



# Understanding Biochar Series

Understanding Biochar – What Happens When Biomass Is Heated

By Hugh McLaughlin, PhD, PE – CTO





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### Understanding Biochar – what happens when Biomass is heated (pyrolyzed)

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Biochar is made from biomass, usually vegetable residues (for this discussion, we will be using animal, vegetable, mineral as the major groups), that are heated in an atmosphere that is hot enough to transform the starting material into something new (biochar) and does not have enough oxygen or air to have the carbon in the biochar burn away and leave behind only “ash” (the mineral part).

This explanation is intentionally simplified and designed to capture the major changes that occur as biomass is transformed into biochar by heating. Let’s start by looking at the changes in each principle constituent of the biomass – which can be a very broad set of possible starting materials. Biochar is best made from residues that do not have any higher value use, so if it can be fed to an animal (two-legged or four) or used as a soil amendment as is, that outlet should be weighed against value of the biochar and, in some cases, the value of any heat or energy that can be used in addition to the biochar produced.

Agricultural and forestry residues consist, in large, of a mixture of non-edible plant matter, animal manures and dirt. We need to include dirt, or soil, for two reasons; it always seems to be present at some level, and handling practices, including how the material is harvested, stored or gathered for conversion into biochar, can introduce a variety of minerals that

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contribute to the final ash level in the biochar and may influence the quality and utility of the final biochar.

Let's start by envisioning the starting biomass as a blend of animal, vegetable and mineral-based materials, co-mingled and structured by the living processes that created the once-living portions – and some amount of water. The water part is easy – free water either drains or evaporates away as the biomass is heated, and water that is bound to the once-living tissue breaks free at low temperatures during heating and evaporates. Before biomass becomes biochar, all the original water leaves, so let's set the water aside and imagine “bone-dry” or moisture-free biomass as the starting material.

The “mineral” portion is also fairly straightforward – it also dries out, but in general, remains basically where it already is and chemically the same. For dirt, that means the clumps stay together, and for the trace minerals in living tissue, the mineral atoms and molecules stay intact, but still distributed throughout the rest of the “pyrolyzing” mass as they were in the original biomass.

There is really only one change, beyond drying out (which includes any water of “hydration” in the individual mineral complex) that can happen to individual minerals in biochar, relative to the starting biomass – they can transform to a new chemical form, typically at some relatively high temperature. The most common change is the conversion of carbonates to the oxides, as in the case of calcium carbonate (limestone) losing CO<sub>2</sub> and forming calcium oxide, which converts to calcium hydroxide the next time it gets wet. Both calcium oxide and calcium hydroxide are referred to as “lime” and both have an effect of neutralizing acids and raising the pH of the receiving soils. So, the limestone can turn into lime.

Thus, to summarize, the water leaves and the minerals stay where they are in the solid material, sometimes changing into a related chemical form by having some portion cook off at some high temperature. In very rare cases, the mineral can vaporize (leaving the solid



material) or alternately aggregate into bigger clumps of minerals, but both phenomena are rare and do not typically impact the resulting biochar properties.

So far, we have accounted for the major changes in everything except the animal and vegetable matter – but that is where the significant chemical and physical changes occur that turn the biomass into biochar. As such, we will take these components and break them down individually, but first we need to use some technical terms used to describe what is happening: the biomass is “pyrolyzing”, meaning being transformed because of being heated; vapors are formed, called “volatiles”, which leave as gases in a phenomenon called “de-volatilization” – implying fewer volatiles can be formed from the solid left behind; and the solid portion is undergoing “carbonization”, the phenomenon where the changing solid becomes more carbon-rich, relative to the starting biomass.

To simplify the number of things to be considered, let’s postulate that biomass sources that will yield efficient conversion to biochar are predominately “vegetable”, as in plant-based material. Even most animal manures contain significant portions of undigested plant residues, and those manures yield biochar to the extent that the plant residuals convert to biochar. In practice, most animal tissue is either food for people or turned into food for another animal. As such, let’s set “animal” and animal tissue aside as a biochar starting material.

Since the vast majority of dry vegetable biomass is composed of cellulose, hemicelluloses and lignin, we can expect the broader class of “vegetable” matter to convert into biochar by following the chemical transformations observed during pyrolysis of the three major constituents. Studies have shown that all three plant constituents transform, when heated to appropriate pyrolysis temperatures, into volatiles and a significant minority, by weight, of carbonized solids (or biochar). Cellulose and hemicelluloses yield about 20 weight percent carbon-rich solids, and lignin yields in the range of 40 weight percent, with higher pyrolysis temperatures yielding a more carbon-rich material at lower remaining weight of biochar. Unfortunately, since different plant biomass sources vary in the lignin content, it is hard to



predict the yield of biochar from mixtures of dry plant biomass. However, as a rule of thumb, on an ash-free basis, most plant matter yields about 25 weight percent carbon-rich biochar.

**Now here is the really tricky part:** while the dry ash-free plant matter is turning into 75 weight percent volatiles, which leave as vapors, and leaving 25 weight percent carbon-rich solids behind, the VOLUME of the resulting solid is reduced to about one half (50%) of the volume of the starting biomass. After a little reflection, please arrive at the observation that the biochar must be less DENSE than the starting biomass, and the lower overall density is comprised of the combination of residual carbon-rich solids and the empty spaces left behind by the departure of vapors. Upon comparing the resulting biochar to the original biomass, these observations are easy to believe; the biochar is black (carbon-rich), light (low density) and full of cracks and crevices (aka voids) of many sizes.

Furthermore, the empty spaces add up to much more volume than the volume comprised of the carbon-rich solids. On a dry ash-free basis, high quality biochar is over 85 volume percent empty space, technically occupied by air and comprising the spaces between individual biochar particles and especially the internal voids or “pores”, having been created inside the biochar particles during by the pyrolysis process.

Let's take an example to see if this weight-volume-density transformation makes sense as one goes from plant biomass to biochar. The starting biomass consists of one cubic meter (1000 liters) of dry wood chips, which weigh 400 kilograms on a dry ash-free basis. The 400 kilograms of wood chips turn into 100 kilograms of solid biochar and the volume shrinks from 1000 liters to 500 liters. Thus, the starting density of the wood chips was 0.4 kg/l and the final biochar is 0.2 kg/l. The biochar is composed of a carbon-rich material, called microporous amorphous graphite, which has a solid density of the pure material of over 2 kg/l and an average density in biochar of 1.5 kg/l (measured very carefully using methods that Archimedes inspired and accounts for any impurities or defects in the graphite structures). Thus, the 100 kilograms of biochar actually only has  $100 \text{ kg} / 1.5 \text{ kg/l} = 66.67$  liters of solid material – the rest



is voids and spaces inside and between biochar particles. So, the solids represent  $66.67 / 500 \text{ l} = 13.33$  volume percent, leaving 86.67 volume percent empty space or voids. Q.E.D.

In summary, via pyrolysis, the vegetable portion of the starting biomass turned into a new solid form, chemically like graphite, but physically mostly open space or voids. Most importantly, the organic portion of the original biomass is converted into new molecular structures that have different properties compared to the starting biomass, including pronounced resistance to breakdown by biological processes in the soil. The mineral portion remains essentially the same, and is distributed wherever it was in the original biomass. The water leaves and there is rarely enough “animal” material to concern ourselves with, so combining these simultaneous changes gives us the essence of what happens when biomass is pyrolyzed into biochar.

Subsequent discussions will delve into the properties of the composite biochar (consisting of microporous graphitic solids, derived from vegetable matter, and containing original minerals present in the starting biomass) and how to measure the “quality” of biochar. This will allow prediction of how it will impact various crop-growing soil applications and how to exploit unique biochar properties to remediate specific soil toxicity and soil physical shortcomings.





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