the lower char quantity requirements, and adaptability to all superstructures. Disadvantages include the significant, potentially prohibitive, technology and power requirements.

3.2.3 Biochar mesh filter for passive adsorption in a latrine superstructure

One of the major findings of this research is the significant difference between a forced-flow continuous flow column, and passive adsorption in a batch reactor. Given that the batch reactor design gave way to adsorption capacities an order of magnitude higher, it is worthwhile to propose an odor treatment method that mimics the process of passive adsorption in a batch reactor. Similar to the batch adsorption experiments of this report, this filter would be in a location with significant RH, but would not force water vapor onto biochar at a significant loading rate. Therefore, a lower use rate was assumed for the char in this filter design at 0.7 g/m^3, to mimic the dose of char in the odorous batch experiments.

One filter design that could achieve passive adsorption is a mesh bag with a thin layer of biochar, that would line the ceiling. A polyester multifilament media is an economic mesh that could contain the ground biochar down to 100 microns, which would be sufficient for powdered biochar passing US mesh size 50, as in this research [52]. A simple, square or rectangular frame could be made to match the superstructure's ceiling dimensions, and sewn inside a mesh bag of the same dimension in order the keep the resting surface for the char taut. The lightweight, square mesh bag filter could be easily suspended from or attached to the superstructure's ceiling. A very thin layer of powdered biochar could be distributed along the horizontal, taut surface of the char to allow for passive adsorption of odors in the latrine.

Assuming the need for odor treatment described in the previous section that results in same ACH of 0.5, and the typical values described above, the biochar filter would need to be replaced approximately once per month. All relevant design parameters and resulting filter lifetimes are described in Table 15.

Table 15: Design parameters proposed mesh biochar filters for passive adsorption of superstructure fecal odor

Design parameter	Superstructure passive adsorption mesh filter	Units	Source
Char use rate	0.7	g/m^3	*This report*
Volume of superstructure	1.8	m^3	*Mara and Ryan [47]*
Ceiling area	0.9	m^2	*Kunzle and O'Keefe [53]*
Air changes per hour	2	*ACH*	*Assumed*
Depth of char in mesh filter	1	*mm*	*Assumed*
Average bed density	469	kg/m^3	*This report*
Mass of biochar inside filter	0.42	*kg*	
Filter lifetime	29	*days*	
Biochar requirement	0.43	*kg-char/ month*	

Advantages of the biochar mesh filter for passive adsorption of odor in a latrine superstructure include the significantly lower char quantity requirements, and adaptability to all superstructures. Disadvantages include a potential issue for adequate mass transfer in adsorption. This design, and all, have much room for interpretation and further development in pilot testing.

3.3 Field trials

The methods of this proof-of-concept study included the synthesis and treatment of latrine malodor in a laboratory bench-scale setting. While this method was successful, it is a significant step from an adequate understanding of this technology's ability to be a feasible solution to malodor nuisance issues in FSM supply chains. Results demonstrated that adsorption in continuous-flow was inefficient compared to a theoretical maximum adsorptive capacity, even under the controlled conditions in a laboratory. Some of these results indicate a potentially prohibitively high biochar requirement for a cartridge filter. Therefore, a major conclusion of this study is the necessity of carefully designed field trials to better understand the resilience of adsorption by biochar under dynamic conditions.

Design of field trials should consider investigation of the following variables: humidity, intermittent operation, dynamic air loading rates, dynamic odor loading rates, latrine type and structure, and filter style and design specifications. It is hypothesized that high humidity will decrease char lifetime, based on results of this study (see *Section 2.3.3 Importance of Humidity*). However, results also suggested that adsorption of water vapor onto char may be reversible. The ability and feasibility to reverse fouling by water vapor must be better understood; this study demonstrated a drastic negative affect of fouling on adsorption performance and capacity. If fouling is better understood, fouling conditions may be better controlled and then lead to better technology success. Control for fouling could be achieved by a dehumidification process, or more simply specifications for filter placement in the most well-ventilated areas of a latrine. Furthermore, regeneration of biochar may be possible but was not purposely investigated in this study. Results may indicate that if malodor adsorption was achieved by physical adsorption processes, reversal and volatilization from the char may be simple. Regeneration could significantly extend biochar lifetime. It is hypothesized that perhaps even intermittent operation may regenerate char from water vapor fouling or reverse physical adsorption, which would extend char lifetime. Conversely, intermittent operation could have a nominal effect on filter performance, as in water phase adsorption [54]. Perhaps it is even possible that dynamic air loading rates may imitate intermittent operation. Based on expected adsorption characteristics, increased odor loading rate should increase adsorption capacity. Additionally, decreased odor loading rates, as a result of a decrease in odor level after a malodor event from latrine use has been treated by the char, could increase char lifetime.

In field trials, odor measurement method should be carefully considered. The primary decision regarding methods will be between quantitative and qualitative methods. Differences between and opportunities for these methods are explained in *Section 2.1.2 Odor Measurement.* Results of this study would inform this decision based on the demonstrated non-linearity on odor detection throughout results. Since the concentrations were at relatively low levels in this study (somewhat near their ODT), a higher degree of

nonlinearity is such a fashion that as concentration decreases, odor detection would also decrease but at a decreasing rate. In other words, at low odor levels, a significant reduction in concentration of malodor molecules would result in a less significant reduction in odor detection. For example, if a quantitative method is used in a field trial and a 90% reduction in odor concentration is observed, the reduction in malodor nuisance on the user may still be minimal at low odor levels. Conversely, for example, a 10% reduction in odor concentration at very high odor levels may be quite dramatic. The degree and characteristics of nonlinearity of fecal malodors is unknown in the scientific community such that we may only draw a qualitative description between "high" and "low" odor levels. Unfortunately for adsorption's ability to reduce malodor nuisance, odor levels exhibited probably in most latrine settings would fall closer towards the "low odor" end of the spectrum.

Finally, it must be noted that the implementation of a biochar filter in latrine for malodor treatment may represent a significant change for latrine users, owners, or other stakeholders. It would represent a technology intervention that would require a behavior change (to replace or maintain the filter appropriately). Behavior change in developing world contexts is a complex and important field of study. As the simplest investigation, willingness of users to use latrines with biochar filters, and willingness of owners to maintain or replace biochar filters, must be understood for the implementation of this technology to be successful.

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Appendix A: Breakthrough Curves

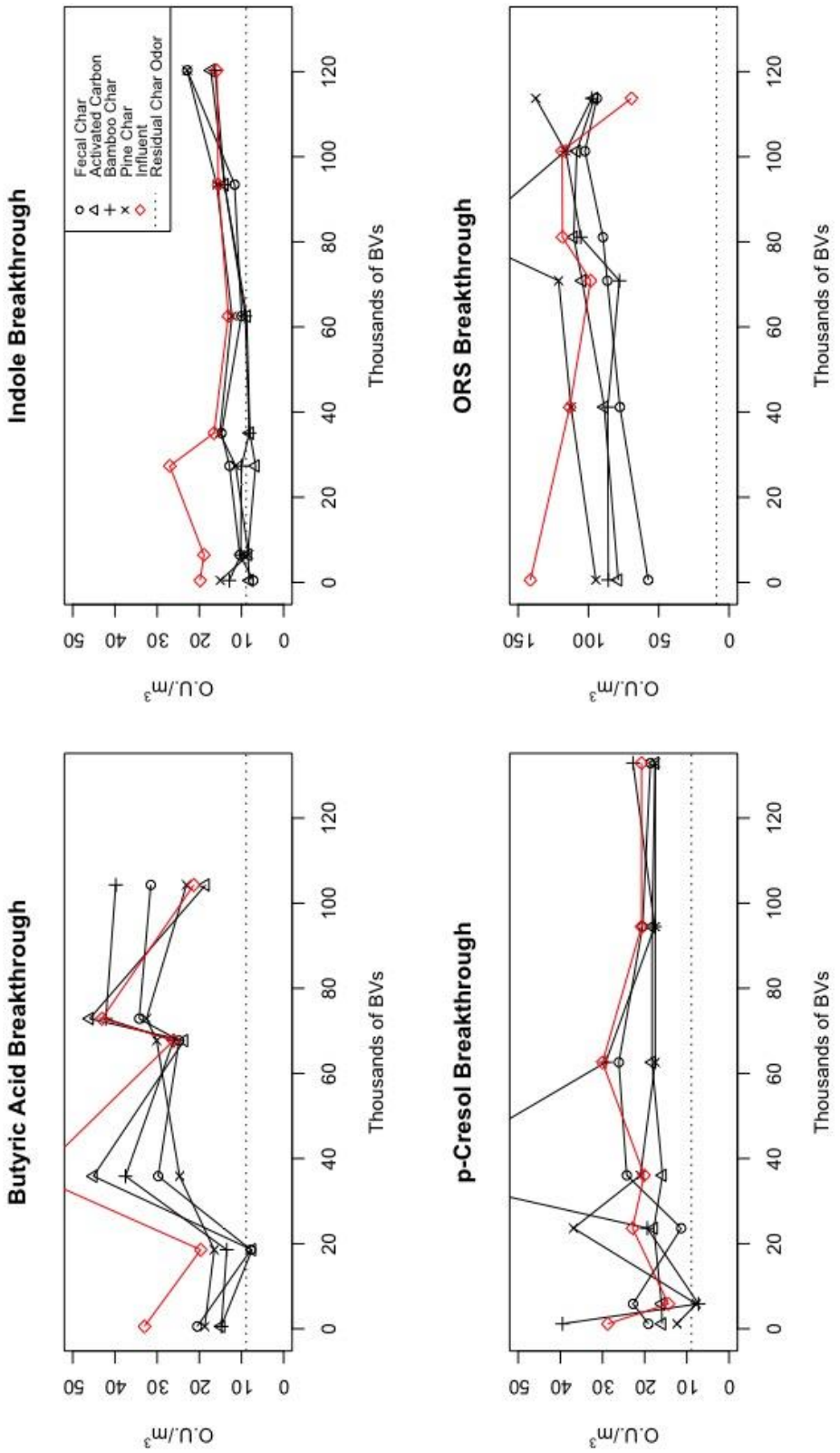

Figure 16: Breakthrough curves of flow-through adsorption experiments for all odor solutions treated by all char types, plotted with the variable influent odor levels. Definition of saturation is theoretically when a breakthrough for a char crosses the control curve, but due to error in odor panel results may also be defined between 0.8-0.9 of C_0

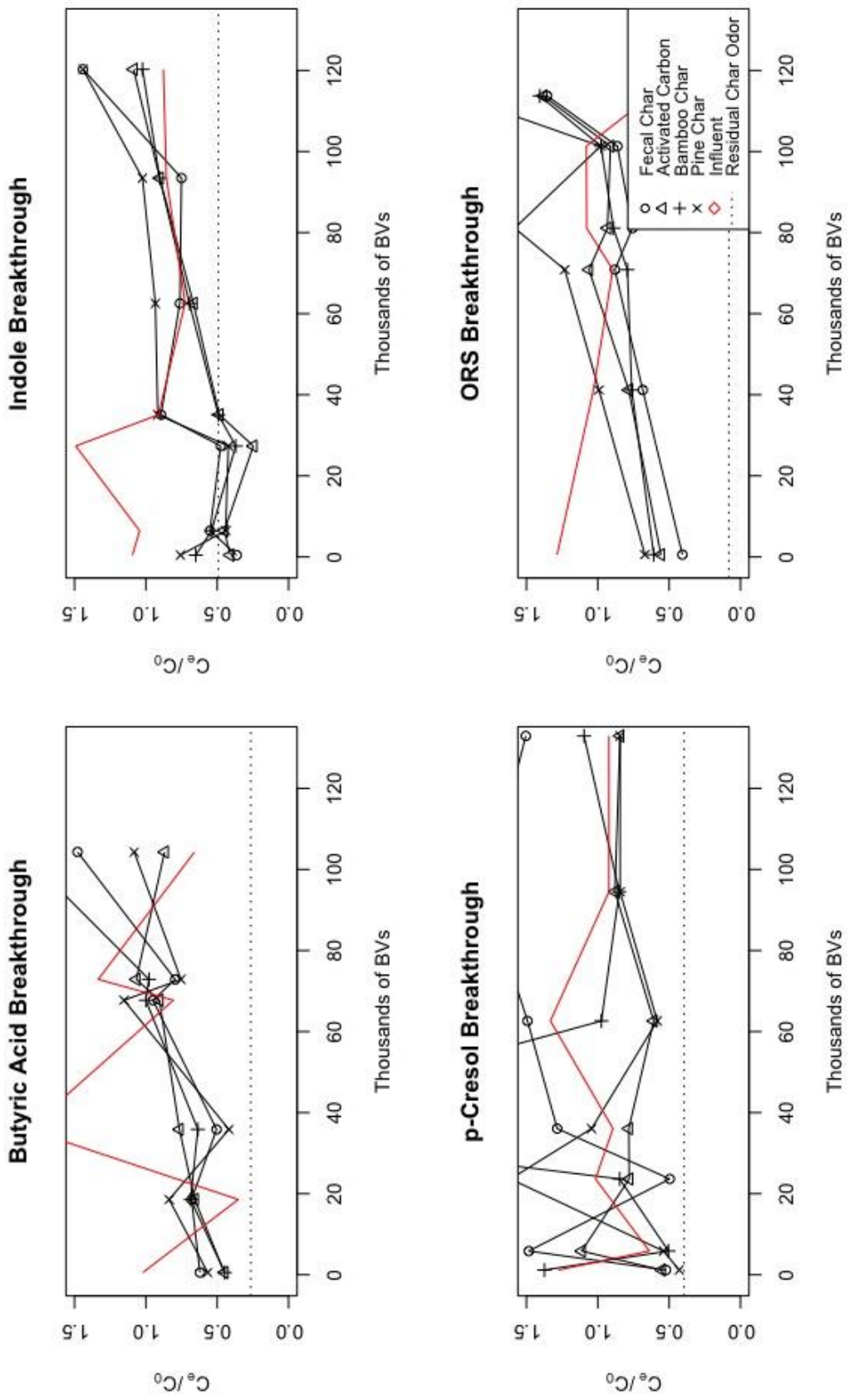

Figure 17: Breakthrough curves of flow-through adsorption experiments for all odor solutions treated by all char types (normalized by variable influent odor levels). The normalized variable influent odor curved is also shown in red, which is defined by $C_0/C_{0,avg}$. Definition of saturation is theoretically 1.0, but due to error in odor panel results may be defined between 0.8-0.9 of C_0.

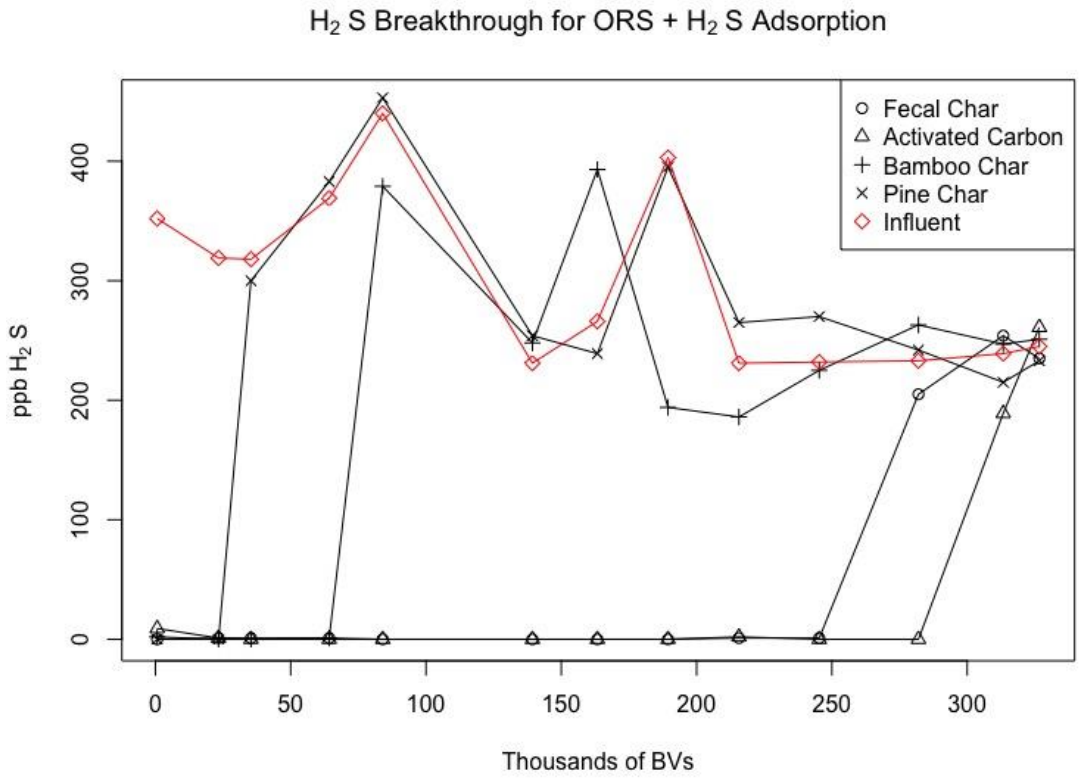

Figure 18: Breakthrough curves of flow-through adsorption experiments for ORS+H_2S treated by all char types, plotted with the variable influent H_2S levels. Definition of saturation is defined as the point when the breakthrough curve for a char crosses the control curve.

Appendix B: Adsorption Isotherm Plots

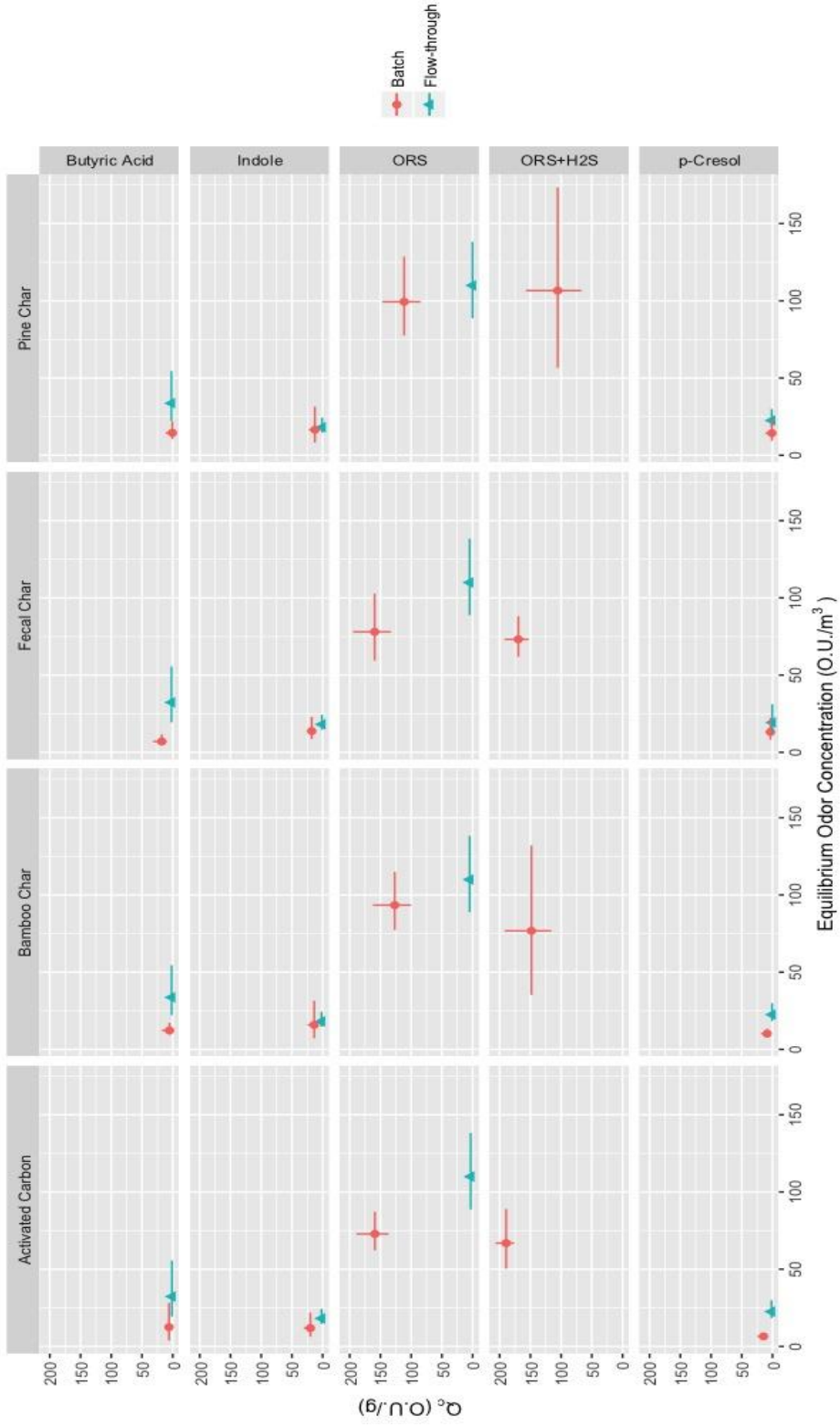

Figure 19: Adsorption experiment data plotted on isotherms plots for all four chars' adsorption of the odor solutions on a linear scale. Each isotherm plot has two points on it: one for the batch adsorption experiment, and one for the flow-through adsorption experiment. ODT was not measured for ORS+H_2S for flow-through experiments.

Appendix C: Photos of Laboratory Set Ups

Figure 20: Odor Bag

Figure 21: SM-100 Olfactometer (Scentroid/IDES, Ontario, CA)

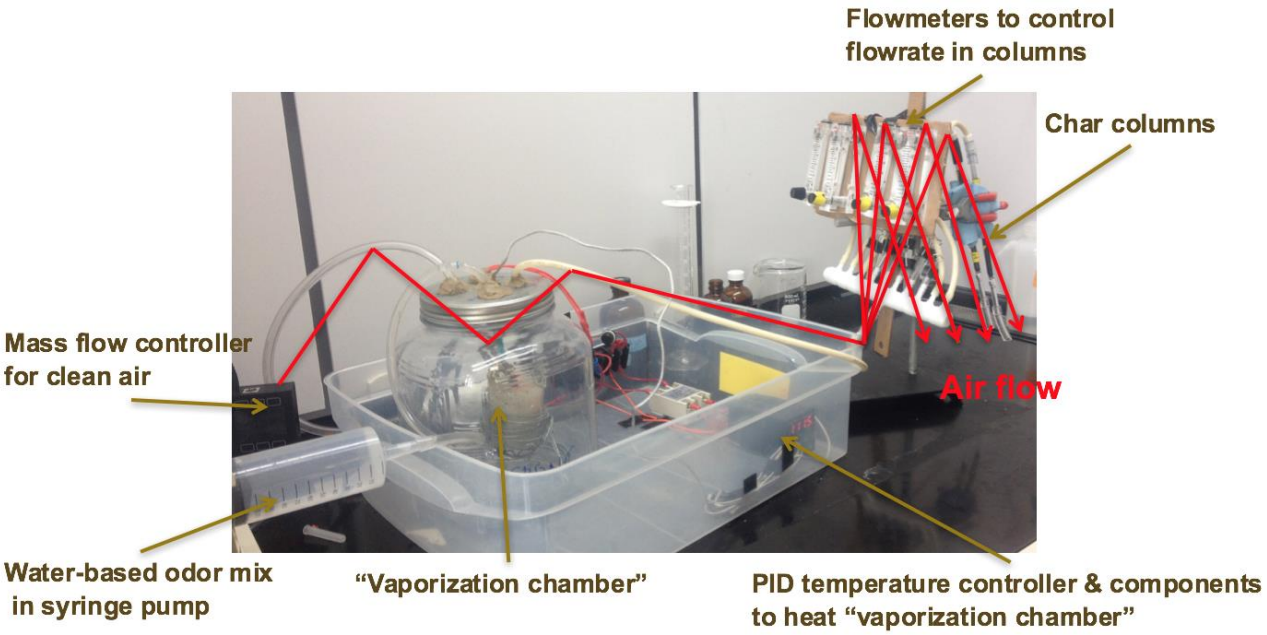

Figure 22: Odor synthesis process and flow-through adsorption columns set up inside fume hood

Appendix D: Adsorption Experiments Data Tables

Batch Adsorption Experiments Data Tables

Table 16: Odor panel data for batch adsorption. Data is organized by odor solution. Panelists' names are truncated to the first two letters. Data show both the position on the olfactometer at which the panelists detected odor, and the corresponding D/T calculated by the geometric mean of the binding dilutions. The data for the screening bag is also shown, and removed results based on the screening bag reading are highlighted in red.

Odor Solution:	Butyric Acid													
		Activated Carbon Bag Dose: 0.433 mg/L		Fecal Char Bag Dose: 0.367 mg/L		Bamboo Char Bag Dose: 0.467 mg/L		Pine Char Bag Dose: 0.367 mg/L		Control Bag		Screening Bag	
Panelist	Plate in olfactometer	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
My	A	7	29.5	15	4.5	9	15	8	20.5	7	29.5	7	29.5
Au	A	12	7.5	12	7.5	12	7.5	12	7.5	9	15	8	20.5
Ev	A	13	6.5	10	11.5	10	11.5	9	15	8	20.5	9	15
Ka	A	13	6.5	15	4.5	10	11.5	10	11.5	9	15	7	29.5
Odor Solution:	**Indole**												
		Activated Carbon Bag Dose: 0.567 mg/L		Fecal Char Bag Dose: 0.533 mg/L		Bamboo Char Bag Dose: 0.533 mg/L		Pine Char Bag Dose: 0.533 mg/L		Control Bag		Screening Bag	
Panelist	Plate in olfactometer	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ra	A	12	7.5	9	15	11	9	10	11.5	7	29.5	8	20.5
Na	A	15	4.5	15	4.5	15	4.5	15	4.5	14	5.5	9	15
Ka	A	8	20.5	9	15	9	15	8	20.5	7	29.5	7	29.5
Mi	A	8	20.5	9	15	7	29.5	8	20.5	7	29.5	8	20.5

Odor Solution:	p-Cresol																	
		Activated Carbon Bag Dose: 0.500 mg/L		Fecal Char Bag Dose: 0.567 mg/L		Bamboo Char Bag Dose: 0.533 mg/L		Pine Char Bag Dose: 0.500 mg/L		Control Bag		Screening Bag	
Panelist	Plate in olfactometer	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	*A*	*13*	*6.5*	*10*	*11.5*	*10*	*11.5*	*9*	*15*	*8*	*20.5*	*8*	*20.5*
Au	*A*	*12*	*7.5*	*12*	*7.5*	*12*	*7.5*	*12*	*7.5*	*10*	*11.5*	*10*	*11.5*
Ev	*A*	*14*	*5.5*	*8*	*20.5*	*10*	*11.5*	*8*	*20.5*	*8*	*20.5*	*11*	*9*
Ky	*A*	*12*	*7.5*	*10*	*11.5*	*11*	*9*	*10*	*11.5*	*9*	*15*	*9*	*15*
Odor Solution:	**ORS**																	
		Activated Carbon Bag Dose: 0.633 mg/L		Fecal Char Bag Dose: 0.600 mg/L		Bamboo Char Bag Dose: 0.633 mg/L		Pine Char Bag Dose: 0.667 mg/L		Control Bag		Screening Bag	
Panelist	Plate in olfactometer	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	*3*	*8*	*88*	*7*	*101.5*	*6*	*120*	*6*	*120*	*3*	*274*	*4*	*192*
My	*3*	*11*	*63*	*10*	*69.5*	*8*	*88*	*8*	*88*	*6*	*120*	*3*	*274*
Na	*3*	*11*	*63*	*8*	*88*	*9*	*77.5*	*10*	*69.5*	*3*	*274*	*6*	*120*
Ra	*3*	*9*	*77.5*	*13*	*53*	*8*	*88*	*6*	*120*	*4*	*192*	*5*	*148*
Odor Solution:	**ORS + H2S**																	
		Activated Carbon Bag Dose: 0.600 mg/L		Fecal Char Bag Dose: 0.633 mg/L		Bamboo Char Bag Dose: 0.700 mg/L		Pine Char Bag Dose: 0.700 mg/L		Control Bag		Screening Bag	
Panelist	Plate in olfactometer	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	*3*	*13*	*53*	*9*	*77.5*	*12*	*57.5*	*8*	*88*	*4*	*192*	*2*	*492*
My	*3*	*14*	*49*	*10*	*69.5*	*13*	*53*	*9*	*77.5*	*5*	*148*	*3*	*274*
Na	*3*	*8*	*88*	*12*	*57.5*	*14*	*49*	*10*	*69.5*	*4*	*192*	*4*	*192*
Ra	*3*	*9*	*77.5*	*8*	*88*	*5*	*147.5*	*4*	*192*	*4*	*192*	*4*	*192*

Flow-through Adsorption Experiments Data Tables

Table 17: Odor panel data for flow-through adsorption. Data is organized by odor solution. Panelists' names are truncated to the first two letters. Data show both the position on the olfactometer at which the panelists detected odor, and the corresponding D/T calculated by the geometric mean of the binding dilutions. The data for the screening bag is also shown, and removed results based on the screening bag reading are highlighted in red.

Odor Solution:	Butyric Acid																	
			Activated Carbon Column Effluent Dose of char: 3.35 g		Fecal Char Column Effluent Dose of char: 3.35 g		Bamboo Char Column Effluent Dose of char: 3.35 g		Pine Char Column Effluent Dose of char: 3.35 g		Column Influent (Control)		Screening Bag Measurement at Time of Sampling	
Panelist	Liters treated	Bed Volumes Treated	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	0.005	0.556	12	7.5	8	20.5	11	9	13	6.5	7	30	7	29.5
Ka	0.158	18.566	-	-	13	6.5	13	6.5	-	-	8	21	7	29.5
Ka	0.305	35.854	14	5.5	8	20.5	6	48.5	11	9	5	80	6	48.5
Ka	0.576	67.718	8	20.5	8	20.5	7	29.5	11	9	7	30	6	48.5
Ka	0.619	72.865	9	15	8	20.5	7	29.5	11	9	6	49	5	80
Ka	0.886	104.284	8	20.5	8	20.5	7	29.5	6	48.5	6	49	5	80
Au	0.005	0.556	12	7.5	6	48.5	8	20.5	12	7.5	11	9	7	29.5
Au	0.158	18.566	12	7.5	11	9	8	20.5	12	7.5	11	9	7	29.5
Au	0.305	35.854	9	15	6	48.5	13	6.5	9	15	11	9	7	29.5
Au	0.576	67.718	-	-	7	29.5	10	11.5	9	15	10	12	7	29.5
Au	0.619	72.865	11	9	9	15	10	11.5	14	5.5	11	9	9	15
Au	0.886	104.284	-	-	6	48.5	8	20.5	-	-	12	7.5	9	15
My	0.005	0.556	5	80	7	29.5	6	48.5	7	29.5	7	30	6	48.5
My	0.158	18.566	4	137	6	48.5	5	80	5	80	8	21	6	48.5
My	0.305	35.854	5	80	6	48.5	9	15	10	11.5	6	49	8	20.5
My	0.576	67.718	7	29.5	9	15	7	29.5	7	29.5	6	49	8	20.5
My	0.619	72.865	6	48.5	8	20.5	6	48.5	7	29.5	7	30	5	80
My	0.886	104.284	11	9	7	29.5	8	20.5	13	6.5	9	15	5	80
El	0.005	0.556	7	29.5	5	80	5	80	8	20.5	6	49	4	137
El	0.158	18.566	4	137	8	20.5	4	137	6	48.5	8	21	4	137
El	0.305	35.854	5	80	6	48.5	6	48.5	4	137	8	21	7	29.5
El	0.576	67.718	9	15	7	29.5	6	48.5	6	48.5	7	30	7	29.5
El	0.619	72.865	4	137	7	29.5	6	48.5	6	48.5	5	80	6	48.5
El	0.886	104.284	7	29.5	5	80	5	80	7	29.5	9	15	6	48.5
Ca	0.005	0.556	6	48.5	7	29.5	5	80	7	29.5	6	49	6	48.5
Ca	0.158	18.566	4	137	5	80	3	247.5	6	48.5	7	30	6	48.5
Ca	0.305	35.854	5	80	8	20.5	5	80	7	29.5	4	137	7	29.5
Ca	0.576	67.718	7	29.5	7	29.5	10	11.5	6	48.5	10	12	7	29.5
Ca	0.619	72.865	8	20.5	6	48.5	4	137	6	48.5	6	49	7	29.5
Ca	0.886	104.284	9	15	6	48.5	5	80	10	11.5	8	21	7	29.5

Odor Solution:	Indole																	
	Time of Sampling		Activated Carbon Column Effluent Dose of char: 3.35		Fecal Char Column Effluent Dose of char: 3.35 g		Bamboo Char Column Effluent Dose of char: 3.35 g		Pine Char Column Effluent Dose of char: 3.35		Column Influent (Control)		Screening Bag Measurement at Time of Sampling	
Panelist	Liters treated	Bed Volumes	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	0.004	0.446	12	7.5	13	6.5	10	11.5	9	15	7	30	4	137
Ka	0.055	6.466	10	11.5	11	9	9	15	12	7.5	6	49	7	29.5
Ka	0.232	27.358	14	5.5	15	4.5	11	9	8	20.5	6	49	8	20.5
Ka	0.297	35.073	9	15	8	20.5	10	11.5	9	15	7	30	7	29.5
Ka	0.53	62.543	15	4.5	13	6.5	9	15	8	20.5	10	12	7	29.5
Ka	0.791	93.447	9	15	8	20.5	8	20.5	12	7.5	8	21	7	29.5
Ka	1.018	120.281	7	29.5	7	29.5	7	29.5	6	48.5	7	30	8	20.5
Mi	0.004	0.446	12	7.5	15	4.5	15	4.5	12	7.5	15	4.5	7	29.5
Mi	0.055	6.466	15	4.5	15	4.5	15	4.5	15	4.5	15	4.5	7	29.5
Mi	0.232	27.358	11	9	15	4.5	15	4.5	15	4.5	9	15	11	9
Mi	0.297	35.073	15	4.5	15	4.5	15	4.5	15	4.5	15	4.5	11	9
Mi	0.53	62.543	15	4.5	15	4.5	15	4.5	15	4.5	10	12	11	9
Mi	0.791	93.447	-	-	14	5.5	10	11.5	15	4.5	14	5.5	8	20.5
Mi	1.018	120.281	15	4.5	15	4.5	13	6.5	15	4.5	15	4.5	9	15
Ev	0.004	0.446	10	11.5	15	4.5	-	-	7	29.5	7	30	7	29.5
Ev	0.055	6.466	13	6.5	7	29.5	14	5.5	-	-	13	6.5	10	11.5
Ev	0.232	27.358	-	-	-	-	-	-	-	-	-	-	-	-
Ev	0.297	35.073	-	-	-	-	-	-	-	-	-	-	-	-
Ev	0.53	62.543	-	-	-	-	-	-	-	-	-	-	-	-
Ev	0.791	93.447	-	-	-	-	-	-	-	-	-	-	-	-
Ev	1.018	120.281	-	-	-	-	-	-	-	-	-	-	-	-
Na	0.004	0.446	13	6.5	14	5.5	9	15	10	11.5	8	21	6	48.5
Na	0.055	6.466	-	-	15	4.5	14	5.5	-1	-1	14	5.5	6	48.5
Na	0.232	27.358	14	5.5	-	-	9	15	10	11.5	9	15	12	7.5
Na	0.297	35.073	15	4.5	15	4.5	12	7.5	8	20.5	10	12	8	20.5
Na	0.53	62.543	14	5.5	15	4.5	14	5.5	11	9	8	21	7	29.5
Na	0.791	93.447	13	6.5	12	7.5	11	9	11	9	13	6.5	11	9
Na	1.018	120.281	14	5.5	11	9	14	5.5	11	9	11	9	9	15
Ra	0.004	0.446	12	7.5	9	15	8	20.5	10	11.5	9	15	5	80
Ra	0.055	6.466	10	11.5	9	15	8	20.5	11	9	7	30	6	48.5
Ra	0.232	27.358	-	-	7	29.5	10	11.5	11	9	7	30	7	29.5
Ra	0.297	35.073	-	-	7	29.5	11	9	8	20.5	8	21	8	20.5
Ra	0.53	62.543	8	20.5	9	15	10	11.5	9	15	11	9	7	29.5
Ra	0.791	93.447	8	20.5	10	11.5	9	15	8	20.5	7	30	8	20.5
Ra	1.018	120.281	7	29.5	6	48.5	9	15	7	29.5	8	21	9	15

Odor Solution:		p-Cresol												
	Time of Sampling		Activated Carbon Column Effluent Dose of char: 3.35		Fecal Char Column Effluent Dose of char: 3.35		Bamboo Char Column Effluent Dose of char: 3.35		Pine Char Column Effluent Dose of char: 3.35		Column Influent (Control)		Screening Bag Measurement at Time of Sampling	
Panelist	Liters treated	Bed Volumes	Position of detection	D/T	Position of	D/T	Position of detection	D/T	Position of	D/T	Position of	D/T	Position of	D/T
Ka	0.01	1.171	7	29.5	5	80	7	29.5	11	9	5	80	7	29.5
Ka	0.05	5.853	7	29.5	5	80	14	5.5	-	-	7	30	7	29.5
Ka	0.2	23.635	11	9	10	11.5	9	15	10	11.5	8	21	8	20.5
Ka	0.305	36.061	12	7.5	12	7.5	9	15	11	9	11	9	8	20.5
Ka	0.53	62.61	8	20.5	9	15	11	9	10	11.5	6	49	9	15
Ka	0.8	94.473	9	15	9	15	9	15	12	7.5	10	12	10	11.5
Ka	1.125	132.913	10	11.5	7	29.5	7	29.5	9	15	7	30	10	11.5
Au	0.01	1.171	10	11.5	9	15	11	9	12	7.5	13	6.5	8	20.5
Au	0.05	5.853	8	20.5	8	20.5	11	9	13	6.5	11	9	8	20.5
Au	0.2	23.635	9	15	9	15	12	7.5	12	7.5	9	15	7	29.5
Au	0.305	36.061	8	20.5	6	48.5	12	7.5	10	11.5	13	6.5	9	15
Au	0.53	62.61	11	9	7	29.5	8	20.5	10	11.5	12	7.5	10	11.5
Au	0.8	94.473	12	7.5	8	20.5	11	9	14	5.5	10	12	9	15
Au	1.125	132.913	13	6.5	11	9	8	20.5	14	5.5	13	6.5	9	15
Ev	0.01	1.171	9	15	8	20.5	5	80	8	20.5	6	49	14	5.5
Ev	0.05	5.853	13	6.5	7	29.5	14	5.5	-	-	12	7.5	12	7.5
Ev	0.2	23.635	7	29.5	12	7.5	6	48.5	4	137	6	49	11	9
Ev	0.305	36.061	8	20.5	8	20.5	3	247.5	9	15	6	49	14	5.5
Ev	0.53	62.61	11	9	6	48.5	7	29.5	-	-	12	7.5	7	29.5
Ev	0.8	94.473	8	20.5	8	20.5	7	29.5	7	29.5	4	137	8	20.5
Ev	1.125	132.913	11	9	7	29.5	9	15	11	9	11	9	9	15
Ky	0.01	1.171	12	7.5	10	11.5	-	-	-	-	10	12	12	7.5
Ky	0.05	5.853	12	7.5	10	11.5	11	9	11	9	-	-	10	11.5
Ky	0.2	23.635	-	-	-	-	13	6.5	5	80	12	7.5	11	9
Ky	0.305	36.061	14	5.5	8	20.5	7	29.5	5	80	10	12	15	4.5
Ky	0.53	62.61	11	9	10	11.5	13	6.5	14	5.5	13	6.5	12	7.5
Ky	0.8	94.473	15	4.5	13	6.5	11	9	-	-	-	-	11	9
Ky	1.125	132.913	-	-	13	6.5	10	11.5	-	-	15	4.5	11	9

Odor Solution:		ORS															
	Time of Sampling		Activated Carbon Column Effluent		Fecal Char Column Effluent		Bamboo Char Column Effluent		Pine Char Column Effluent		Column Influent (Control)		Screening Bag Measurement at Time of Sampling	
			Dose of char: 3.35 g		Dose of char: 3.35 g		Dose of char: 3.35 g		Dose of char: 3.35 g					
Panelist	Liters treated	Bed Volumes Treated	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T	Position of detection	D/T
Ka	0.005	0.557	6	120	15	45.5	6	120	7	101.5	5	148	8	88
Ka	0.349	41.18	5	148	12	57.5	7	101.5	-	-	6	120	8	88
Ka	0.6	70.863	4	192	8	88	12	57.5	4	191.5	5	148	7	102
Ka	0.687	81.105	14	49	7	101.5	9	77.5	8	88	5	148	7	102
Ka	0.858	101.312	4	192	7	101.5	7	101.5	4	191.5	6	120	5	148
Ka	0.963	113.715	6	120	7	101.5	8	88	7	101.5	9	78	5	148
Em	0.005	0.557	15	45.5	10	69.5	2	492	7	101.5	9	78	4	192
Em	0.349	41.18	7	102	8	88	5	147.5	4	191.5	9	78	4	192
Em	0.6	70.863	-	-	7	101.5	11	63	5	147.5	9	78	8	88
Em	0.687	81.105	11	63	10	69.5	5	147.5	2	492	3	274	8	88
Em	0.858	101.312	3	274	7	101.5	9	77.5	-	-	12	58	9	77.5
Em	0.963	113.715	7	102	10	69.5	5	147.5	4	191.5	11	63	9	77.5
My	0.005	0.557	8	88	12	57.5	-	-	6	120	8	88	6	120
My	0.349	41.18	7	102	10	69.5	10	69.5	12	57.5	12	58	6	120
My	0.6	70.863	14	49	14	49	12	57.5	6	120	9	78	6	120
My	0.687	81.105	7	102	10	69.5	9	77.5	11	63	8	88	6	120
My	0.858	101.312	9	77.5	8	88	11	63	10	69.5	9	78	7	102
My	0.963	113.715	12	57.5	9	77.5	7	101.5	7	101.5	-	-	7	102
El	0.005	0.557	12	57.5	10	69.5	11	63	14	49	6	120	7	102
El	0.349	41.18	10	69.5	4	191.5	7	101.5	13	53	6	120	7	102
El	0.6	70.863	4	192	4	191.5	9	77.5	9	77.5	11	63	8	88
El	0.687	81.105	4	192	6	120	9	77.5	5	147.5	9	78	8	88
El	0.858	101.312	10	69.5	6	120	6	120	5	147.5	3	274	9	77.5
El	0.963	113.715	5	148	6	120	8	88	4	191.5	8	88	9	77.5
Ca	0.005	0.557	10	69.5	15	45.5	9	77.5	7	101.5	3	274	7	102
Ca	0.349	41.18	5	148	13	53	12	57.5	5	147.5	4	192	7	102
Ca	0.6	70.863	5	148	7	101.5	8	88	10	69.5	9	78	7	102
Ca	0.687	81.105	4	192	8	88	5	147.5	5	147.5	9	78	7	102
Ca	0.858	101.312	11	63	7	101.5	11	63	12	57.5	5	148	8	88
Ca	0.963	113.715	13	53	7	101.5	11	63	7	101.5	14	49	8	88