
JEFF HUTCHENS/GETTY

Biochar — a soil additive made by heating biological material — is catching attention as a means to improve crop growth and clean up contaminated water.

STATE-OF-THE-ART SOIL

A charcoal-rich product called biochar could boost agricultural yields and control pollution. Scientists are putting the trendy substance to the test.

BY RACHEL CERNANSKY

For more than 150 years, the Brooklyn Navy Yard constructed vessels that helped to stop the slave trade from Africa, lay the first undersea telegraph cable and end the Second World War. Now, this sprawling industrial facility in New York City is filled with artists, architects, producers of artisanal moonshine and people growing organic vegetables. On a drizzly day in autumn, Ben Flanner tends a sea of red and green lettuce on a 6,000-square-metre rooftop farm.

The soil beneath the plants looks ordinary, but Flanner grabs a handful and holds it up for inspection. Amid the brown clods of dirt are small black particles — remnants of charcoal fragments that were mixed into the soil two years ago. Flanner thinks that this carbon-rich material, known as biochar, has helped the crops to thrive, possibly even increasing their yield, and he hopes for more impressive results over the next few years.

Across the United States, sales of this long-lasting soil additive have surged over the past few years, tripling annually since 2008, according to some estimates. The Biochar Company in Berwyn, Pennsylvania — which supplied Flanner's Brooklyn farm — sells it both wholesale and direct to consumers, through outlets including Amazon and some Whole Foods stores. And countries ranging from China to Sweden are using biochar on agricultural fields and city lawns.

Proponents see big potential for the soil enhancer, which is produced by heating biological material — such as husks and other agricultural waste — in a low-oxygen chamber. Biochar can be made as a by-product of biofuel generation, so some companies are hoping to cash in on both products as demand grows for greener forms of energy.

Interest in biochar is also growing among scientists, who are quickly ramping up studies to test its potential. They are particularly interested in how the chemical and physical properties of biochar particles affect water moving through soil, remove pollutants, alter microbial communities and reduce emissions of greenhouse gases. The hope is that biochar can help farmers around the world, particularly those in Africa and other developing regions, who often struggle with poor soils.

Johannes Lehmann, a crop and soil scientist at Cornell University in Ithaca, New York, says that different types of biochar "have unique potential to mitigate some of the greatest soil-health constraints to crop productivity — for example, in highly weathered and sandy soils".

But there are still many questions about biochar, particularly in terms of making sure that it is affordable and has positive effects. In some studies, the material has actually reduced yields. Part of the difficulty is that biochar can be produced from all kinds of biomass and at different temperatures and speeds, which leads to huge variation in the substance — and in results. "I always say we should not even use the singular for biochar," says Lehmann. "There are only biochars."

AMAZONIAN ROOTS

Although it is just starting to catch on with farmers today, biochar has ancient roots. Hundreds to thousands of years ago, residents of the Amazon produced it by heating up organic matter to create rich, fertile soils called *terra preta*. But the practice was abandoned around the time that European nations invaded South America, and relatively few farmers elsewhere have routinely used biochar. Scientists first took a big interest in the material about a decade ago, when growing concerns over global warming led some to tout biochar as a way to store huge amounts of carbon underground. Hope for that application has faded somewhat, but soil scientists are now exploring its use in agriculture and remediating pollution.

A particular focus has been explaining how biochar affects water movement through soils. Rebecca Barnes, a biogeochemist at Colorado College in Colorado Springs, and some of her colleagues tested that by adding biochar to different materials[1]. In sand, through which water typically drains very quickly, biochar slowed the movement of moisture by an average of 92%. In clay-rich soil, which usually retains water, biochar sped up movement by more than 300%.

The researchers suggest that the biochar alters how water moves through the interstitial space — the gaps between grains in the soil.

"Clays tend to be flat grains and sand tends to be circular grains, but biochar is very amorphous — and so it's not only creating these crazy pathways through the biochar, but it's also creating crazy pathways in that interstitial space," says Barnes. She and her colleagues suggest that these convoluted pathways help to slow down drainage in sand and speed it up in clays.

That is significant, Barnes says, because even though clays can hold large amounts of water, that moisture has a hard time moving through the grains and reaching plant roots. Some studies have shown that plants grow better in soil with added biochar than in plain soils or those treated just with compost[2].

> THE HOPE IS THAT BIOCHAR COULD HELP FARMERS, PARTICULARLY IN AFRICA AND OTHER DEVELOPING REGIONS.

Researchers are also teasing apart how biochars influence microbial activity in soil. Microbes typically act as a community; for example, many pathogenic bacteria attack a plant's roots only when they have sufficient numbers to overwhelm the host's immune response. Caroline Masiello, a biogeochemist at Rice University in Houston, Texas, and her co-workers have found[3] that biochar can inhibit this by binding to the signalling molecules that bacterial cells secrete to coordinate their activity.

"They all think they're alone, because the telephone wires have been cut," says Masiello. With further research, she says, it might be possible to fine-tune this function of biochar to reduce plant infections.

Other researchers are exploring how biochars can cut emissions of nitrous oxide, a greenhouse gas, from agricultural fields. Last year, Xiaoyu Liu, a soil scientist at Nanjing Agricultural University in China, and his colleagues reported[4] that after biochar had been applied to maize (corn) and wheat fields once, nitrous oxide emissions declined over the following five crop seasons, a period of three years. Other studies have shown reductions as well, but researchers have not yet been able to determine what exactly causes this effect. Applying biochar "can also improve some soil properties, like it can increase the potassium availability, and the soil organic-matter content", says Liu, who has obtained some funding from biochar producers.

But not all studies show biochar to be a wonder material. In some cases it has reduced crop yields[5], and one study[6] suggests that it lowers the activity of plant genes that help to defend against insect and pathogen attacks.

Lehmann says that this may come down to improper applications of biochar. In some of the studies that showed decreases in yields, he says, the soils were perfectly fine to start with. Other work suggests[7] that using the wrong type of biochar can negatively impact the soil's microbiota or, potentially, its carbon-storage capacity. A biochar made from rice straw, for example, will function differently in a certain soil than will biochar made from wood or manure.

Overall, however, the positive impacts of biochar seem to outweigh the negative ones. A 2011 meta-analysis[8] found an overall average yield increase of 10%, rising to 14% in acidic soils. Biochar's greatest potential might be in places where soils are degraded and fertilizer scarce, in part because it helps the soil to better retain any nutrients that it does have. Andrew Crane-Droesch at the University of California, Berkeley, has been studying the impacts of biochar in such degraded soils in western Kenya. His preliminary data suggest that farms using biochar averaged 32% higher yields than controls.

In June, a World Bank report[9] said that biochar probably holds the most potential for small farmers in developing countries, not just because they are working with the soils most likely to benefit, but because biochar may be a key element of 'climate-smart' agriculture — practices that both help to mitigate climate change and reduce vulnerability to its effects.

POLLUTION WRANGLER

Biochar's start may have been in agriculture, but researchers are now looking at other applications. Biochar can bind to heavy metals in soil, which helps to keep them from reaching plants or entering water supplies. That has attracted the notice of the US Environmental Protection Agency, other agencies, and companies seeking to reclaim land formerly used in mining. At the Hope Mine near Aspen, Colorado, biochar added in 2010 helped to neutralize the impacts of decades-old mine refuse by immobilizing the metals and increasing the amount of water held on the slope — thereby reducing the opportunity for contaminated water to become run-off. It also helped to spur plant growth on the formerly barren hillside, according to the Aspen Center for Environmental Studies.

Biochar is also showing promise in cleaning up polluted water, perhaps as a much cheaper replacement for activated charcoal, which is used at sites ranging from treatment plants to areas that are heavily contaminated with toxic chemicals. Biochar particles have a relatively large surface area, which expands even further in water, providing a vast number of sites for contaminants to bind to, says Charles Pittman, a retired chemist at Mississippi State University in Starkville. He says that this type of pollution remediation may be particularly beneficial in countries that lack full water-treatment systems. It could also help to remove antibiotics or chemical wastes, which are difficult to strip out with conventional water treatments.

Scientists have even explored biochar's

Workers at the Villa Carmen Biological Station in Peru turn soil containing black flecks of biochar, produced by burning bamboo in metal drums.

potential for treating fluids used in oil and gas drilling, and as a component of print toners and paint products. "There's a lot of other markets that haven't fully been explored yet," says Kurt Spokas, a soil scientist with the US Department of Agriculture's Agricultural Research Service in St Paul, Minnesota.

Experts caution, however, that it is not clear when or whether remediation — or other applications — will be economical, particularly in agriculture. Poor soils and poverty often go together. After demonstrating yield increases in Kenya, Crane-Droesch looked at the economic viability of biochar in the same communities. "What we found was almost nobody was willing to pay for biochar when offered at roughly the price it took to make it," he says.

Biochar prices vary widely, but in the United States some products cost US$3 per kilogram, comparable to certain fertilizers and more than many composts. On a large scale, biochar production may make economic sense only when biofuel production does — for example if it is subsidized or because policies to reduce carbon emissions drive fossil-fuel prices up.

And if demand ever does surge, there will be questions about the environmental impact of producing biochar. One key concern is the choice of feedstock. China is eager to use agricultural waste, such as rice and wheat straw, and some researchers in the United States are even pushing animal manure, but neither may be the most efficient way to produce it on a massive scale. And using wood could spur deforestation or harmful land-use practices.

"It's an incredibly important question to ask: what is the sustainability of the feedstock?" says Alfred Gathorne-Hardy, research director of the India Centre for Sustainable Development at the University of Oxford, UK. "This is the kind of debate I don't think we're seeing enough about within the biochar world."

GROWTH INDUSTRY

That debate may grow as consumer interest does — something that is slowly happening around the world. Björn Embrén, who is responsible for tree planning and protection in Stockholm, says that the city has been using biochar to boost local vegetation since 2009; he credits it with the city's healthiest tree growth in recent years. In September, the New York-based charity Bloomberg Philanthropies awarded Stockholm €1 million (US$1.2 million) to launch a city-wide programme that will turn residential garden waste, and eventually food waste and even sewage, into biochar.

Back in Brooklyn, Flanner continues to monitor his crops. The lettuces and carrot tops glisten under the rain as he steps carefully between rows in his bright yellow rain jacket. He thinks that the biochar will be good for his soils over the long term because it helps them to retain nutrients and water. "Those are both very important, especially in such a well-drained soil as on a green roof," he says. "We tend to lose both of those quickly."

But before he adds more of the black grains to other parts of his farm, he will wait to see how the crops respond over the next few years. Like the scientists studying biochar, he is eager to see whether it will live up to its bright promise or fade like so many other would-be wonder materials. ■

Rachel Cernansky *is a freelance writer in Denver, Colorado.*

1. Barnes, R. T., Gallagher, M. E., Masiello, C. A., Liu, Z. & Dugan, B. *PLoS ONE* **9,** e108340 (2014).
2. Liu, J. *et al. J. Plant Nutr. Soil Sci.* **175,** 698–707 (2012).
3. Masiello, C. A. *et al. Environ. Sci. Technol.* **47,** 11496–11503 (2013).
4. Liu, X. *et al. Agric. Syst.* **129,** 22–29 (2014).
5. Rajkovich, S. *et al. Biol. Fert. Soils* **48,** 271–284 (2012).
6. Viger, M., Hancock, R. D., Miglietta, F. & Taylor, G. *GCB Bioenergy* http://dx.doi.org/10.1111/gcbb.12182 (2014).
7. Zimmerman, A. R., Gao, B. & Ahn, M.-Y. *Soil Biol. Biochem.* **43,** 1169–1179 (2011).
8. Jeffery, S., Verheijen, F .G. A., van der Velde, M. & Bastos, A. C. *Agric. Ecosyst. Environ.* **144,** 175–187 (2011).
9. Scholz, S. M. *et al. Biochar Systems for Smallholders in Developing Countries* (World Bank, 2014).