Sustainable Decentralized Water Treatment for Rural and Developing Communities Using Gasifier Biochar

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Corresponding author
Josh Kearns
Director of Science, Aqueous Solutions
PhD Candidate, Environmental Engineering
Engineering for Developing Communties
University of Colorado-Boulder
josh@aqsolutions.org

Co-authors and contributors
Research Advisory Committee: Professors R Scott Summers, Karl Linden, and Fernando Rosario-Ortiz (University of Colorado-Boulder), Detlef Knappe (North Carolina State University), Stephen Joseph (University of New South Wales)

Technical advising and analytical support: Professor Gerard Cornelissen (Norwegian Geotechnical Institute), Lisa Lentz (North Carolina State University), Elisabeth Mansfield (National Institute of Standards and Technology, Boulder, CO), Hugh McLaughlin (Alterna Biocarbon), Colleen Rostad and David Rutherford (US Geological Survey), Wanna Sanjaikla (Dusit University, Thailand), Carl Saquing (North Carolina State University), Professor Pakawadee Sutthivaiyakit (Kasetsart University, Thailand)

Facilities support: Nathan Bailey (Director Structural Engineering Laboratory) and Sid Gustafson (Director Physics Trades Teaching Laboratory) University of Colorado-Boulder, Chirapong Kuhakanchana (Royal Forestry Department Wood Energy Research Centre, Thailand), Jon Jandai, Nathan Reents and Peggy Reents (Pun Pun Center for Self-Reliance, Thailand)

Gasifier cookstove project (CU-Boulder): Professor Bernard Amadei, Mike Barbee, Kristen Matsumura, Boston Nyer, Anna Segur

Research and fieldwork support: Mike Barbee, Saw Rocky Khu Bittakah, Damien Bohler, Alexsandra Guerra, Fedde Jorritsma, Ryan Mahoney, Boston Nyer, Rachael Ramsey, Nathan Reents, Kyle Shimabuku, Lauren Wellborn

Field-site hosts: Reents family (Jefferson, CO), Ponderosa house (Boulder, CO), Pun Pun Center for Self-Reliance (Thailand), Royal Forestry Department Wood Energy Research Centre (Thailand)

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Editing and helpful comments for this document: Sara Beck, David Kempisty, and Ryan Mahoney (CU-Boulder), Stephen Joseph (University of New South Wales), Rick Burnette (ECHO-Asia)

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Contents

Terminology and Abbreviations

Adsorption / Absorption / Sorption

"*Ad*sorption" signifies a surface interaction between dissolved species and solid material (in this case, char). This process is distinct from "*ab*sorption," which means "to soak up" or "to take into." To be exact, however, in water treatment contaminants diffuse into char pores (*ab*sorption) where they bind to char surfaces (*ad*sorption). This has led wide use of the nonspecific term "sorption."

Biochar / Charcoal / Char

"Biochar" refers to the practice of applying charred biomass to agricultural soils in order to increase crop yields, and/or to sequester carbon in the soil. "Charcoal" refers to a biomass-derived char product most often used as cooking fuel. "Char" is a nonspecific term used for convenience referring to biochar or charcoal.

Biomass / Feedstock

Here, "biomass" refers to any woody or cellulosic material (e.g. wood, agricultural and forestry residues) that serves as the precursor, or "feedstock," for making char.

Gasifier

A device for heating biomass in order to cause it to evolve volatile and flammable gases, which are then combusted to provide energy, typically for cooking or space-heating.

Micro-porosity / Surface Area

A "micro-porous" material possesses very fine pore structure at the nanometer to micrometer (10^{-9} – 10^{-6} m) scale. "Surface area" refers primarily to internal surface area, i.e. within micro-pores.

Pathogen

Human-disease-causing waterborne microbiological agent.

Pyrolysis

The process by which char is generated, wherein biomass is heated under restricted oxygen atmosphere. Distinct from combustion ("burning") wherein biomass is heated with sufficient oxygen present, leaving only ash as the solid residue.

2,4-D	2,4-dichlorophenoxyacetic acid, a prevalent herbicide
AC/GAC	activated carbon / granular activated carbon
BSF / SSF / S-BSF	biological sand filter / slow sand filter / slow biological sand filter
SOC	synthetic organic compound
TLUD	"top-lit, up-draft" – referring to a mode of operation of biomass gasifier units
WASH	water-sanitation-hygiene

Executive Summary

Contamination of drinking water sources by synthetic organic compounds (SOCs – e.g. pesticides, pharmaceuticals, fuel compounds) is a growing worldwide problem. Many of these chemicals bio-accumulate in the human body and cause cancer, birth defects and diseases of the reproductive system, and disrupt endocrine and neurological systems. However, few low-cost, sustainable and appropriate treatment technologies are available to rural and developing communities for SOC removal. Moreover, SOCs are rarely or not-at-all addressed in the majority of safe drinking water programs implemented by major international development NGOs and government agencies, university research programs, philanthropic organizations, non-profits, faith-based charities, etc.

In advanced centralized water treatment systems, adsorption by activated carbon (AC) is considered the best available technology for the removal of SOCs. However, the manufacture of AC is a sophisticated (and often proprietary) industrial process and cannot be replicated at the location and scale of rural and developing communities. Under these circumstances, charcoals produced by traditional kiln systems may serve as an effective, low-cost local surrogate for commercial AC as they exhibit similar molecular-scale properties (e.g. porosity and internal surface area, surface reactive sites). In fact, water filtration using charcoal is an ancient practice that continues today in non-industrialized regions around the world, though it has not yet been rigorously demonstrated for removal of modern industrial pollutants.

Unfortunately, charcoal production by traditional kiln systems is often a resource-intensive and highly polluting process. Moreover, traditional charcoals are manufactured primarily as fuel for cooking or smelting of ores; kiln processes are typically not optimized for production of water filter char. Low cost, energy efficient, environmentally sustainable and scalable local production of optimal water filter char can be accomplished with biomass gasification. Char-producing gasifier stoves are rapidly being disseminated for household cooking and heating as they provide energy efficient combustion with reduced emissions. Intermediate- and large-scale gasifier systems are being deployed around the world for generation of “biochar” as an agricultural soil amendment to increase crop yields and sequester carbon.

The purposes of this document are to (1) summarize preliminary results of collaborative field and laboratory research pertaining to the use of traditional kiln charcoals and gasifier chars in decentralized water treatment that targets SOCs, (2) provide a detailed how-to guide for construction and operation of an intermediate scale (200 L) gasifier char production unit using local materials, and (3) provide a detailed how-to guide for integration of biochar filtration into a multi-barrier intermediate-scale (2000 L/day) water treatment system constructed from inexpensive and widely available materials.

The information and design specifications presented here are open source / open architecture. We invite critical feedback from field engineers and WASH (water-sanitation-hygiene) sector development practitioners, university researchers, sustainable development NGOs, etc.

I. Synthetic Chemical Water Contaminants: An Often Overlooked Challenge in Sustainable Community Development

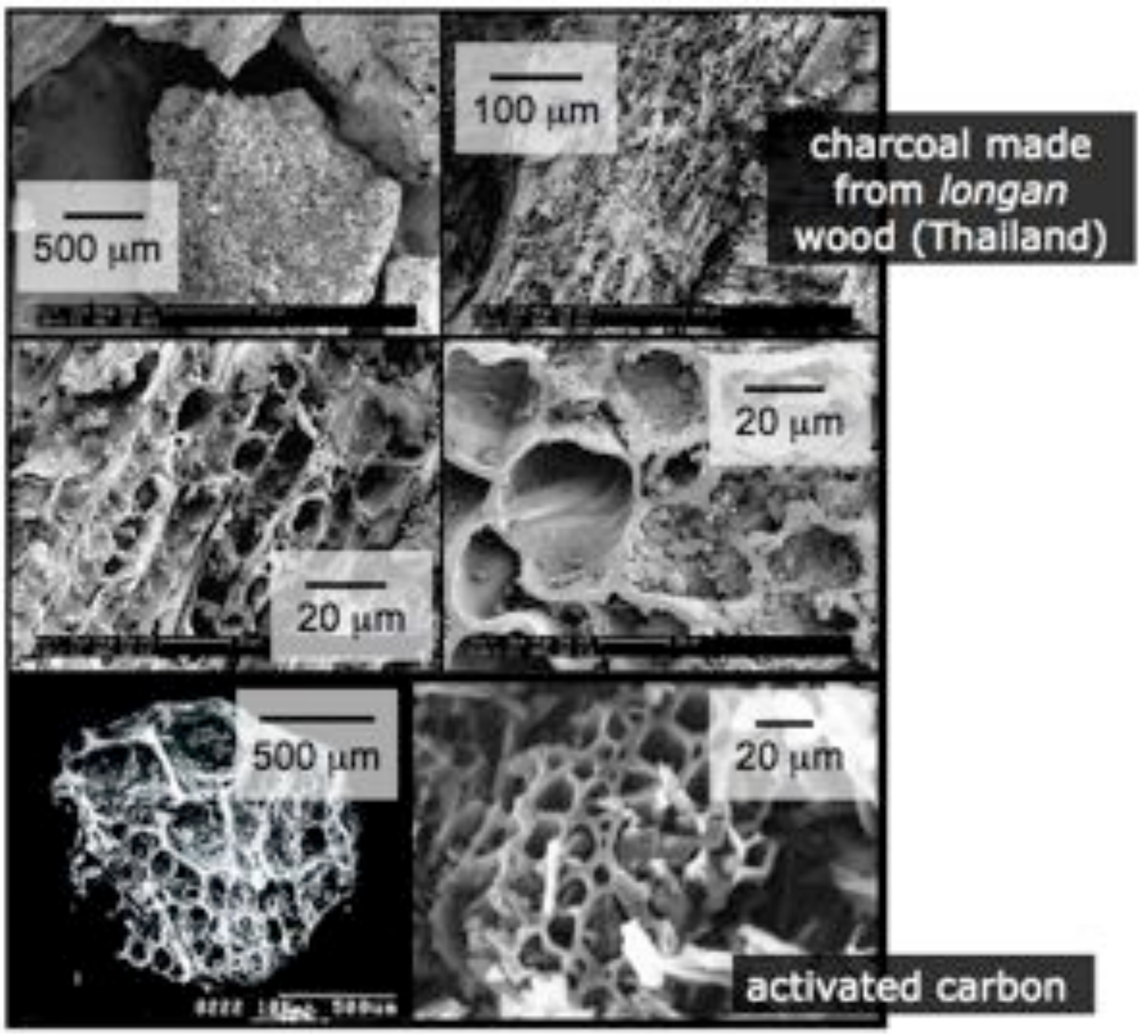
Contamination of drinking water sources by harmful synthetic organic compounds (SOCs) such as pesticides is a major worldwide problem. "Pesticide pollution" appears twice in the top ten of *The World's Worst Toxic Pollution Problems Report 2011*[1] by the Blacksmith Institute, and has been indicated every year's report since initial publication in 2006. Effective, affordable and scalable "green" treatment technologies for SOC removal that are accessible to communities in the developing world or in remote areas of developed countries are, however, lacking.

A recent review in *Science*[2] indicates that the 300 million tons of SOCs produced annually, including 5 million tons of pesticides, constitute a major impairment to water quality on a global scale. The report highlights particular challenges in developing countries including the overuse of pesticides, prevalent ignorance of relevant environmental and health hazards, and widespread unauthorized use of "black market" chemicals. In Thailand, for example, 75% of the pesticides used are banned or heavily restricted in the West due to deleterious ecological and human health effects.[3] The *Science* authors specify that "small-scale, household-based removal techniques are often the only possible mitigation strategy due to the lack of a centralized infrastructure," and call for the development of "reliable, affordable, and simple systems that local inhabitants could use with little training."

Unfortunately, SOCs are not yet "on the radar" of major actors in the water-sanitation-hygiene (WASH) sector of international development. The UN Millennium Development Goals, for example, are only concerned with mitigation of biological agents of waterborne disease.[4] I recently attended a major international conference on global water and health in developing communities.[5] My presentation was the only one that considered SOCs in drinking water and presented a potential treatment technology.[6] Microbial pathogens are often the most immediate threat to human health (e.g. diarrhea) and so focus on these disease agents is warranted. However we cannot discount the threat of bio-accumulating chemical toxins such as pesticides. The immediacy and scale of this problem is highlighted by, for example, a survey of *Hmong* tribe women living in *Mae Sa Mai* village, Chiang Mai Province, Thailand, that reported detection of DDT in 100% of mothers' milk samples. A number of other biocides were also frequently detected, and infants' exposure exceeded by up to 20 times the acceptable daily intakes as recommended by UN-FAO and WHO.[7]

II. Charcoal/Biochar Filtration: An Appropriate, Low-Cost and Sustainable Option for Decentralized Water Treatment?

Charcoal filtration has been used to treat drinking water for thousands of years,[8] and is still widely practiced today – particularly in rural areas of the major charcoal producing countries such as Brazil, India, China, Thailand, and throughout SE Asia.[9] Locally managed charcoal filtration might represent the most effective barrier to SOC exposure available to households and communities in remote and impoverished regions of the world, as charcoal can exhibit properties similar to activated carbon.[10] To-date, however, no studies have quantified how effective charcoals are for water treatment.[11]



Scanning election microscope (SEM) images of *longan* charcoal and commercial activated carbon showing morphological similarities. (Charcoal SEM images courtesy of Carl Saquing, North Carolina State University.)

Our research aims to demonstrate the applicability of locally generated traditional charcoals and gasifier chars for decentralized household and small community water treatment in developing communities. This work realizes a triple-benefit for human health, environmental sustainability, and local economies: (1) to offer economical and technologically accessible water treatment where currently none exists; (2) to offset polluting and energy-inefficient charcoal production with a "green" technology; and (3) to support village level microenterprise in the manufacture of enhanced sorbents. Through partnerships with governments, small businesses, and local and international NGOs, we disseminate these research outcomes in the deployment of appropriate technologies that benefit human livelihoods as well as the environment.

III. Summary and Discussion of Field and Laboratory Research Outcomes

This section outlines the outcomes of recent field studies and laboratory experiments investigating the potential effectiveness of traditional kiln charcoals and gasifier chars for water treatment. To clarify: traditional kiln systems are used to produce charcoals from wood feedstocks typically for use as cooking fuel. Kilning processes are often highly polluting, energy-inefficient, and time- and labor-intensive. Energy efficient, clean burning gasifier units that are typically used for cooking and space-heating produce a residual char, are easier and more pleasant to operate, and make use of a wider range of biomass feedstocks including agricultural and forestry wastes and by-products. More detail on the conceptual background of biomass gasification for char production is given in Section V. Also, an instructional video explaining the conceptual background, construction, and operation of a 200 L drum gasifier unit can be accessed from the Aqueous Solutions website: www.aqsolutions.org.

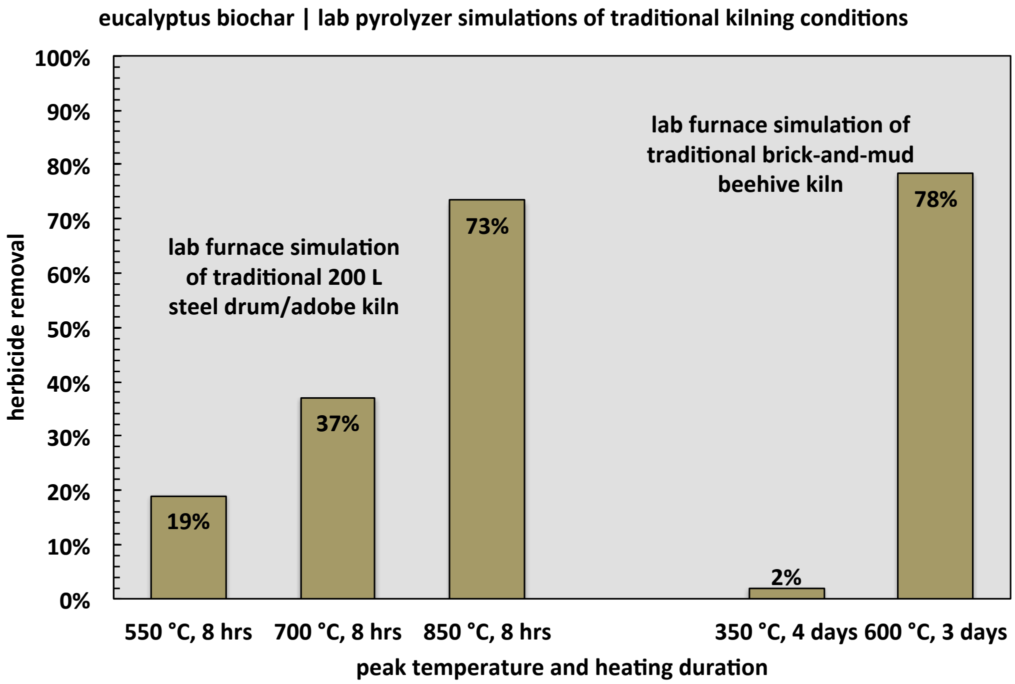
a) Charcoals produced from traditional kiln systems

Our preliminary experiments show that some charcoals produced from traditional Asian village kilns (e.g. the 200 L horizontal drum[12] and brick-and-mud beehive models) exhibit appreciable sorption capacity for herbicides. However, our studies indicate wide variability in SOC uptake among charcoals produced by traditional technologies.[13] Although these initial results are promising, traditional charcoal manufacture systems are energy inefficient and highly polluting, contributing substantial greenhouse gas emissions, and often making use of unsustainably, and sometimes illegally, harvested feedstocks.[14,15,16]

traditional charcoal generation
(Thailand)

200 L steel drum/adobe kiln

brick-and-mud “beehive” kiln

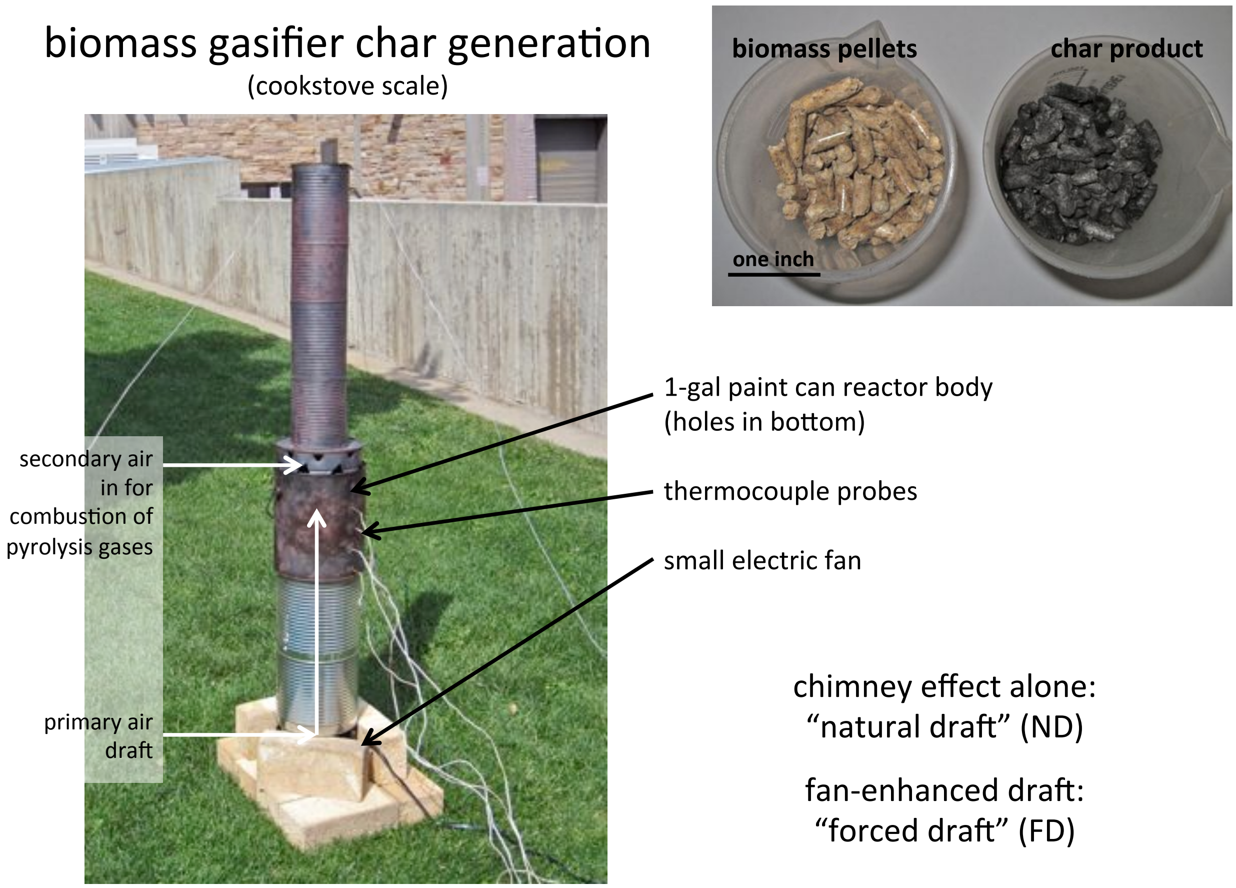


Herbicide removal by a representative range of simulated traditional kiln charcoals.

When it comes to water treatment, not all traditional charcoals are created equal. We have monitored traditional charcoal production in 200 L steel drum/adobe kilns and brick-and-mud beehive kilns in collaboration with farmers and villagers in northern Thailand and the Thai Royal Forestry Department Wood Energy Research Centre in Saraburi Province. These observations inform simulations of the typical range of peak temperature and heating duration characteristic of traditional charcoal production systems using a programmable laboratory pyrolysis unit to generate experimental chars. The plot above indicates wide variability in herbicide uptake capacity of charcoals produced under a representative range of conditions. Charcoals exhibited essentially no uptake to ~ 80% removal under these experimental conditions. (Experimental methods and additional data are presented and discussed below.) Thus the manufacture conditions and resulting quality of the char product exert a strong influence on its potential effectiveness for water treatment.

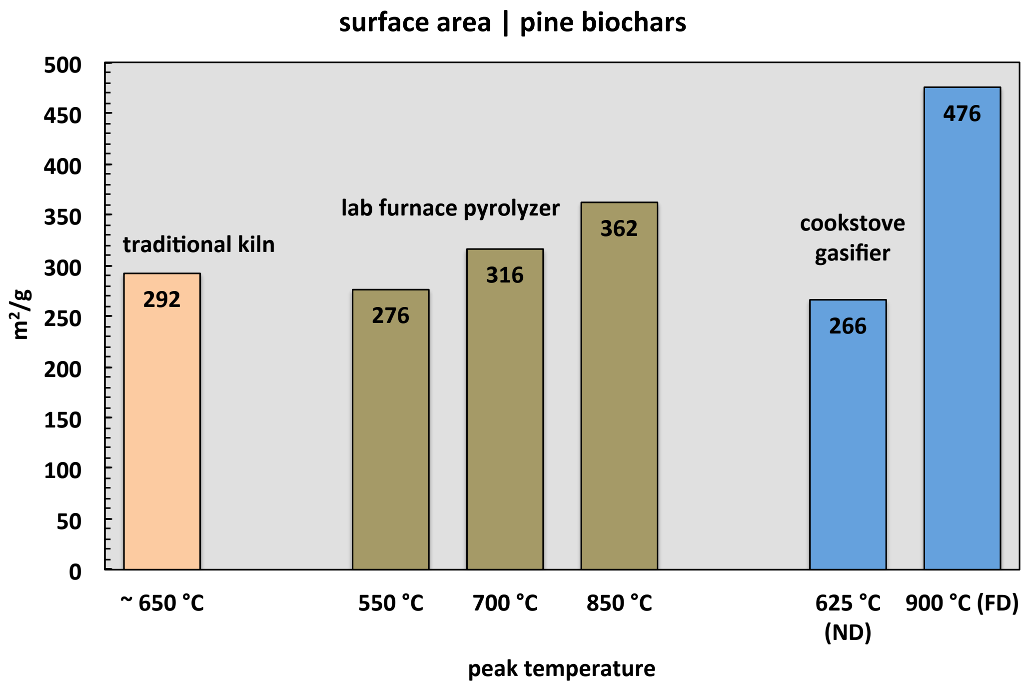
b) Chars produced from biomass gasifiers

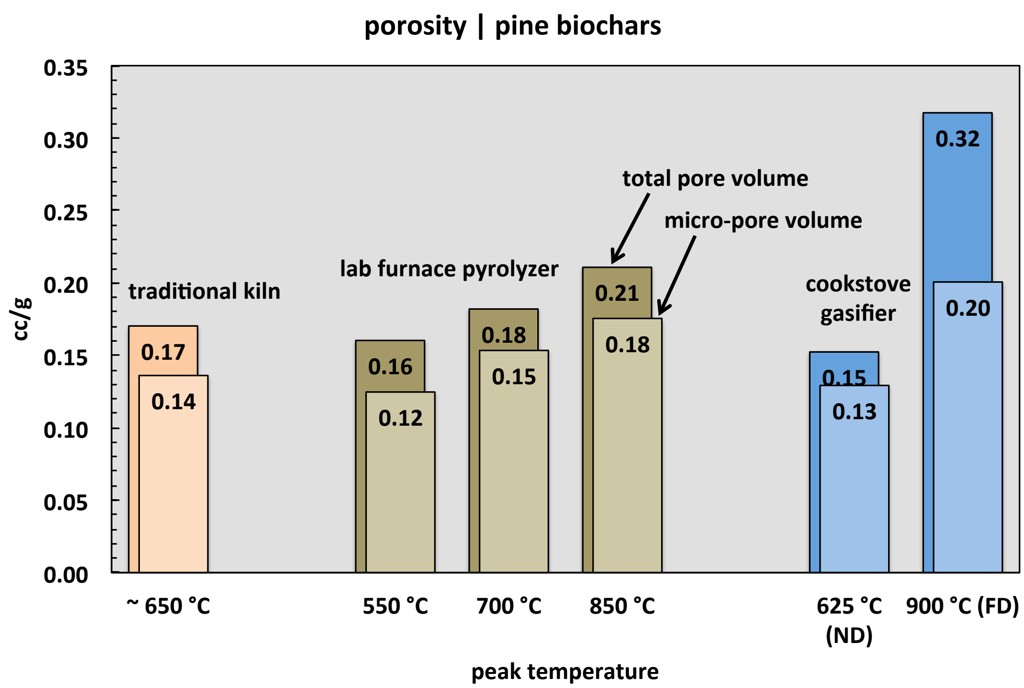
Energy efficient, environmentally sustainable and scalable production of consistent highly sorptive chars can be accomplished with biomass gasification. Biomass gasifier stoves are rapidly being disseminated for household cooking in developing communities as they provide energy efficient combustion with reduced emissions,[17,18] and produce small batches of char from agricultural and forestry by-product fuels during normal daily use.[19,20] Intermediate and large scale gasifier systems are also being deployed around the world for generation of "biochar" as an agricultural soil amendment to increase crop yields and sequester carbon.[21,22,23] Gasifier char production is favorable from environmental and energy standpoints when compared with traditional charcoal manufacture since pyrolysis gases are combusted within the unit rather than emitted as pollutants,[24,25] thereby providing the energy that drives pyrolysis and obviating the need for an external heat energy source. Also, biomass gasifiers can be readily coupled with other unit processes for bio-fuel collection and waste heat utilization.[26]



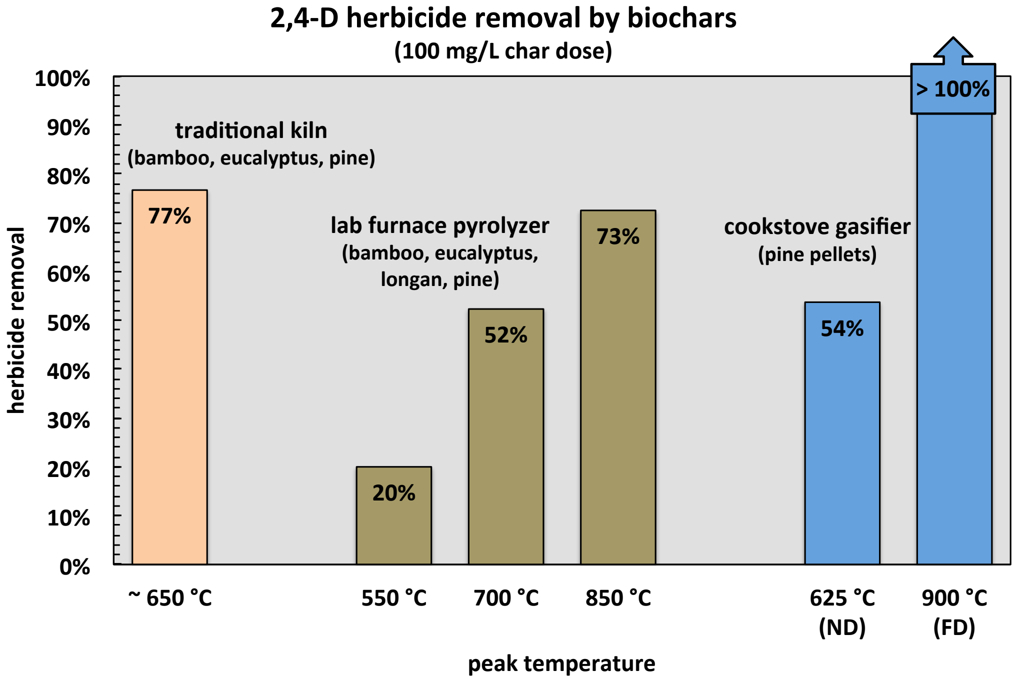
Cookstove-scale biomass gasifier char production unit. See Anderson et al. 2007,[27] Anderson 2010[28] and McLaughlin 2010[29] and 2011[30] for theory and detailed construction notes. (Thermocouple probes are for research purposes and may be omitted.)

Our studies to-date show that gasifier chars, particularly when operated in high-draft mode (for example, by augmenting airflow when necessary by a fan or blower) consistently develop enhanced physico-chemical characteristics such as high surface area, micro-porosity, and herbicide uptake capacity when compared with traditional kiln charcoals.[31,32] Gasifier char may therefore be an optimal choice for sorption of pesticides, industrial and fuel compounds, human and livestock pharmaceuticals, and other SOCs of increasing concern to water quality.





Plots showing surface area (upper) and porosity (lower) of chars made (1) from split pine logs in a 200 L traditional style steel drum and adobe kiln, (2) from uniform pine wood slats in a programmable laboratory pyrolyzer used to manufacture char under controlled temperature and atmospheric conditions, and (3) from a cookstove scale TLUD gasifier using pine pellets. (Surface area and porosimetry courtesy of David Rutherford, USGS.)



Plot showing removal of the common herbicide 2,4-D (2,4-dichlorophenoxyacetic acid) from solution by various chars in batch experiments.

2,4-D was chosen as a test compound because of its environmental relevance as one of the most widely used herbicides worldwide and one of the most commonly detected pesticides in environmental waters,[33] as well as for its human health implications as a potential carcinogen and suspected endocrine disruptor.[34] Its chemical properties also make it a challenging compound to remove by adsorption – thus if 2,4-D is taken up by a char then it is likely that most other pesticides would also be effectively removed.

Batch experiments used 100 mg/L of each char ground by mortar and pestle to pass a 200-mesh US Standard Sieve, and introduced to solutions initially containing 100 µg/L 2,4-D, and background organic matter at a total organic carbon concentration of 4 mg/L (to simulate natural waters). Experiment bottles were agitated for two weeks in order to reach equilibrium. The traditional kiln data is an average for three chars made from bamboo, split eucalyptus and pine logs charred in a 200 L steel drum/adobe kiln. The lab pyrolyzer data displayed are an average of four chars made from bamboo, eucalyptus, longan and pine logs cut into slats of uniform size (15 cm x 10 cm x 1 cm) and pyrolyzed under controlled temperature and atmospheric conditions. The gasifier data displayed are an average from several batches of pine pellet char made in a cookstove-scale TLUD unit under natural-draft ("ND") and forced-draft ("FD", with an electric fan) conditions. The gasifier-FD char also removed 2,4-D below detection limits (4 µg/L) at a dose of only 20 mg/L. Thus as indicated in the plot above, at a dose of 100 mg/L additional capacity exists in the gasifier-FD char even after all 2,4-D is taken up: hence ">100%" removal.

We are currently characterizing chars produced with intermediate-scale gasifiers made from 200 L steel drums (as pictured below) as a means for generating greater quantities of enhanced water filter char from agricultural and forestry residues.

Gasifier biochar production system made from two 200 L drums and scrap metal. (Photo by Lyse Kong.)

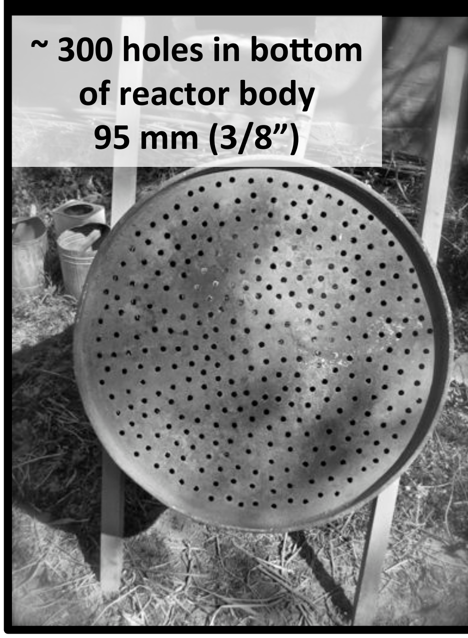
IV. Preliminary Conclusions From Laboratory and Field Research

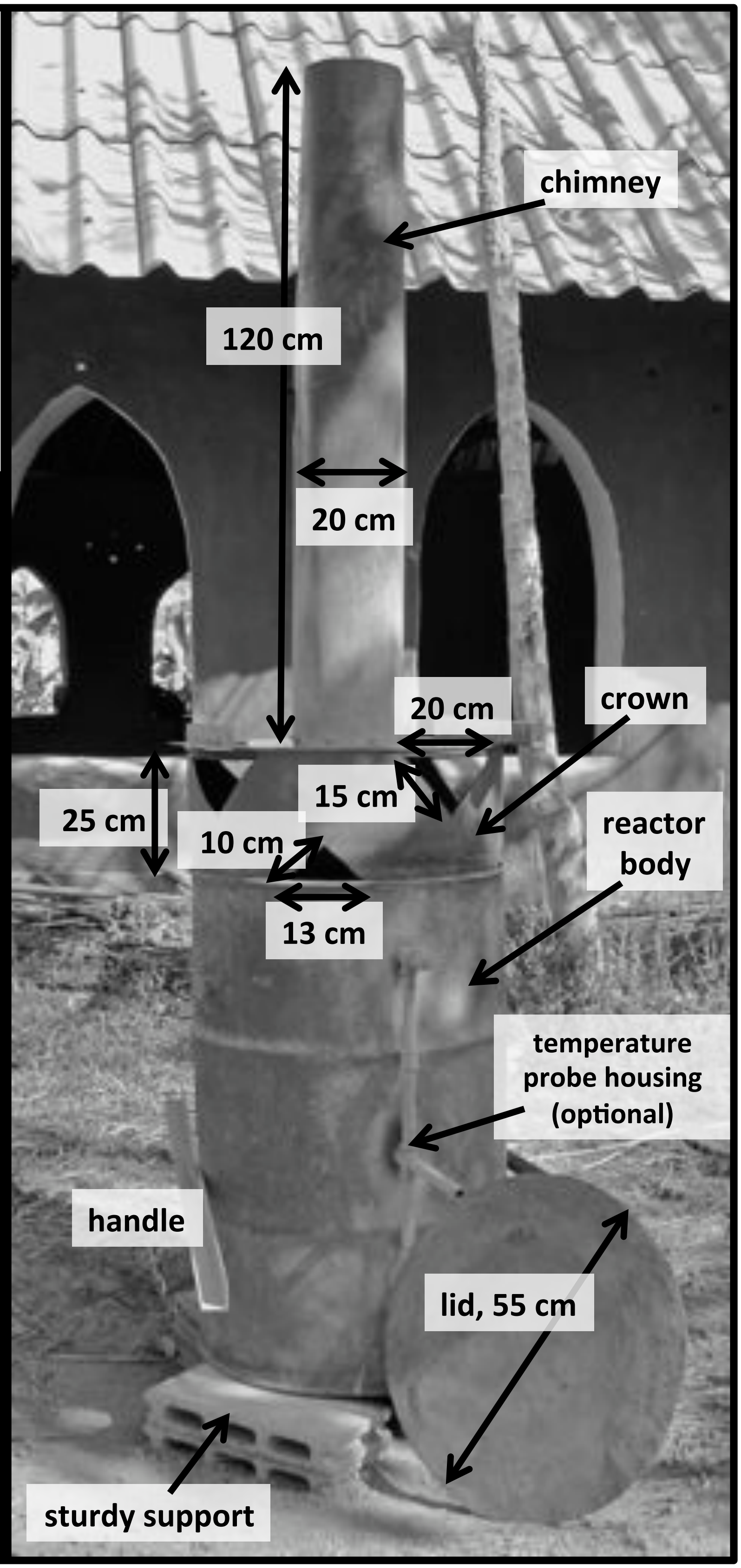
In summary, compared with traditional charcoal production, gasifier char production is more energy efficient and emits far less atmospheric pollution. Furthermore, gasifiers can be operated with agricultural and forestry residues and by-products, are ideally suited for small grained, chipped or pelletized biomass fuels. Gasifiers can readily be linked with other processes and applications for capture and use of waste heat. Our research has shown both small scale (cookstove) and intermediate scale (200 L drum) pyrolyzers to consistently achieve high temperatures (650-950 °C) required for substantial development of surface area and porosity in the char product, concomitant with improved performance for herbicide uptake in batch experiments. Therefore, gasifier biochars are a promising appropriate, low-cost and sustainable technology for affordable decentralized water treatment in rural and developing communities.

Furthermore, the use of biochar for water treatment does not preclude its eventual application as a beneficial agricultural soil amendment and carbon sequestration strategy. In fact, we recommend composting[35] and soil application as the preferred mode of processing spent filter char. The best strategy for rural communities and smallholders to utilize spent filter char is simply to allow ample time and favorable conditions for environmental microorganisms to biodegrade any sorbed contaminants. Elevated temperatures such as those achieved during composting of organic wastes, for example in composting toilets, accelerate microbial activity and biodegradation processes. Moreover, based on recent research with carbon adsorbents we do not expect significant contaminant release to soils and plants by leaching from spent filter char.[36] A conservative approach to land application of spent filter char can also be adopted, using low incorporation rates of ~ 100 kg of char per hectare.

200 L Top-Lit Up-Draft (TLUD) Biomass Gasifier

For Generating Enhanced Water Filter Biochar





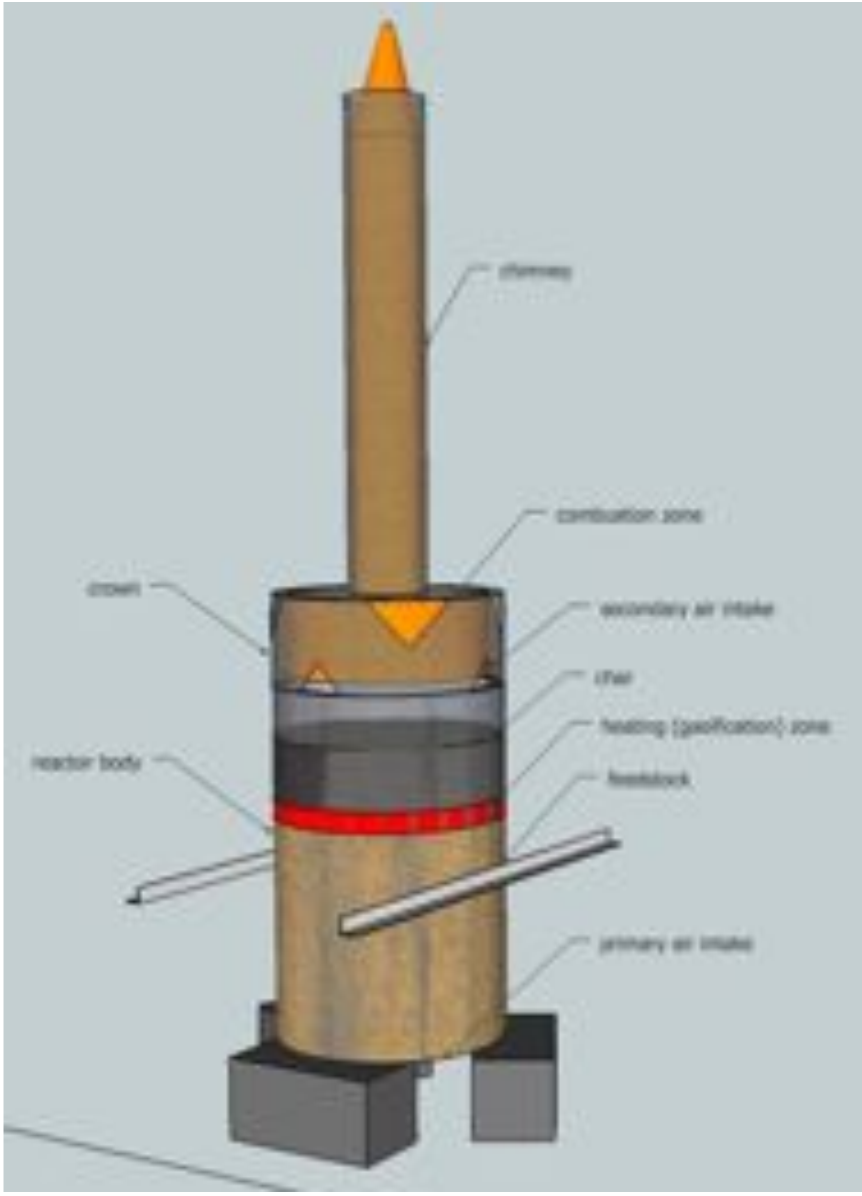
V. How-To Section: Fabricating A 200 L Top-Lit Up-Draft (TLUD) Biomass Gasifier For Generating Enhanced Water Filter Biochar

An instructional video explaining the conceptual background, construction, and operation of this unit can be accessed from the Aqueous Solutions website: www.aqsolutions.org.

a) Conceptual background

The process of creating char from biomass – pyrolysis – involves heating the woody starting material ("feedstock") in an oxygen-restricted environment. The key to generating enhanced water filter biochar (i.e. char with substantial micro-porosity and surface area for the effective uptake and binding of synthetic organic pollutants) is reaching hot enough temperatures to remove the naturally occurring tarry and oily components of biomass while converting the remaining carbon-rich material to a graphite-like structure. In biomass gasification, high temperatures are obtained by ensuring a strong air draft through the feedstock. A strong draft supplies oxygen for a small amount of the feedstock to combust thereby providing heat to gasify and carbonize the adjacent remaining feed. The draft also sweeps the tarry and oily vapors away from the carbonizing feedstock, which allows for the development of extensive porosity in the char.

In a top-lit up-draft (TLUD) gasifier, air draft enters through holes in the bottom of the reactor body and rises upwards through the feedstock ("up-draft"). The fire burns from the top of the reactor body downward ("top-lit"). (See schematic below.) The zone of pyrolysis thus moves from the top to the bottom of the reactor body over the course of the burn. The upward-moving air draft (termed "primary air") supplies limited oxygen to keep the process going but not enough to combust all of the hot feedstock. As primary air draft moves through the pyrolysis zone within the reactor body it sweeps combustible gases rapidly upwards into the combustion zone within the crown and chimney. Vents in the crown admit ample air (termed "secondary air") for complete combustion of the hot pyrolysis gases. The hot combusting gases move upwards through the chimney, augmenting the primary air entering the bottom of the reactor body.



Schematic of TLUD gasifier interior showing feedstock gasification/carbonization in the heating zone and combustion of the rising pyrolysis gases when combined with secondary air in the combustion zone. The heating/pyrolysis zone proceeds from the top to the bottom of the reactor body during firing. (Illustration by Nathan Reents.)

A well-operating TLUD gasifier should emit little or no smoke, since the vapors and particulates that constitute smoke are completely combusted within the unit. This is what makes the process more energy efficient and environmentally friendly than traditional charcoal manufacture. In traditional charcoaling, pyrolysis gases – which include methane, carbon monoxide, nitrogen oxides, particulate matter, and other products of incomplete combustion – are released in large quantities as problematic air pollutants. Furthermore, in traditional charcoaling a separate fuel source in addition to the feedstock is required to provide the heat energy for pyrolysis. TLUD gasifiers solve both of these problems simultaneously by completely burning the pyrolysis gases, releasing primarily only CO_2 and water vapor to the atmosphere, while powering the conversion of the feedstock stock to char. Moreover, gasifiers are less time-consuming to operate: the burn period of a traditional-style 200 L steel drum kiln is typically 5-8 hours with a 12-hour cooling period; the 200 L TLUD gasifier burns for 1-2 hours depending on the feedstock, and takes another 1-2 hours to cool to handling temperatures.

b) Materials and tools

Note that the TLUD gasifier design described here is an open architecture – feel free to modify as needed to achieve desired performance. We invite your feedback on the construction and use of this and similar units. Please send comments to josh@aqsolutions.org.

Materials required include: two 200 L (55 gal) steel drums for the reactor body, crown and lid; scrap metal (square tubular or angle iron) for handles; sheet metal or flue pipe for chimney (NOT tin, aluminum, or thin galvanized steel as these will melt or quickly break down); concrete block or similar to form a study support base; assorted bolts, nuts and washers. Helpful tools include an angle grinder and drill/bits or cold chisel for cutting metal, and a basic welding setup.

c) Construction

Drum #1 will become the reactor body and drum #2 will become the crown and lid.

Cut a circle out of the top of drum #1 leaving a 5 cm lip around the edge. Drill about 300 evenly spaced holes 9-10 mm in diameter (3/8”) in the bottom of drum #1. Alternately, cut radial slots into the bottom of the drum giving a similar total cross-sectional area of openings. Cut some pieces of angle iron or square tubular steel at least 120 cm long for handles. Weld or bolt these securely to the sides of drum #1.

If you don’t have ready access to flue pipe, the chimney can be fabricated by rolling a rectangular piece of sheet steel, then clamping and welding the seam.

Cut the upper and lower triangular vents evenly spaced around one end of drum #2: four upper vents 15x20 cm and four lower vents 10x13 cm offset from the upper vents (see diagram at the beginning of this section). Then cut around the perimeter of drum #2 to make the crown 25 cm tall. Cut a tabbed opening in the center of the crown face, bend the tabs outward and attach the chimney by bolts or welds. Cut the lid out of the other end of drum #2 – about 55 cm in diameter, or large enough to overlap the lip cut in the top of drum #1 by 2-3 cm while still fitting inside the rim.

Cut two 2 m lengths of angle iron or metal tubing to use for removing the hot crown.

Place the reactor body onto concrete blocks or other sturdy support allowing an ample gap with the ground for airflow to the bottom of the drum. Place the crown/chimney on top of the reactor body, with the crown resting on the lip in the top of the reactor body inside the rim of the drum. A snug fit is good. Make sure everything is level, sturdy, and will not tip over during operation.

d) Operation

For best results making TLUD gasifier char, draft must be optimized. Too much draft results in high temperatures but too much combustion of the feedstock and thus low char yields. Too little draft results in insufficient temperatures for the onset of effective gasification – the feedstock smolders, produces a lot of smoke, and does not char well.

Draft is directly influenced by how the feedstock packs into the reactor body. This depends on the size and shape of the feedstock. Ideal materials are dry (not freshly cut) wood branches and bamboo poles 2-5 cm in diameter cut to 10-15 cm lengths. Corncobs are a good size and shape. Smaller branches and twigs, small lumber scrap, chipped and broken coconut shells, and coarse wood chips can also be used. Biomass pellets work well if they are not too small. Small pellets, fine wood chips, rice husks, saw dust and wood shavings are too fine and inhibit draft unless a supplemental fan or blower is applied to enhance primary air supply. Thick materials can be used but need to be thinly cut – whole logs do not char thoroughly. Mixtures of different materials, sizes and shapes, work fine.

The best water filter char comes from woody feedstocks with high lignin content. Switchgrass, straw, and rice husks are mainly composed of cellulose and mineral matter and do not produce good water filter char. Corncobs produce mediocre water filter char and do not require processing (i.e. cutting or chipping) prior to loading into the reactor.

Place the reactor on the concrete block supports and load it uniformly with cut or chipped feedstock. If using dense wood as the primary feedstock, a 5-10 cm layer of chopped bamboo or corncobs can be loaded into the top portion of the reactor body to accelerate the initial heating and gasifying of the wood. Set the crown/chimney firmly in place and stuff a few handfuls of straw inside the crown as kindling. (Accelerants such as kerosene or lighter fluid are not necessary and should be avoided.) If there are any air gaps where the chimney is attached to the crown seal them with mud.

Light the straw through the vent holes of the crown. The material at the top of the reactor body will begin to burn. A small amount of smoke may be emitted from the chimney during this stage. Once sufficient temperatures have been attained for gasification, the feedstock glows while a yellow-orange "fireball" should appear hovering near the top of the reactor body, inside the crown and inside the lower chimney. In preparation for shutdown, make a mud pit adjacent to the reactor body large enough to readily accommodate the drum, and save an additional 1-2 buckets of mud for sealing the top of the reactor.

A candle or chunk of wax can be rubbed on the outside of the reactor body to indicate where the pyrolysis zone is located. When the pyrolysis zone reaches the bottom of the reactor body a red glow will be visible through the primary air holes. The yellow-orange color of the "fireball" in the crown will fade to a clear, bluish flame. This indicates that all wood gases have been burned off from the feedstock and char combustion is commencing. Char combustion occurs at much higher temperatures than gasification (in excess of 1400 °C compared with 700-900 °C typical for gasification). It's undesirable to let char combustion continue for too long since the desired char product is being destroyed, and because the very high temperatures may result in the structural failure of the reactor body. The appearance of a blue flame along with the fading of the yellow-orange flame is thus a dependable visual indicator of when it's time to shut down the process.

Shutting down the gasifier requires two persons. (See photo series below.) Wear study leather work gloves. Place the 2 m lengths of metal tubing or angle iron through the vent holes in the crown to act as handles. With a person on opposite sides of the gasifier, lift off the crown/chimney and set it aside. Place the lid on top of the reactor body, then grasp the handles of the reactor body, lift and set it in the adjacent mud pit to seal the bottom. Use the mud set aside to seal the lid on the top of the reactor body. Allow the reactor to cool at least 1-2 hours, then remove the mud and collect your biochar!

[Note: An alternative shutdown method involves dousing the hot reactor and contents with copious water. This may alter the sorption properties of the product char in favorable or unfavorable ways. We are currently investigating the effects of "wet shutdown" on char properties and cannot recommend for or against this procedure at this time.]

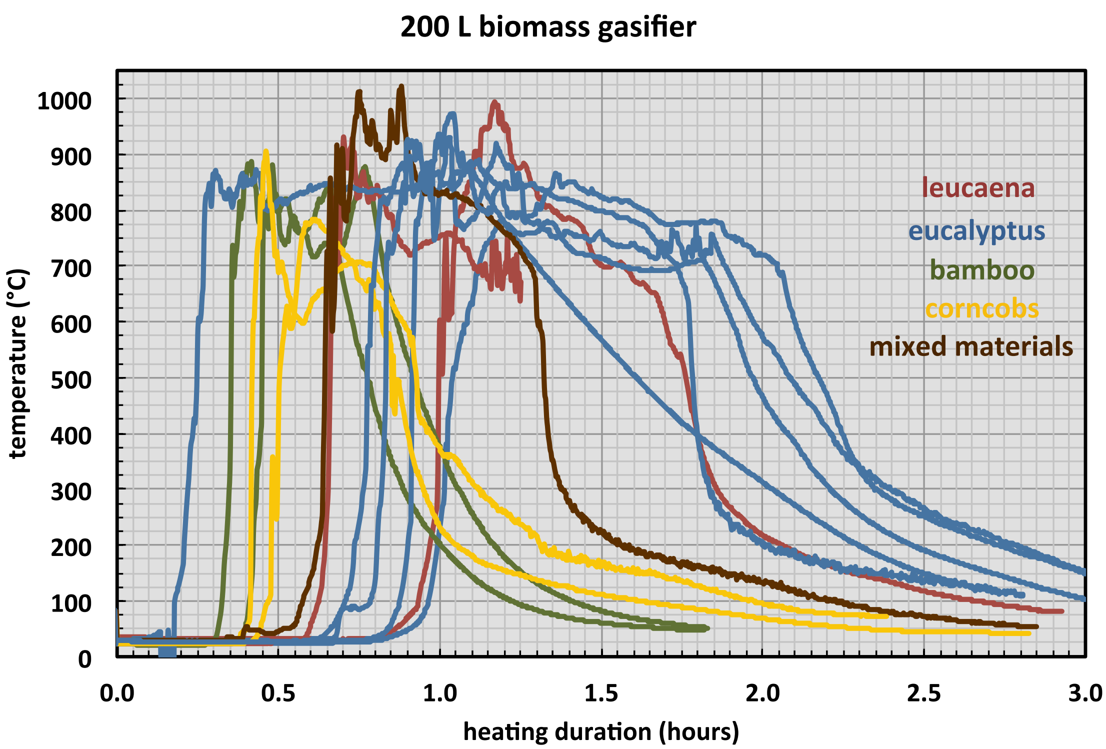
During the charring process the feedstock sinks, subsides, and shifts in the reactor – for making optimal water filter char it is normal and desirable for the volume to have shrunk to one-half or even one-third of the drum.

Photo series showing shutdown procedure: When bottom of drum begins to glow (a) and blue flames appear in crown (b) then pyrolysis is nearing completion. Remove the crown and chimney (c) and (d). Put on the lid and move the reactor body to the adjacent mud pit to seal the bottom (e) and (f). Seal the top with mud to prevent air leaks (g) and (h). (Photography by Lyse Kong.)

e) Optional parameter monitoring and ongoing collaborative gasifier char research

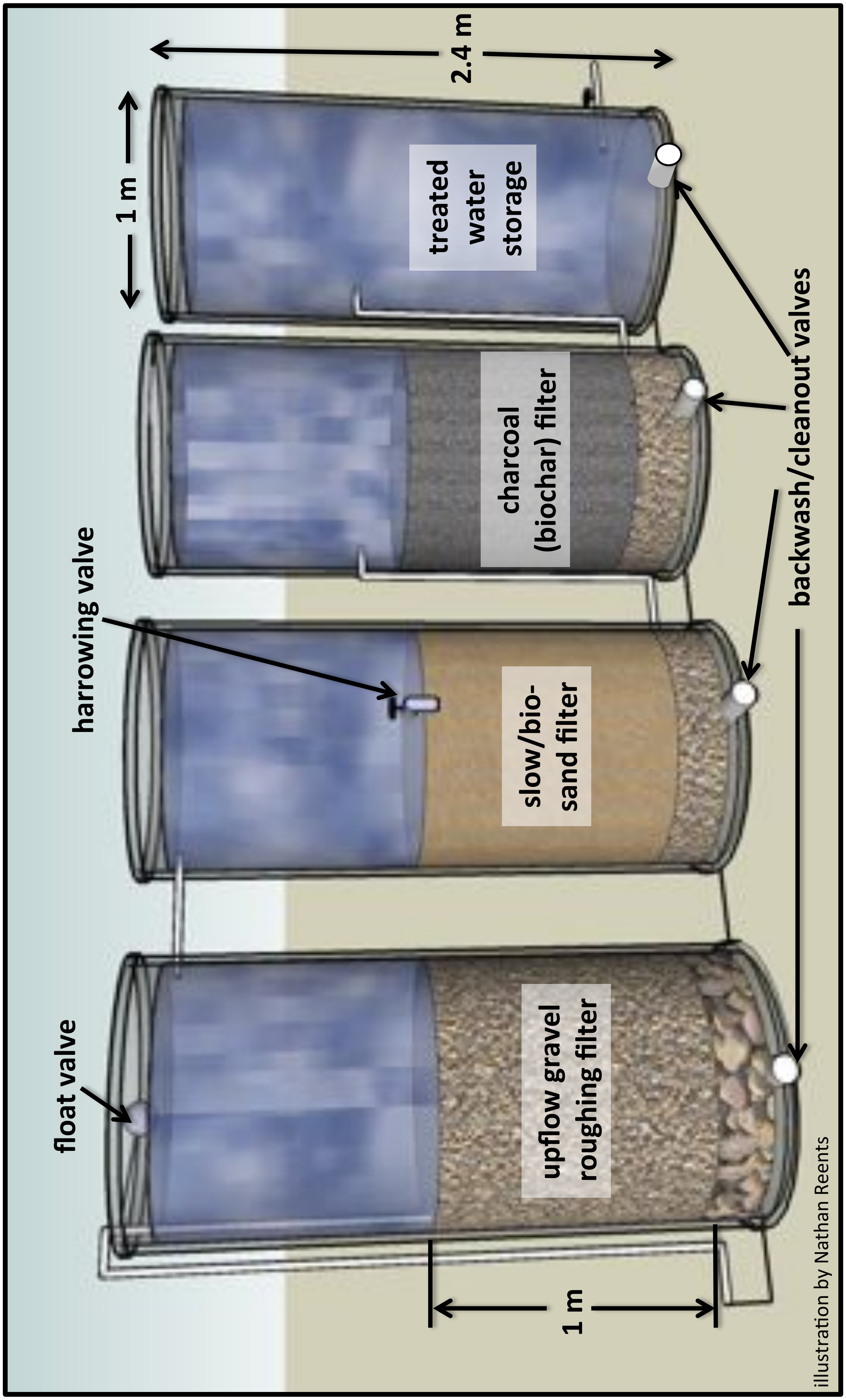
Those who desire a more in-depth experience in making consistent and optimal water filter char can monitor temperature and mass loss during their process. These parameters provide a ready indication of how extensively carbonized and porous the product char is, and how consistent the process is from one batch to the next.

Thermocouple probes positioned inside the reactor body can be protectively housed in a simple manifold made from threaded steel plumbing nipples and connectors. Temperature dataloggers greatly facilitate data collection during the heating phase. Comparing the mass of the product char to the original mass of the feedstock gives an estimate of the extent of conversion – a well-carbonized char undergoes greater mass loss than a poorly carbonized char. Using the model of TLUD gasifier depicted here we have consistently achieved peak temperatures of 750-950 °C for burn durations of 1-2 hours (depending on the type of feedstock), with corresponding mass losses around 85% (a full drum yields 1/3-1/2 drum by volume; or, a 40-75 kg batch of feedstock yields 6-12 kg of char by mass). These conditions are optimal for generation of good quality water filter char.



Temperature data collected from several runs with our gasifier using a variety of feedstocks.

Biochar experimenters who track these parameters are encouraged to submit their data and observations to our open-source database. Contact **josh@aqsolutions.org** to find out more.



1 m
2.4 m
treated water storage
charcoal (biochar) filter
harrowing valve
slow/bio-sand filter
float valve
upflow gravel roughing filter
backwash/cleanout valves
1 m
illustration by Nathan Reents

VI. How-To Section: Constructing A Multi-Barrier Water Treatment System Incorporating Biochar Filtration

Improving water quality involves mitigating disease causing biological agents (pathogens) as well as harmful chemical contaminants and non-harmful compounds that impart an unpleasant taste, odor, or appearance. Pictured above is a multi-barrier water treatment system that addresses these challenges using a sequence of gravel, sand, and char filtration. A system built according to these specifications can provide 1500-2000 L/day of treated water depending upon source water quality.

This water system is an open architecture – we invite and encourage modification, adaptation and improvement! Please share your feedback with josh@aqsolutions.org.

a) Siting and materials

i. Siting

Gravity is the easiest and most dependable way to move water. Ideally, the water system is sited at lower elevation than the source water and higher elevation than the location(s) where treated water will be used. This circumstance enables completely passive operation of the treatment system and very simple control using only a float valve (the same device that refills the tanks of flush toilets): when water is withdrawn from the storage tank the water level in the system drops, opening the float valve. When the system is full, the float valve closes.

ii. Containment

In SE Asia, stackable prefabricated concrete rings are inexpensive and widely available in most rural areas and are commonly used for tank construction. Rings are mortared together with concrete and the tank interior walls sealed with cement slurry. Filling the tank with water when the slurry is still wet pushes it into pores to cure and seals the tank.

Plastic tanks can also be used, or, if appropriately skilled masons are available, custom ferro-cement tanks can be constructed. Tanks need to have a large opening and removable lid so that a person can fully enter for connecting plumbing, installing filter media, conducting routine maintenance (which includes cleaning tank interiors and removal/replacement of the char), and for repairs.

Lids or some cover material to exclude sunlight should be used to inhibit the growth of photosynthetic microorganisms (algae, cyanobacteria) in the system. Tank tops should be wrapped in fine mesh screening to prevent entrance of insects, bird droppings, leaves and bits of debris, etc. into the system.

Tanks should be constructed on a solid and level foundation (preferably of reinforced concrete), and distinguished from other similar-appearing water tanks (e.g. rainwater, irrigation water, septic, etc.) using appropriate and durable local signage.

iii. Plumbing

PVC pipe is ubiquitous and cheap in most locations. 1/2" to 3/4" diameter is fine for most connections to and from the water system and between the tanks. The cleanout valves at the bottoms of the tanks should be larger, typically 3" to 4". 1" to 2" is ideal for the harrowing valve midway up the sand filter tank.

Plumbing in the bottom of filter tanks should be protected from physical damage and blockage by underdrains made from rock and coarse gravel at least 20 cm in depth. Sand and char filter media should be supported by an additional graded underdrain made from pea gravel overlain by coarse sand (at least 10 cm deep of each).

The connection from the gravel filter to the sand filter should be located near the top of the tanks, a few cm below the full-position water line (set by adjustment of the float valve). The connection from the sand filter to the char filter should enter the char tank at a level about 5 cm above the level of the sand. (I.e. at a height of about 145 cm above the bottom of the tank if a 40 cm underdrain is used with 1 m of filter media). The same is true for the connection from the char filter to the storage tank. This ensures that the water level in the sand and char filters will never drop below the level of the filter media. This is essential for maintaining full vigor and functioning of the biofilm in the sand filter, and for utilizing all of the sorption capacity of the char filter.

iv. Media

Standard gravel (1-4 cm sized rocks) is fine for the roughing filter. Standard fine sand (as opposed to coarse or very fine sand) should be used for the sand filter. Sifted sand or masonry sand are very fine and may generate too much head loss, especially if source water contains a lot of organic matter. Large pieces of charcoal should be broken into 1-5 cm pieces. Gasifier char can be used directly since feedstocks are small or pre-cut materials.

b) How it works… (and how to maintain it…)

i. Gravel roughing filter

Source water (controlled by the float valve) enters by a pipe at the bottom of the gravel filter and flows upward through the media. This removes turbidity (particles) and some dissolved matter that sticks to the surfaces of particles as they settle. One or more times during the year (depending upon source water quality), the large valve (at least 3" – bigger is better) at the bottom of the gravel filter is opened, rapidly reversing the direction of flow through the filter ("backwashing") in order to flush out the accumulated sediment and organic matter.

Gravel filter maintenance: As long as the plumbing does not break, or the plumbing or media become irremediably clogged by sediment or debris, the gravel does not need to be removed or replaced within the lifetime of the treatment system. Some "MacGyvering" may be necessary to ensure that the outlet of the float valve completely directs influent water into the pipe leading to the bottom of the tank. The float valve should be periodically examined for potential clogging or misdirection of influent water.

ii. Slow/bio- sand filter

Sand filters remove microorganisms and particles by physical straining, and some dissolved compounds by adsorption onto the surfaces of sand grains. Most importantly, however, biologically active sand filters remove problematic microorganisms and chemical compounds by biodegradation. Unless a disinfectant such as chlorine is added to the system, a biofilm (or *schmutzdecke*) naturally develops within a few days upon beginning use of the filter, and continues to mature over a period of several weeks. The length of this time period, termed "ripening," depends primarily upon ambient temperature and source water characteristics.

The biofilm is concentrated in the top 1 to 3 cm of the media (though exists more sparsely throughout the sand bed) and actively degrades dissolved organic compounds in the influent water. The natural environmental microorganisms that comprise the biofilm prevent the establishment of microbial pathogen colonies through competition and predation. Thus sand filters with healthy established biofilms are an effective and well-demonstrated technique for removal of pathogens as well as some hazardous biodegradable compounds in water treatment. An excellent recent compilation of the scientific literature on micro-pollutant removal through biologically enhanced filtration processes is provided by Shimabuku et al. 2011.[37]

A note on BSFs and SSFs and S-BSFs… Readers may be familiar with smaller (family sized) rapid rate "BioSand Filter (BSF)" units promoted for household water treatment in developing communities, as well as conventional large-scale slow sand filters (SSF) used by municipal drinking water utilities in developed areas. The slow/bio- sand (S-BSF) filter presented here is an intermediate design adapted to address some of the respective limitations of BSFs and SSFs.

In short, in sand filters a longer contact time between the water and sand/biofilm provides better treatment by allowing more time for adsorption and biodegradation mechanisms to occur. However, increasing contact time requires a larger filter unit to treat a similar volume of water, incurring greater construction costs and occupying a larger "footprint" for the treatment system. Furthermore, a slow and steady loading rate (as opposed to a rapid, intermittent loading rate as in household BSFs) contributes to better biofilm function and enhanced treatment as this establishes a quasi-steady-state influx of nutrients to the biofilm.

The S-BSF unit process described here combines a low and more consistent loading rate for optimal contact time with the biofilm and media to achieve effective pathogen removal and contaminant biodegradation, while providing sufficient total throughput of treated water in an economical, small-footprint design.

Slow/bio-sand filter maintenance: The sand filter is the "bottleneck" step (i.e. the flow-rate-determining step) of this water system. As organic material accumulates in the biofilm zone at the top of the sand bed, flow rates may diminish below a minimum threshold of treated water needed by the community. Thus a few times per year it may be necessary to "wet harrow" the sand filter to restore sufficient flow rates. This is accomplished using a long pole to vigorously stir up and suspend the accumulated sediment from the top few centimeters of sand into the water above the filter bed. The harrowing valve (located 5 to 10 cm above the top level of the sand) is then opened to allow the suspended sediment and organic material to wash rapidly out of the upper portion of the tank. The majority of the suspended sand particles are not washed out but resettle, and the biofilm reestablishes full function within a few days. (Some sand is washed out during harrowing and after many cycles it may be necessary to replace some sand to the top of the filter bed.)

The frequency of wet harrowing required to maintain adequate flow rates is determined by the community's water needs and the characteristics of the source water. Since the sand filter is the "bottleneck step" of the treatment system, increased throughput can be achieved by increasing the size (cross-sectional area) of the filter in the original design, or by building additional units in parallel.

iii. Charcoal (biochar) filter

Terminology and key concepts The char filter functions primarily by the process of adsorption. *Ad*sorption, which signifies a surface interaction between dissolved species and the char, is distinct from *ab*sorption, which essentially means "to soak up" or "to take into." To be exact, however, in water treatment contaminants diffuse into char pores (*ab*sorption) where they bind to char surfaces (*ad*sorption). This has led wide use of the nonspecific term "sorption."

The porosity and large surface area of chars provides a multitude of reactive sites for the attachment of dissolved compounds. These reactive sites can bind non-problematic dissolved organic compounds as well as targeted hazardous contaminants. Background dissolved organic matter, present in all natural waters, can occupy sites on char surfaces and thereby exclude contaminants of concern. This is called "fouling."

Fouling in char filters is mitigated by upstream unit processes – in our case, the gravel and sand filters – that act to remove a substantial portion of background dissolved organic matter from the source water before it encounters the char. The principle is to achieve a high level of treatment prior to the char filter, in order to "save the carbon" for removal of targeted problematic dissolved compounds that make it through the previous treatment steps.

Local chars versus activated carbon In treatment system described here, the char filter functions as a "post-filter adsorber," analogous to the use of granular activated carbon (GAC) unit processes in advanced municipal water treatment facilities. The char filter is placed after the gravel and sand filters in order to target specific components of background organic matter (for example, compounds that cause undesirable tastes, odors, or appearance) or SOCs such as pesticides, pharmaceuticals, fuel compounds, etc., that are not well removed by the preceding unit processes. Knappe 2006[38] and Summers et al. 2011[39] provide thorough reviews of the use of GAC in water treatment – the scientific theory and engineering principles described by the authors apply here as well.

There are, however, a few important differences between locally generated charcoals/biochars and commercial activated carbon. First, local chars are (ideally) made from agricultural and forestry residues and sustainably harvested renewable woody biomass. Most commercial activated carbons are made from (nonrenewable) subbituminous and lignite coal. Both local chars and activated carbons undergo a carbonization step where the feedstock is heated to several hundred degrees Celsius under restricted oxygen atmosphere. However, commercial carbons are subsequently "activated" by physical and/or chemical processes to develop the internal pore structure and surface reactivity using high-pressure steam, CO_2, or acids. In other words, the activation step is an industrial process requiring facilities, power, equipment and reagents that are not accessible in developing communities.

Furthermore, compared with activated carbon, local chars may contain substantial proportions of residual incompletely carbonized tarry and oily compounds, particularly if the char is generated at lower temperature (i.e. below ~ 600 °C, as in cooking charcoal manufacture). Local chars may also contain a high proportion of ash if the feedstock consisted of high mineral content grasses or husks (e.g. rice hulls). Since local chars are not "activated" and may contain higher proportions of ash or residual tars and oils, they are not expected to exhibit the same water treatment capacity as commercial/industrial GACs. This disparity is compensated by designing for higher carbon use-rates (i.e. the mass of carbon used to treat a given volume of water).

Carbon bio-filtration In the char filter as in the sand filter, if no disinfectant is added to the system then a natural biofilm readily develops on the surfaces of the filter media. This is generally a good thing. While the biofilm adds to the influx of natural organic matter in the system and thus may contribute to fouling, the environmental microorganisms making up the biofilm prevent the development of pathogen colonies in the media through competition and predation.

Furthermore, recent research on biological activated carbon filters has shown synergism between adsorption and biodegradation mechanisms for enhanced removal of SOCs.[40] The efficiency of the combined adsorption-biodegradation process is higher than either adsorption or biodegradation processes alone. Adsorption by the carbon attenuates dissolved contaminants allowing time for their breakdown by the biofilm, which in turn frees up surface sites on the carbon for additional sorption, extending the life of the filter media.[41] Even some compounds typically classified as non-biodegradable are broken down in long-running carbon bio-filters. Exposure to contaminants retained by the carbon over periods of weeks to months allows microorganisms to acclimate and develop the enzymatic pathways necessary to break down some otherwise environmentally recalcitrant compounds. [42] Thus the synergy between adsorption and biodegradation processes can result in a net elimination of some hazardous SOCs from the system.

Contaminant leaching and spent carbon processing An often-raised concern for carbon filtration is the back-diffusion, or "leaching," of contaminants out of the carbon, either during its lifetime in the filter bed or afterwards during the disposal phase. Recent research on activated carbon systems has shown very little leaching to occur.[43] Rates of back-diffusion (contaminants being released from surfaces and exiting through pores) are very slow due to pore blockage by natural organic matter. Essentially, contaminants diffuse into pores, attach to pore interior surfaces, and are trapped there by incoming natural organic matter that blocks pores over the operational lifetime of the filter. Moreover, most synthetic organic contaminants bind more strongly to carbon surfaces than dissolved background natural organic matter – so natural organic compounds are unlikely to displace adsorbed contaminants.

This suggests that the release of adsorbed contaminants from char should not be a great concern, either during the "use phase" in the char filter or subsequently in the "disposal" phase. As indicated in bio-filtration studies, time and the metabolic activity of microorganisms are the most effective means for breaking down sorbed contaminants. In the rural or developing community context, this can be accomplished through composting the spent filter char and then applying it to agricultural soils in the manner advocated by biochar practitioners. A conservative approach to land application of spent filter char can also be adopted, using low incorporation rates of ~ 100 kg of char per hectare.

Char filter refurbishment The effective lifetime of the char filter media depends upon the quality of the char, as well as the characteristics of the source water and efficacy of upstream treatment steps. In the rural developing community context, these factors are typified by high degrees of variability and uncertainty. Since char can be generated locally and inexpensively a conservative approach is recommended, designing for a much larger carbon use-rate than is employed in advanced GAC systems. A char filter built according to the specifications outlined here and supplying 2000 L/day should be refurbished at least every 2-3 years.

This estimate should be taken as a rough guideline. Ongoing research at Aqueous Solutions and with our collaborators is refining filter system design specifications and recommended operation protocols. However, it is ultimately up to the discretion of the community and water system operator(s) to consider factors such as variability in community water demands and seasonal source water quality concerns (e.g. turbidity and dissolved organic matter increase during the rainy season, local agricultural cycles and pesticide application periods, nearby industrial development that may impact source water, etc.) in determining an appropriate char filter bed lifetime and change-out frequency for each installation.

iv. Safe water storage

The storage tank should be sized to meet the water needs of the community with an appropriate buffer. Great caution must be exercised to ensure that treated water is not re-contaminated during storage, in the distribution system, or in water receptacles such as jerrycans used by community members.

VII. Concluding Remarks

This document summarizes our efforts to-date to evaluate traditional, local and sustainable decentralized water treatment technologies for the potential to mitigate human health impacts associated with pesticides and other synthetic industrial water contaminants. Here we present a simple system for the generation of enhanced water filter char using local materials, and the steps to integrating char filtration in multi-barrier household and small community water treatment systems.

A companion instructional video explaining the conceptual background, construction, and operation of the 200 L drum gasifier can also be accessed from the Aqueous Solutions website: www.aqsolutions.org.

Everything presented here and in the video is considered open source / open architecture, and is made available free-of-charge to concerned researchers and practitioners in the water-sanitation-hygiene (WASH) sector of sustainable domestic and international development. Through broad web-based promotion of these materials we hope to stimulate conversation about appropriate technologies targeting chemical water contaminants, and to invite criticism, modification, adaptation, improvement and advancement of the related science and engineering design.

This work is part of our mission as a consortium of research scientists, field engineers, and ecological designers working to promote livelihood security, environmental and economic sustainability, and local self-reliance through ecological design and appropriate WASH technologies, in particular serving rural/remote, indigenous, and politically and economically marginalized communities in SE Asia. Learn more about our efforts and how you can get involved at **www.aqsolutions.org**.

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