A farmer's guide to the production, use and application of biochar

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Table of Contents

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Front cover photo: Shahla Hosseini Bai (foreground) and Negar Omidvar (background)
Photo credit:Dr Michael Farrar

Introduction

Biochar is biomass that has undergone thermal decomposition in an oxygen-starved environment. The potential of biochar to improve crop yields, increase resistance to plant disease, remove toxic substances from soil, and sequester carbon is well documented.

Extensive experimentation has shown that biochars produced from different feedstocks at different temperatures can have different effects on different plants, in different soils, climates, and ecosystems. There is a growing recognition that biochars and biochar-based amendments and fertilisers must be strategically chosen or enhanced to help overcome soil/environment constraints .

Over the last 5 years training courses have been run on design, production, and application of biochar. During these courses people have asked for specific recipes and guidelines, and for methods for making, enhancing, testing, and application. This guide has been developed to at least in part meet this need. It is complementary to the range of more scientific and technical publications.

The publication collects the experience of people – gardeners, farmers, and researchers – who have made and used biochar to produce food crops in home gardens, smallholdings, and farms in many countries around the world. It draws on the collective wisdom of people who have used biochar for centuries, on innovations developed in the last 100 years, and on the latest scientific research.

This is the first complete draft that we are sharing to get feedback on content and organisation. We will update the Guide in approximately 3 months incorporating suggestions.

The primer is divided into 11 chapters

1. Principles of biomass pyrolysis for biochar production
2. Indigenous practices of biochar production and utilisation
3. Choosing a biochar unit that meets your needs
4. Properties of fresh biochars and wood vinegar
5. Properties of biochar change after interaction with soils, compost, or animals
6. Effects of biochar on crop production and soil properties
7. How to choose and enhance biochars to meet specific soil constraints
8. Methods for applying biochar
9. Case studies
10. Biochar in regenerative agriculture and carbon draw down
11. Testing biochars

Chapter 1

Principles of biomass pyrolysis for biochar production

Key Points

- **Pyrolysis is the thermal decomposition of biomass in an oxygen-limited environment. Carbonisation is the enrichment of carbon in the biochar.**
- **The type of biomass and operating conditions of pyrolysis mainly determine the properties of biochar.**
- **To make good-quality biochar the feedstock should be sourced sustainably, not be contaminated by toxic substances (like paint, tars, glues, or heavy metals), and have moisture content of 15–20% when entering the kiln.**
- **For net drawdown of CO_2, the feedstock must come from fast-growing biomass, or from wastes and residues that would otherwise decompose.**
- **Don't confuse making biochar with burning or combustion – they are different processes. During pyrolysis, half the carbon in the biomass is fixed in the biochar and about half the energy in the biomass is made available.**
- **Pyrolysis and carbonisation are complex multistage processes, which proceed at about an hour per inch (2.5 cm) through a thickness of wood. By controlling each stage, different products or qualities can be produced.**
- **Wood vinegar is a valuable product from pyrolysis. It can be used to promote germination, increase crop yields and beneficial microbes, or control harmful pests.**
- **There are three generic methods to provide the heat to the biomass: flaming pyrolysis, externally heated retorts, and heating by recirculating hot combustion gases. Each method has pros and cons.**
- **Optimise the environmental benefits of biochar by making use of the carbon and energy in the biomass. If possible:**
  - Sun-dry the biomass,
  - Capture wood vinegar as well as biochar,
  - Use the energy in the pyrogas to offset fossil fuel emissions.

INTRODUCTION

Biochar is obtained through the process of pyrolysis, which involves heating the biomass in a limited oxygen environment. The resulting decomposition of the biomass produces energy containing gases, oils, and a solid residue, or biochar, which all have a range of uses. For biochar production the process is usually adjusted so biochar is the main product.

A portion of the gases and oils (known as pyrogas) produced during pyrolysis can be combusted to provide the heat for the process. If the biomass is relatively dry, then surplus gas over what is needed to sustain the pyrolysis is produced, and this can be burned for useful energy, offsetting fossil fuel use and emissions. Vapours that are emitted during the low-temperature phase of pyrolysis can be condensed and processed into wood vinegar, also known as pyroligneous acid, which is a valuable aid in pest and disease control and in soil and plant fertilisation.

Biochar can also be produced through a process known as gasification. In this process, biomass is first pyrolysed and then more oxygen is used to break down some of the biochar and vapours to produce more gas that is rich in hydrogen, methane, and carbon monoxide. Typically, the yield of biochar from pyrolysis is 20–30% more than in an equivalent gasification process.

This chapter introduces the principles of biomass pyrolysis for biochar production. It covers the requirements of the biomass feedstock, the relationship between pyrolysis and combustion, and the stages of pyrolysis. The chapter also introduces the important factors that influence the properties of the biochar, which include the properties of the feedstock, the highest temperature that the biochar reaches, the rate of heating of pyrolysis, the methods of heating, and the energy balance in pyrolysis.

The potential of biochar to improve crop yields, increase resistance to plant disease, remove toxic substances from soil, and sequester carbon is well documented.

REQUIREMENTS OF BIOMASS FEEDSTOCK FOR BIOCHAR

Biomass is a term referring to living or once-living materials, which can be used as feedstock for making biochar. Nearly all reasonably dry organic materials, such as wood, bark, nutshells, crop residues, invasive species, and animal by-products, including manures, bones, fish waste, and biosolids, can be used to make biochar (Figure 1.1). The best biochars for agricultural amendment often come from fine-grained, high nutrient density residues from agriculture, animal husbandry, and other wastes such as clean biosolids.

Figure 1.1 Biochar can be made from many kinds of biomass.

The type of biomass and the operating conditions of the pyrolysis reactor that converts the biomass are the main factors that determine the properties of biochar. Hence, it will be helpful to understand the basic composition, characteristics, and requirements of biomass feedstock.

While any biomass can be pyrolysed, biochar's environmental credentials require that the feedstock for making it be sourced sustainably. When producing biochar for agricultural applications in soil, water, or animal husbandry, it is also crucial to exclude biomass with high levels of toxic organic and inorganic chemicals, such as chromium, lead, arsenic, cadmium, and creosote. Finally, for the resultant biochar to lead to effective net drawdown of CO_2 it is necessary that the feedstock be sourced from fast-growing biomass that quickly replaces the carbon emitted to the atmosphere during pyrolysis, or from wastes or residues that would otherwise decay or be burned sending all their C to the atmosphere as CO_2.

The moisture content of biomass is also an important consideration. The water content affects the process chemically and physically, impacting the quality of biochar, the moisture content in released gas, the efficiency of the combustion of the released gas, and the amount of excess energy. Biomass with moisture content (MC) above 20% usually needs to be dried before high-quality biochar can be produced, and there may be insufficient energy for pyrolysis to proceed if the MC is greater than 40–50%. On the other hand, some moisture is important for the conversion of the biomass to biochar. The ideal moisture content for making biochar is around 15%. Air and sun drying of the biomass is a good practice for reducing the pyrogas energy needed for evaporating water, thus maximising the amount of surplus energy that is available for external use such as processing crops, heating greenhouses, or producing electricity.

HOW DOES PYROLYSIS RELATE TO BURNING OR COMBUSTION?

The process to make biochar, pyrolysis, should not be confused with burning or combustion of the biomass. Pyrolysis of biomass is the breakdown and volatilisation of the biomass under heat, which can take place in limited or no oxygen. On the other hand, combustion is a gas phase reaction that occurs when combustible gases mix and react with oxygen to create flames and heat (See Figure 1.2).

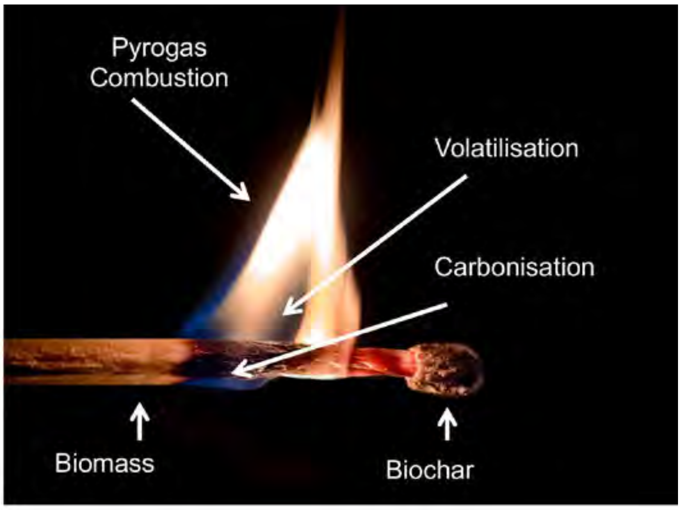


Figure 1.2 A burning match shows the volatilisation and carbonisation of the biomass occurs in oxygen deficient zones inside the flame, while combustion is a separated gas phase reaction occurring in excess oxygen. The flame provides the heat for continued pyrolysis, and the oxygen-depleted gases and flames protect the char from oxidation. This illustrates all the principles of flaming pyrolysis to make biochar.

Combustion of biomass is therefore a multistage process that first requires the pyrolysis of the biomass to release the combustible gases (see Figure 1.3). Once ignited, flames from the burning gases heat the biomass, continuing the pyrolysis until a carbon rich residue is left. The flame zone around the biomass is depleted of oxygen, which protects the carbon from oxidising. After the flames die back, oxygen can reach the charcoal leading to a further stage of combustion in which the carbon is oxidised to carbon monoxide, which in turn burns with a blue flame to CO_2. The final residue of complete combustion is just ash, representing the oxidised mineral content of the biomass. To limit the production of ash and preserve the charcoal for use as biochar, the hot char must be quickly cooled or separated from oxygen at the end of the pyrolysis stage. This can be done by quenching with water, or by covering the biochar with dirt or transferring it to an airtight vessel.

Understanding the multistage nature of biomass burning, and that the char is protected from oxidising when surrounded by flame, enables the simple production of biochar by direct ignition of the biomass in a low-tech environment, provided that the process is interrupted before the final char-oxidising stage by snuffing or quenching the biochar.

Pyrolysis as a phase of combustion

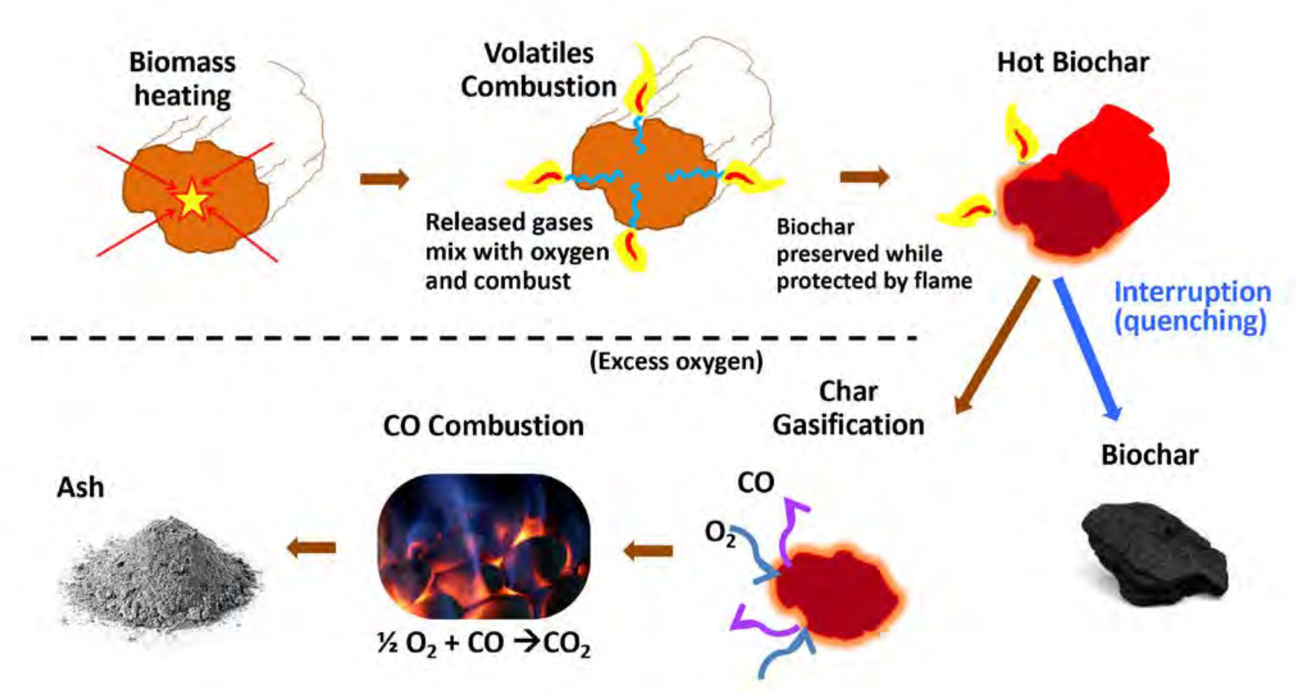


Figure 1.3 Combustion of biomass is a multistage process. If the combustion is limited or interrupted the biochar can be preserved. Pyrolysis can also proceed in the absence of any oxygen, with the gases directed to another location for combustion or other uses. Note: like biomass, biochar contains hydrogen – for simplicity the $H+O_2$ and CH_3+O_2 reactions that occur in char gasification are not shown.

CARBON RELEASE DURING PYROLYSIS

During pyrolysis, up to half of the carbon in the biomass is fixed in the biochar, while the rest is released into the atmosphere as CO_2. However, if the biomass used is derived from fast-growing plants, which can quickly replace the harvested carbon, or from wastes or residues that would otherwise decompose or be burned, biochar production can result in a net drawdown of CO_2.

PYROLYSIS OF AN INDIVIDUAL PIECE OF BIOMASS

When heat is applied to a particle of biomass, such as a piece of wood or a nutshell, the biomass piece dries, shrinks, changes colour through brown to black, and loses weight (Figure 1.4). Reactions progress through a series of stages, starting on the surface of the biomass particle and penetrating into the centre of the particle. Since heat and gases diffuse through the wood and char slowly, all stages of pyrolysis can be present simultaneously in a single piece of wood, with fully charred wood on the outside and moist unchanged wood on the inside. Shrinking and cracks in the wood speed up the progression of pyrolysis by facilitating the flow of heat in and the release of gases out.

Charring of wood proceeds at about 0.4 mm/min. Typically it takes about an hour per inch (2.5 cm) to complete the process of pyrolysis through a thickness of wood, whereas pyrolysing small particles can occur in seconds.

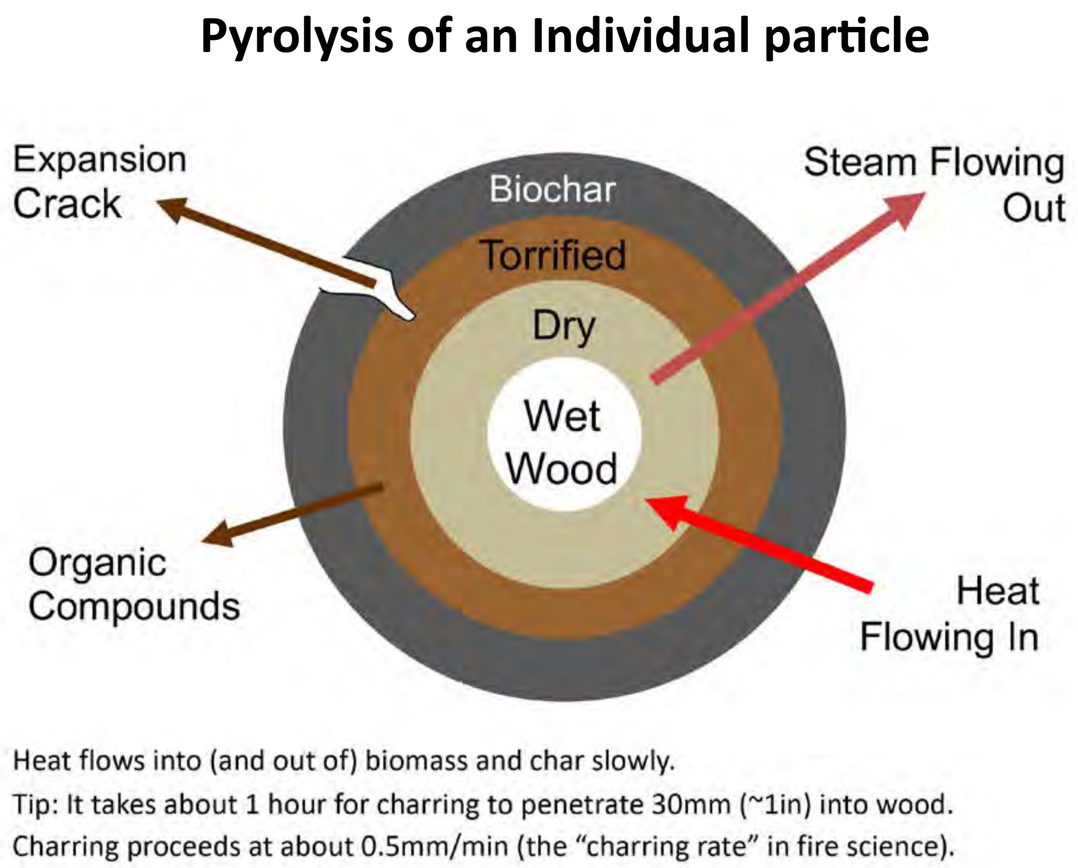


Figure 1.4 The progression of the stages of pyrolysis into a piece of biomass. The pyrolysis front progresses into the core of the particle as heat diffuses in and gases out, and all stages can be present in a single piece of biomass.

STAGES OF PYROLYSIS

The series of changes that occur when biomass is heated in an air-starved environment is shown in Figure 1.5.

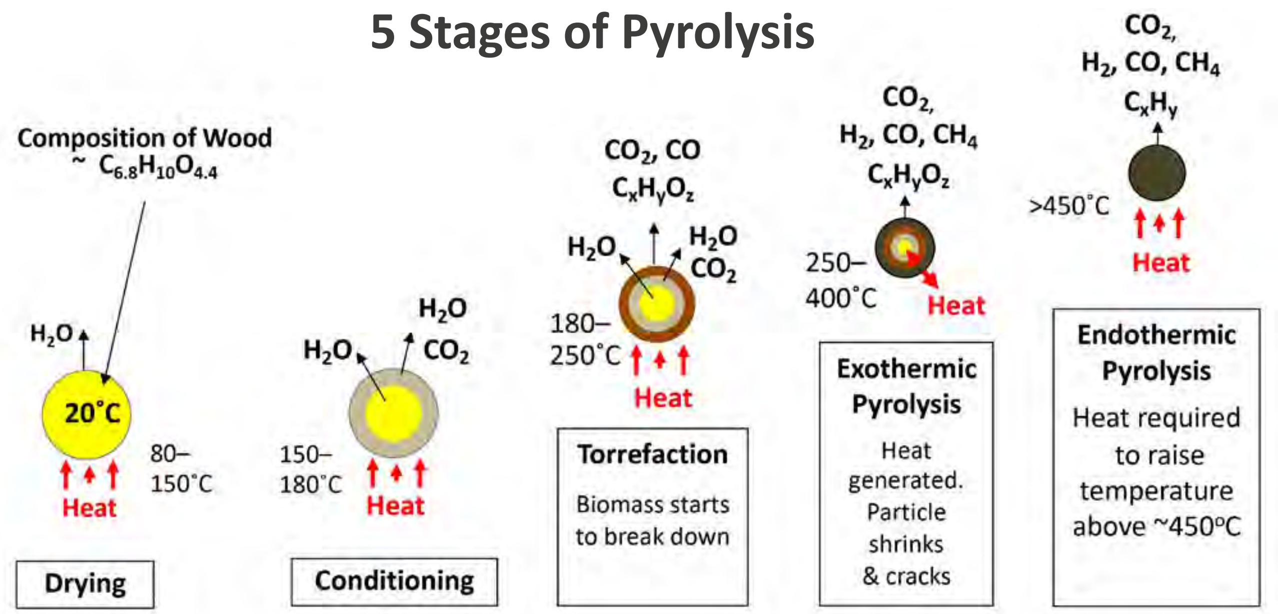


Figure 1.5 Flow diagram of the five stages of pyrolysis progressing into a biomass particle. The stages are colour coded. As pyrolysis progresses beyond the drying stage in each zone, the biomass begins to break down into molecular fragments that are released first as simple gases and progressively as more complex oil and tar vapours as the temperature increases. Each stage emits the gases depicted in the first occurrence of the stage (only main emissions for each stage are shown). Once the stage of exothermic pyrolysis begins, heat generated by the decomposition flows into and out from the exothermic zone, driving the pyrolysis deeper into the particle.

Stage 1 Drying

In this initial phase, biomass is heated externally to eliminate moisture as vapour. Pre-drying the biomass before pyrolysis increases the efficiency and biochar quality.

Stage 2 Conditioning

Even after drying, about 5% of biomass weight is chemically bound water, which is released between 150°C and 180°C. This stage, known as conditioning, can impact the properties of the final biochar.

Stage 3 Torrefaction

Between 180°C and 250°C, biomass begins to progressively decompose, releasing volatile gases including methanol and acetic acid. This stage where the biomass browns is known as torrefaction. ***Torrefied biomass*** is reduced in weight and size, and increased in energy density and hydrophobicity. Torrefaction is used to densify biomass for easier transport as a biofuel. The light volatile gases produced at this stage can be condensed to make an acidic solution known as wood vinegar, smoke water, or pyroligneous acid. This can be used as a biopesticide, a fungicide, an aid to germination, or a growth enhancer, and is a helpful conditioning agent for biochar.

Stage 4 Exothermic pyrolysis

Beyond 250°C, the biomass begins to break down quickly, producing combustible gases like methane and hydrogen. The process becomes exothermic; the decomposition of the biomass produces heat, which quickly raises the temperature of the biomass to 350°C–400°C. This is the onset of true pyrolysis, also known as carbonisation, in which the carbon rich matrix of biochar is formed.

Stage 5 Endothermic pyrolysis and final conditioning

Above 400°C, external heating is again required to further raise the temperature. This releases more organic compounds and some volatile inorganic compounds. This produces the low-volatile, high-carbon, porous biochars desired for certain applications. Air or hot steam (or both) can be introduced to the kiln to heat the biochar, and further tailor the biochar properties by activating its surfaces.

THE EFFECTS OF TIME AND TEMPERATURE

Biochar formation requires temperatures ranging from 250°C to 900°C, with lower temperatures necessitating a longer time for the creation of stable carbon structures (Figure 1.6). At 250°C, the low-temperature limit of smouldering pyrolysis in traditional kilns, it can take days to completely carbonise. Conversely, at higher temperatures, pyrolysis can occur within seconds if the biomass particles are small enough for the heat to penetrate quickly. The properties of the biochar are influenced by the "soak time" in the temperature. Lower temperatures typically leave more volatile materials in the char, which can be a source of nutrients, while higher temperatures result in more persistent carbon.

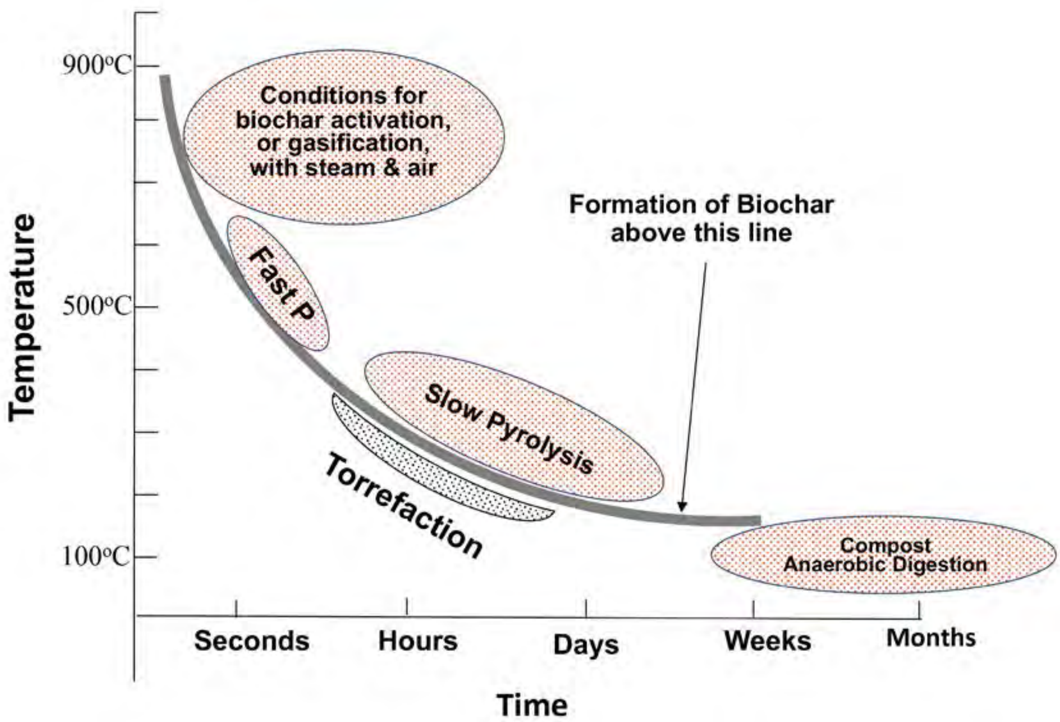


Figure 1.6 A schematic of the effect of time and temperature on formation of biochar and the operating zones for different thermal and microbial processes. Temperature and time ranges are approximate and schematic.

Composting, a slower process that takes place over months at temperatures below 60°C, can also be mapped on this temperature–time relationship. Like biochar, composting involves the decomposition and transformation of biomass, resulting in gas emissions (e.g. CO_2, CH_4) and a limited amount of long-lasting solid products, consisting of stable large organic molecules, often referred to as humic substances, which possess qualities and complexity akin to biochar.

Chemically, the process of conditioning, torrefying, pyrolysing, and activating biomass and biochar is very intricate and complex, leading to a diversity of useful properties and products. There is a complex interplay between the inputs, outputs, kind of reactor, and control parameters of the reactor that is depicted schematically in Figure 1.7. Designing the process for production of biochar starts with considering the desired end-properties, which guides the selection of the kind of biomass, the kiln type, the temperature range, process speed, and any pre- or post-conditioning to be applied. These important subjects are covered in future chapters.

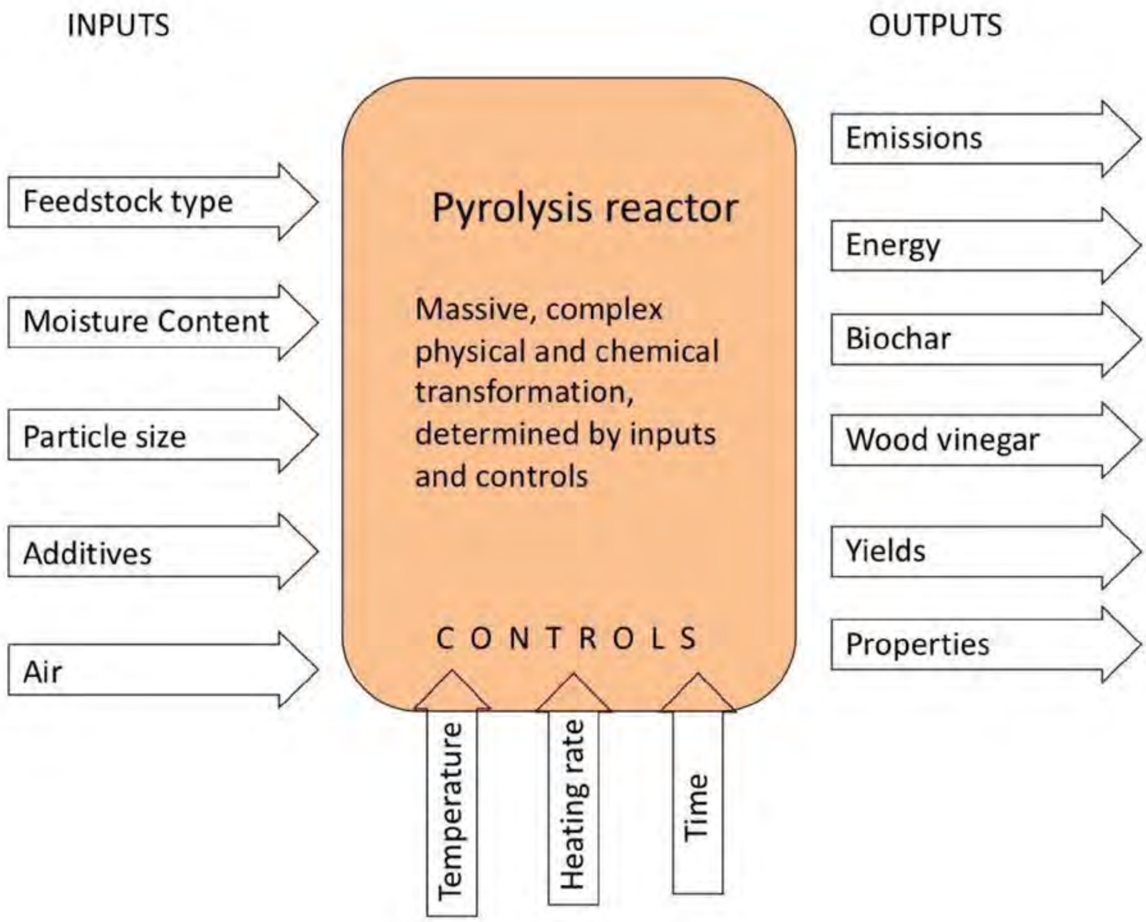


Figure 1.7 Dynamics of the pyrolysis process

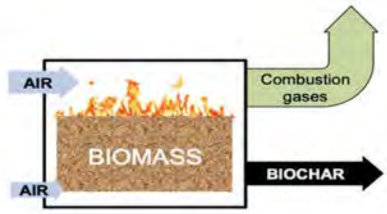
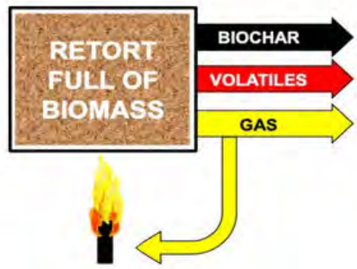
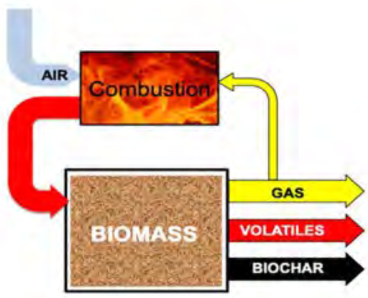
WOOD VINEGAR PRODUCTION

Wood vinegar, also known as pyroligneous acid, or smoke water, is a by-product of the pyrolysis process used to produce biochar. It is a yellow to brownish liquid that has a strong smoky smell and acidic taste. Wood vinegar contains a complex mixture of organic compounds, including acetic acid, methanol, acetone, and phenols. Wood vinegar is collected by cooling, in a condenser, the vapours, and smoke released by the kiln. Wood vinegar should only be collected in the initial stages of pyrolysis, usually in the kiln temperature range from 180°C–250°C. After collection the wood vinegar is left to stand while it separates into a heavy tar fraction at the bottom, a thin layer of light oil at the top, and a middle fraction from which the wood vinegar is drawn. To further enhance quality, the wood vinegar needs to be refined by some combinations of prolonged standing, filtering, or distillation. For example, in the traditional Japanese practice to produce the highest quality wood vinegar for use with animals, the wood vinegar may be left to stand for 6 to 12 months with several repeated decantings of the middle layer. It can also be filtered through charcoal. To learn more about the techniques involved in producing wood vinegar from basic kilns, and the subsequent purification process, refer to *The Handbook of Charcoal Making*.[1]

Good-quality wood vinegar is commercially available. The wood vinegar is diluted between 100 and 500 times depending on its application for promoting germination, plant growth, and beneficial microbes, or for control of harmful pests (higher concentrations). Wood vinegar can be refined to produce "liquid smoke", a flavouring agent in food and a preservative for meat and fish. In traditional medicine, wood vinegar is used for various purposes, including as a treatment for skin diseases and to improve blood circulation.

METHODS OF HEATING

Pyrolysis requires heat, but not necessarily flame. There are three generic methods to provide the heat to the biomass, each with advantages (✓) and disadvantages (✗) summarised in the table:

Direct Heating or **Flaming Pyrolysis –** Oxidative • Part of the raw material in the reactor is burned. • The biomass is directly heated from the flames. ✓ Air is limited in the charring zone, while, in best practice, liberated gases are cleanly combusted in an excess air zone. ✓ Simple DIY design, fabrication, and operation. ✗ Lower yield, fire care needed due to open design, small scale.	
External Heating of Biomass in a Retort • An external heat source is applied to a vessel full of biomass, called a retort, while air is excluded. • Liberated gases leave and are burned in excess air. • Heat is recycled back to heat the retort. ✓ Volatiles can be condensed as wood vinegar. ✓ Excess heat or gas can be controllably utilised (for drying, greenhouse, electricity generation, etc.). ✓ More control of oxygen and temperature. ✗ Heat takes longer to penetrate large retorts. ✗ Flammable gas can explode if O_2 enters the retort.	
Heating with Re-circulated Gas • Pyrolysis vapours are directed to a separate combustor for clean combustion, and some of the hot oxygen-depleted exhaust is circulated into the reactor to transfer heat to the biomass. ✓ Efficient transfer of heat to the biomass ✓ Circulating hot gas flushes volatiles and cracks them to small molecules – less secondary char. ✓ Excess heat or gas can be used elsewhere. ✓ Volatiles can produce wood vinegar. ✗ Can be complicated/expensive.	

MASS AND ENERGY BALANCE

Pyrolysis of biomass starts with the evaporation of the bulk water in the biomass received into the pyrolysis reactor. This is followed by the breakdown of the dry biomass into a char residue and pyrogas (often referred to as syngas), a mixture of non-combustible and combustible gases:

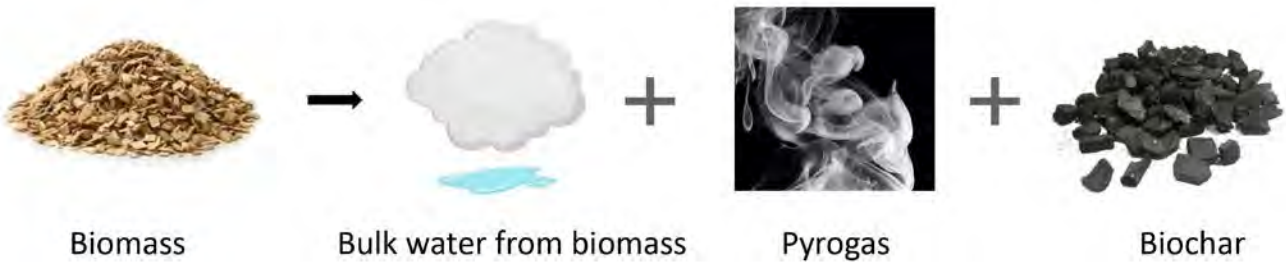


Figure 1.8 A simple concept of the mass balance in pyrolysis.

In addition to the bulk water, the pyrogas includes "chemical" water that is released or formed during the pyrolysis. Usually the pyrogas will be combusted fully in excess air to release its energy, bringing the mass of air and exhaust gases into the mass balance. Some of this released energy is used to drive the pyrolysis, after which the residual energy in the exhaust gas is either wasted to the atmosphere, or a portion of it can be applied for heating (e.g. greenhouses or water) or producing electricity.

The energy needed to heat the biomass to pyrolysis temperature (250°C–280°C) and to break down chemical bonds is known as the heat or enthalpy for pyrolysis, which varies with biomass.[2] (At approximately 280°C the process becomes exothermic and no further heat is needed for the temperature of the charring biomass to rise to 350°C–400°C.) Additionally, some energy is lost by radiation and convection from the kiln.

The mass balance and energy balance for running a typical kiln are shown in the Appendix. In this model about 15% of the biomass energy is needed to drive the pyrolysis processes (vapourising water, heating dry biomass, volatilisation, and heat loss). About 28% is retained in the char, leaving 57% of the biomass energy released in the pyrogas.

Appendix and References

APPENDIX: Mass and energy balance computations

MASS BALANCE

Pyrolysis: Mass of moist biomass = Mass of dry char + Mass of bulk water + Mass of pyrogas

Combustion of pyrogas: Mass of pyrogas + Mass air = Mass of exhaust gases

ENERGY BALANCE

Energy in moist biomass = Energy in dry char + Heat for vapourising chemical water + Energy in pyrogas + Enthalpy for pyrolysis + Energy lost from the kiln

For 1 kg of moist biomass, with 20% moisture content on a wet basis, and 20% biochar yield on a dry basis (such as might be achieved in a low-tech farm kiln that is well-run), the mass balance, specific energies, and energy balances are expressed in the table.

	Mass balance, kg	Specific energy	Energy content MJ (/kg)	% of energy in biomass
Moist biomass	1.0	14.9	14.9	100%
Dry wood	0.8	18.6	14.9	100%
Water	0.2	2.8	0.56	3.8%
Biochar	0.16	26	4.16	28%
Pyrogas	0.64	15.9	10.16 (difference)	68.3%
Energy for pyrolysis	0.8 (dry biomass)	1.5	1.2	8.1%
Energy loss	0.64 (pyrogas)	0.65	0.42	2.8%
Net pyrogas energy			6.66 (difference)	57.4%

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Chapter 2

Indigenous practices of biochar production and utilisation

Key Points

- Traditions of using biochar go back thousands of years in all continents.
- Understanding traditional techniques may improve the use of biochar in modern agriculture.
- Traditional practices involved thermal treatment of fresh and composted biomass mixed with mineral sources like soil and clay, bones, shells, fired clay fragments, and discarded pottery.
- The biomass reacts with the minerals and nutrients in a smoky environment to form a biochar-organo-mineral complex.
- Chinese and Japanese made biochar from bamboo and hardwood, and also captured, condensed, and refined the smoke to produce wood vinegar. It was used to improve germination, enhance plant growth, and kill pests.
- Traditional methods of making biochar include:
  - Firing biomass in pits, piles, or mounds on or near the field beds, covered with clay or soil (sometimes leaving air holes), igniting it, and leaving it to smoulder;
  - Firing brick, pottery, or tiles with rice or coconut husk, or sawdust in low-tech kilns.
- Specific traditional practices were developed to apply biochar for seed germination and the production of vegetable, grain, and tree crops.
- Indigenous people allow 1–3 weeks (or a whole season) before planting in the biochar-amended soil. This allows time for the biochar to age and develop favourable characteristics, and for microorganisms to flourish.
- The application of biochar by Indigenous communities continued for centuries producing increased pH, cation exchange capacity, available plant nutrients, organic carbon, total carbon, durable fertility, and higher crop yields in soils.

INTRODUCTION

The tradition of using biochar in all continents goes back thousands of years. The modern world was alerted to the agricultural and sequestration benefits of biochar when studies associated the fertility and longevity of the Terra Preta ("Dark Earth") soils of the Amazon Basin with the presence of ancient anthropogenic charcoal.

Scientists consider that the incorporation of carbonised biomass from village fire management practices into the settlement soils eventually led to the intentional production and application of biochar to enhance soil fertility. This hypothesis is supported by the widespread practice found among existing Indigenous cultures in South America, Australia, Africa, and Asia, of incorporating carbonised materials into soil to increase fertility. These practices represented progress from a nomadic "slash and burn" method of agriculture, and still continue in areas where settled people cannot afford to buy chemical fertilisers.

In this chapter, we present an overview of historical and contemporary Indigenous use of biochar with an emphasis on what we can learn about their techniques in order to improve the effectiveness of biochar applications in our agricultural practices.

METHODS OF MAKING BIOCHAR-BASED AMENDMENTS

Traditional practices involved thermal treatment of mixtures of fresh and composted biomass accompanied with mineral sources like soil and clay, bones, shells, fired clay fragments or pellets, and discarded pottery. The biomass included wood, bark, bamboo, and agricultural residues such as rice husks and straw, along with nutrient-dense biomass like food scraps, manure, and human waste. In these processes the biomass reacts with the minerals and nutrients to form a biochar-organo-mineral complex (BOMC) in a smoky environment. For centuries, Chinese and Japanese traditional techniques of making biochar from bamboo and hardwood have also captured, condensed, and refined the smoke to produce a liquid used to improve germination, enhance growth, or act as a biopesticide.

The specific methods used for the traditional production of biochar-based amendments vary across cultures and regions. The simplest method is to mix or layer the different biomass and minerals (ash) and ignite them in an open fire. The average temperature of the biochar in the fire is usually below 450°C, although there are hot spots where the temperature can exceed 600°C. A lot of smoke and ash is often produced, and some of the smoke and ash chemicals are absorbed onto the surfaces of the biochar and minerals.

In Australia and New Zealand, biochar was made in pits (Figure 2.1). Research of sites with these high-carbon soils found that, in comparison to their adjacent sites, the dark soils had higher pH and cation exchange capacity. They also had higher levels of organic and total carbon, and of total N, Ca, K, and P.[1]

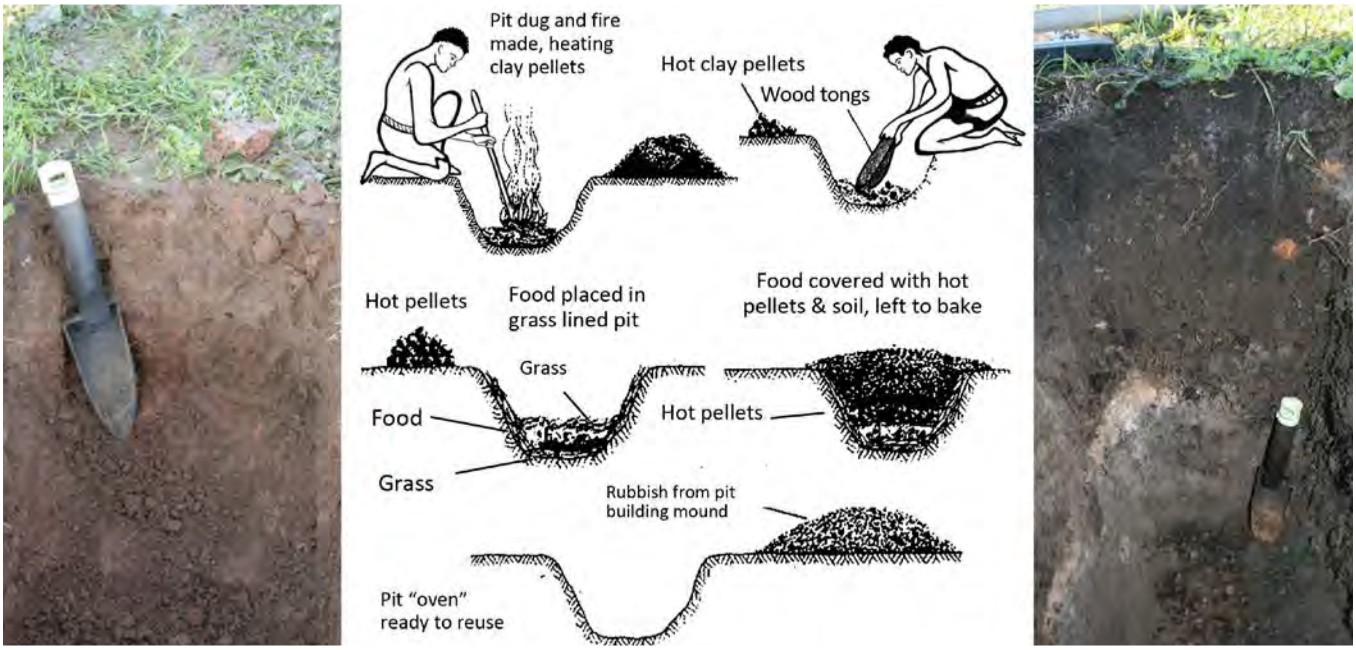

Figure 2.1 Indigenous Australian methods of cooking resulted in the formation of dark earth soils with charcoal and baked clay pieces (right), compared to adjacent soils (left). A pit was dug, and a fire used to heat clay pellets. After food was cooked the waste dirt, clay, and pyrolysed grass formed the mound. (Adapted from Downie et al.[1] and Coutts et al.[2])

Another widely used method involves layering the biomass on the field beds to form a mound, covering it with clay or soil, and igniting it. A team visiting Nepal found a farm in a Tamang village in the mountains where this technique had been practised for many generations (Figure 2.2). The farmer said her millet seeds might not germinate and set without the biochar. Only rarely, in severe stress such as drought or temperature events, does she need to add expensive chemical fertiliser, and then only a tiny amount of urea, because the biochar renders it very effective.

Figure 2.2 Making biochar in a Tamang village in Nepal. Left to right: 1 Hoeing the ground. 2 Laying straw and grass on the soil. 3 Laying smouldering dung on the biomass. 4 Covering with a layer of leaf and twig litter. 5 Covering with loose dirt, after which it is left to smoulder for three days, turning the soil reddish and making biochar. 6 The charred material is worked into the ground and left for 15 days before planting millet. Photos: S Joseph[3]

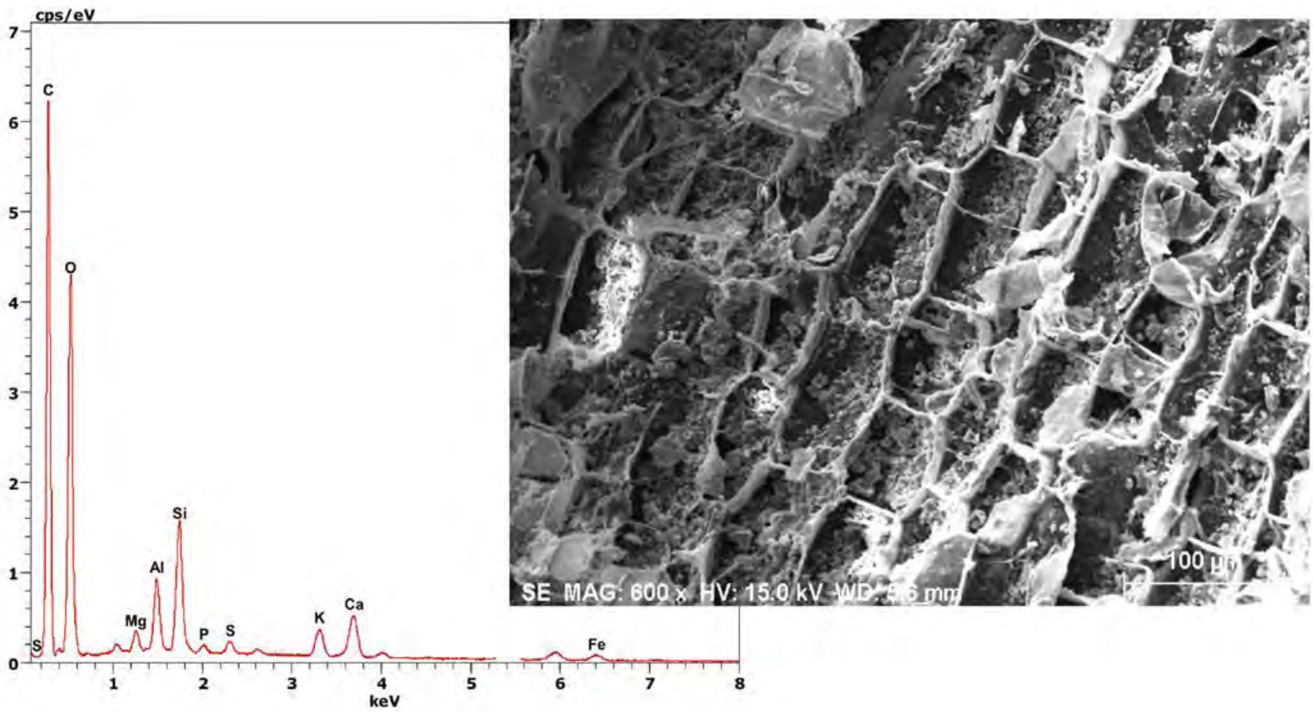

Figure 2.3 Scanning electron microscope examination of biochar from a millet field showing the carbon matrix filled with minerals available for plant and microbes. The four largest peaks in the X-ray spectrum are C, O, Si, and Al.[3]

Another method is to fill pits or trenches with biomass, cover with soil leaving some air holes, ignite the biomass, and leave to smoulder. Figure 2.3 shows a version of this method practised in Vietnam.

Figure 2.4 Making biochar with the trench method in Vietnam involves laying straw and rice husk on the garden bed, or in a shallow trench, forming chimneys at intervals with the straw (top and bottom left), covering with soil, igniting at the chimney holes (bottom right), and leaving to smoulder.

In South East Asia, it was common practice to fire brick and tile with rice husk and sawdust in inefficient kilns made from bricks. The residual mixture of charred biomass and pottery or brick fragments was used for their own food crops or sold to farmers. Wood charcoal kilns made from earth or bricks have also been used to produce charcoal for cooking and biochar.

In Vietnam, some households soak fuel wood and bamboo for six to twelve months in the mineral-rich sludge in ponds at the bottom of their rice terraces (Figure 2.4). The minerals incorporated on and inside the biomass reduce the rate of volatile emissions, so the combustion occurs more closely around the fuel and is hotter and cleaner. The char is protected from oxidation, resulting in a high yield of mineral-rich biochar and ash, which is used in home gardens for growing vegetables. The biochar was found to contain minerals such as K, Ca, Mg, and Si bonded to its surface and pores.

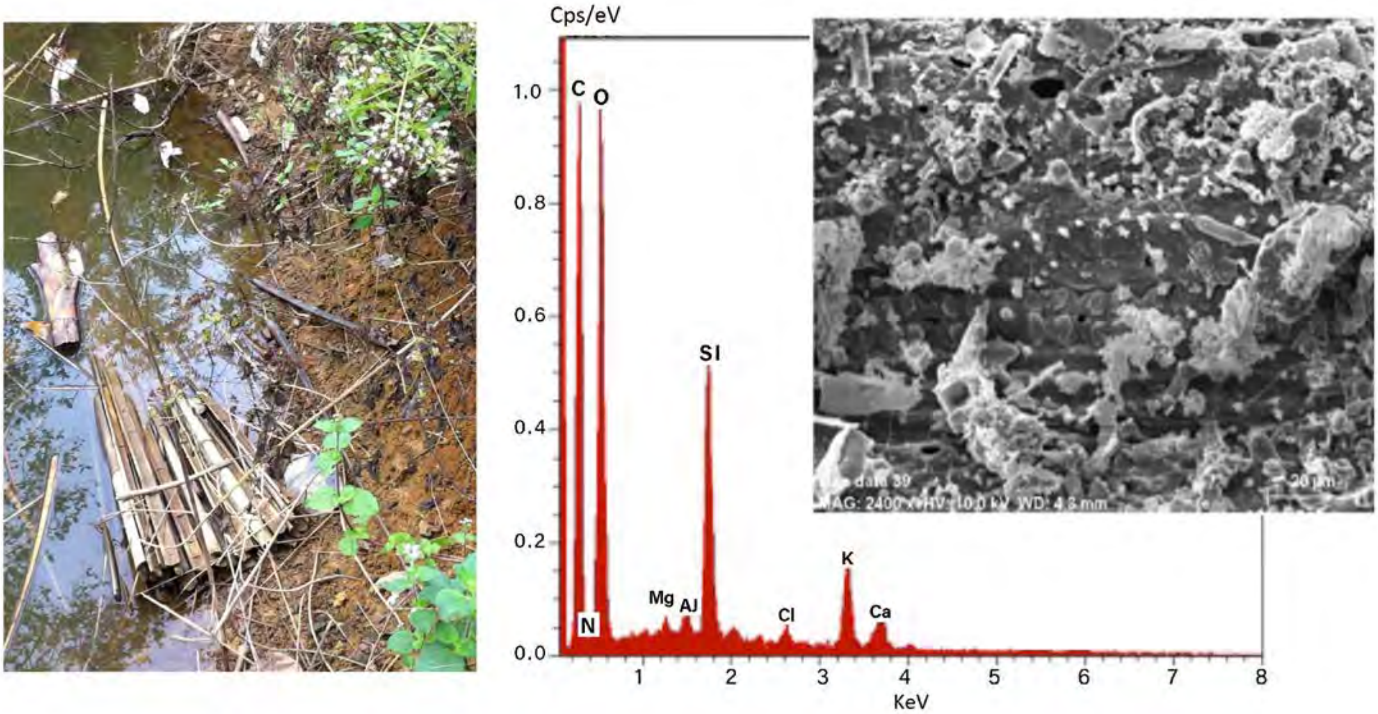

Figure 2.5 Soaking bamboo and wood in nutrient, clay, and mineral-rich ponds in Vietnam. After burning the dried fuel in an open fire, the biochar and ash are used in the garden. Electron microscopy found the surfaces and pores of the biochar coated with minerals. The X-ray diffraction showed high peaks for C, O, Si, K, and lower peaks for Mg, Al, Cl, and Ca. (Modified from Joseph et al.[4])

METHODS OF APPLYING BIOCHAR MINERAL MIXES

There is limited documentation on how people applied biochar mineral mixes in the past, but contemporary Indigenous practices are likely continuations or rediscoveries of historical practices.

The following is a summary of common application practices, based on both literature and the author's observations, which can still be found in remote places around the world:

Seed germination	Biochar, especially biochar produced from straw and husks, is used widely in Asia in potting mixes to germinate seeds and grow seedlings for transplanting.
Grain crops	Biochar amendments are mixed into the soil, often with manure, usually 2 to 3 weeks before planting.
Vegetables	Furrows are dug and biochar amendments, along with manure, are concentrated at the bottom of the furrow (Figure 2.3). The furrow is refilled with soil, forming a mound on top, and vegetables are planted in the mound. For some plants (e.g. spring onions and brassicas), biochar is placed on the surface around the plant stem.
Tree crops	Biochar-based amendments are placed underneath saplings. For cuttings to be transplanted, small amounts of the amendment are placed on the roots. For mature trees that have disease, a trench is dug around the drip line and biochar inoculated with microorganisms is placed in this trench.

Invariably Indigenous people allow a period of time, at least 1 to 3 weeks and sometimes a season, before seeds or plants are placed in the biochar-amended soil. This can be for several reasons:

- When the biochar is made in-situ with the soil, both pathogenic and beneficial microorganisms can be sterilised. As well, nitrogen and soil organic carbon can be temporarily lost from the soil affected by heat.
- Fresh biochar, if not made from nutrient-rich material or not preloaded with nutrients, can compete with microorganisms and plants to absorb nutrients from the soil.
- Biochar made in smoky fires contains condensates of smoke, which can include toxic compounds. Specific soil microbes can decompose these toxins over weeks to a level where toxicity is not an issue for the plant.
- Other properties of the smoky biochar can stimulate beneficial microorganisms (and seed germination).

In all cases it takes time for microorganism populations to grow or regrow, for heat-affected soil to regenerate, and for beneficial biochar-soil-microorganism interactions to mature, thus reducing toxicities and loading the biochar with nutrients.

LONG-TERM CHANGES IN SOIL WITH INDIGENOUS BIOCHAR USE

The continual application of biochar by Indigenous communities, sometimes for millennia as in the Terra Preta Soils of the Amazon, Aboriginal midden soils in Australia, and Palaeolithic anthropogenic soils in Europe, has enabled studies of long-term changes, rarely accessible in modern practices. Studies comparing long-standing biochar-amended soils with adjacent soils where biochar had not been applied have revealed that the biochar-amended soils have:

- Increased pH and cation exchange capacity (CEC) in the soil
- Increased availability of plant nutrients such as nitrogen and phosphorus
- Increased levels of organic and total carbon in the soil
- Increased crop yields

Biochars formed from ingredients that include iron-rich clay can be magnetic. Research has indicated that specific microbes that fix carbon and make Fe and S available will grow in areas where there are small, iron-rich mineral particles on the surface of the biochar.

To consider one example, the Amazonian Terra Preta soils are a mixture of red clay, sand, silt, organic matter, weathered wood charcoal (black carbon), burned pottery, shells, and biochar-organo-mineral complexes (BOMCs). The BOMCs are agglomerates of small pieces of black carbon, minerals of various kinds, fossils, and organic matter. The Amazonian dark soils, relative to adjacent nutrient-poor, iron-rich red-earth soils, have:

- High carbon and nutrient content
- High nutrient exchange capacity
- High abundance of beneficial microorganisms
- Magnetic properties

When biochar is extracted from Terra Preta soils, researchers have found pieces ranging in size from less than 0.1 mm to over 10 mm, buried up to one metre below the surface. A thin layer of organic compounds and minerals is found to cover the biochar exterior, and roots and root hairs have entered the biochar pores. These observations of traditional practices and formulations have been an inspiration for developing enhanced biochars for specific soil conditions and plant nutrient requirements.

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Chapter 3

Choosing a biochar unit that meets your needs

Key Points

- Choose a biochar reactor and related production systems that are suitable for the feedstock, resources, and the desired biochar end-properties.
- Ensure the biochar reactor will meet the local emissions regulations. Ideally, the excess energy from the pyrolysis would be utilised.
- To help you choose from many available biochar reactor designs, Part 1 of this chapter summarises the main classes of kilns and their characteristics, applications, advantages, and disadvantages.
- For do-it-yourself (DIY) and small business or farm operations, flame cap kilns, like the Kon-Tiki, are most popular. Instructions for their safe and efficient operation are given in Part 2, including ways they can be used to make enhanced biochar-organo-mineral complexes (BOMC).
- Biochar-making stoves can be divided into Retort Stoves and Top-Lit UpDraft Gasifier stoves (TLUDs). TLUDs can be scaled up and used to pyrolyse fine feedstocks, while Retort Stoves can burn multiple fuels and make BOMC. Part 3 outlines their design, operation, and a variety of commercial stoves.
- Commercial kilns are divided into batch and continuous operation. Part 4 provides a summary of different kilns available in Australia.
- Consult the design principles and safety tips outlined in Part 5. Consider attending a training workshop or enlisting the support of professional or skilled kiln designer or operator.
- Ensure safety!
    - Avoid unwanted fires and burns.
    - Don't breathe smoke or charcoal dust – it's toxic.
    - Pyrogas can explode if mixed with air in any enclosed space.
    - Ensure biochar is completely cooled and wetted to 30% moisture content before storage or shipping to supress dust and fire-risk.

INTRODUCTION

Biochar production has become increasingly popular and there are now many different biochar reactor designs published on the Internet or available for purchase. This chapter aims to assist you in choosing a suitable kiln, whether you will buy from a vendor, build from a published design, or develop your own. If you intend to purchase biochar, this chapter will help you understand how the method of production may affect some properties of the biochar. The chapter is divided into five parts.

Part 1: Categories of reactors

Part 2: Simple DIY methods for making biochar

Part 3: Biochar-making stoves

Part 4: Commercial batch kilns

Part 5: Specifying a biochar reactor, and safe operation

PART 1: CATEGORIES OF REACTORS

Biochar reactors or pyrolysers are commonly referred to as stoves, ovens (smaller) or kilns (larger), and retorts in alignment with the common definitions of these terms (see Box: Terminology). However, the biochar reactors are specialised for producing biochar, and should be designed to:

- Be easy to load and unload,
- Handle high heat,
- Burn or separate the released gases without pollution,
- Meet local emissions regulations,
- Be safe to operate,
- Utilise any residual energy, if possible.

TERMINOLOGY

A **Stove** is an enclosed space in which fuel is burned to provide heating, either to heat the stove itself and the space in which it is situated, or to heat items placed on the stove.

An **Oven** is a thermally insulated chamber for the heating or baking of a substance.

A **Kiln** is a specialised kind of oven that produces temperatures sufficient to complete some process such as drying or chemical change.

A **Retort** is a vessel in which substances are externally heated, usually producing gases to be collected or further processed.

A **Reactor** is a vessel designed to contain and control reactions.

A **Pyrolyser** is a reactor designed for thermal decomposition of biomass in a limited oxygen environment (pyrolysis).

A **Gasifier** is a reactor in which air is intentionally injected into the process to produce a greater quantity of cleaner pyrogas. It usually operates at a higher temperature than a pyrolyser.

Biochar can be produced in a wide variety of ways, which have different advantages and disadvantages. The choice of reactor depends on many factors including feedstock, scale, and budget. To help you select a reactor that is suitable for your needs and conditions, Table 3.1 outlines the main categories and considerations in choosing a biochar reactor. Table 3.2 provides key operating characteristics and cost ranges. This information should be used in conjunction with the information in the following chapters on the properties of biochars, enhanced biochars, and soil constraints.

Table 3.1 The main categories and characteristics of biochar reactors

<table>
<tr><td>Internal heating flaming pyrolysis
• Energy for pyrolysing the feedstock comes from directly igniting it in a kiln or open burn.
✗ An old polluting method is smouldering in limited air.
✓ A better method is flaming pyrolysis, where gases burn in excess air, and flames protect the char.</td><td>External heating (retorts)
• External heat is applied to a vessel containing biomass.
• Pyrogas from the retort is sent to a separate burner, which externally heats the retort, or hot exhaust from the burner can be passed through the biomass.
✓ Enables better yield and temperature control.</td></tr>
<tr><td>Oxic pyrolysis
• Oxygen is present — required for flaming pyrolysis.
• Higher temperature.
• Minerals and C are oxidised making biochar with enhanced surface area and adsorption.</td><td>Anoxic pyrolysis
• No or little oxygen is admitted to the reactor.
• Typical in an externally heated retort.
• Can be higher yield.
• Controlled oxygen can be injected if or when needed.</td></tr>
<tr><td>Stoves
• Designed to apply heat to a device for cooking.
• Pyrogas separates from the char and ignites in a burner.
• Usually small sub-kg scale production but can be large.</td><td>Kilns
• Term commonly applied to batch devices.
• Heat is not easily applied to other uses, but where possible it should be.</td></tr>
<tr><td>Batch pyrolysers
• Fill with biomass, run to completion, and then empty.
✓ Advantages are low cost, ability to use larger feedstock, ease of operation, and portability.
✓ Low emissions if well designed and operated.
✗ Heating or cooling between loading and unloading leads to variable production conditions and emissions.
✗ Unsuitable for large-scale production due to intensive labour for operation, and low productivity per machine.
✗ Unsuitable for fine feedstock like sawdust, manure.</td><td>Continuous pyrolysers
• Biomass is fed into one end of the process line while biochar is continuously discharged from the other.
✓ Provides a larger output from a given amount of equipment and labour.
✓ Can run steadily, giving more control over the process conditions of the biochar, and lower emissions.
✓ Used for large-scale industrial production, over 100 kg/hour, and can process fine feedstocks.
✗ More complex and expensive.</td></tr>
<tr><td>Fixed pyrolysers
• Installed in fixed locations to which the biomass is brought and which may include facilities for storing and processing the biomass.
✓ May be larger and cheaper than a mobile pyrolyser.</td><td>Mobile pyrolysers
• Transported to the location of the biomass.
✓ Produces biochar to be used on location, and avoids transporting biomass, which is typically three times heavier and bulkier than the resulting biochar.</td></tr>
<tr><td>Chunky feedstock
• Larger pieces such as limb wood, clean scrap timber, flooring offcuts, and larger bark pieces.
✓ Readily available and can be processed more quickly than fine feedstock. Chunk feedstock is often used in large-scale biochar production.</td><td>Fine feedstock
• Powdered or granular, such as sawdust, rice husks, nutshells, manures, and dewatered municipal sludge.
✓ Can be quickly and uniformly heated during pyrolysis.
✓ Produces a homogeneous, granular biochar.
✓ Is easier to transport, store, and handle than chunky.</td></tr>
<tr><td>Manual biochar pyrolysers
• Relies on manual labour to feed biomass into the reactor, remove the biochar, and adjust the parameters.
✓ Simple and low cost, but more time and effort to operate.
✗ The quality of the biochar depends on operator skill.</td><td>Automatic biochar pyrolysers
• Uses advanced technology, monitoring, and control systems.
✓ Efficient and consistent in producing high-quality biochar, with less labour and intervention.
✗ More expensive and may require a skilled operator.</td></tr>
<tr><td>DIY (Do-It-Yourself) pyrolysers
• Built by individuals and farmers with limited resources using simple designs and materials.
• Usually manually operated.
• Might not be approved by local or state governments.</td><td>Commercially bought pyrolysers
• Available from many manufacturers.
• Can range in size from tabletop models to large industrial-scale systems.
• May have automated controls and materials handling.</td></tr>
</table>

Key Takeaways

- Internal heating is an oxic pyrolysis producing a higher treatment temperature, lower yield, higher C content, and more oxygen on the surface of the biochar.
- External heating of biomass in a retort can be anoxic with capability to produce a higher yield of low-temperature biochars. Oxygen may still be admitted to the kiln at a late stage to “finish” the biochar to produce characteristics of higher temperature, oxidised biochar.
- A reactor suitable for the feedstock must be chosen, and vice versa. Fine feedstocks are usually best processed in continuous feed pyrolysers. Chunky feedstocks may be conveniently processed in a flame cap kiln. The economic batch-operated Top-Lit UpDraft gasifier (TLUD) requires a uniform, granular feedstock like nutshells, pellets, or wood chips.
- If the resources of the production facility limit the choice of pyrolyser, then the feedstock must be acquired or processed to suit. Chunky feedstock can be chipped or ground, while fine feedstock like sawdust or agricultural residues may be pelletised.

Table 3.2 Characteristics of various categories of biochar reactors. All categories, depending on the design, can have internal or external heating; can vary in emissions from low to high; and can take wood or agriculture residues. Sludges and manures usually require continuous machines. All numerical ranges are approximate. HHT = Highest Heating Temperature.

Type	Feedstock Type, kg biochar produced per time	Emissions of CO and NOx HHT of biochar	Production of heat (th) electricity (el)	Ease of use	Estimated cost and lifetime
Stoves	Dry wood & ag. waste, 0.5–1 kg in 3 cook sessions/day	300–5000 ppm HHT 350-500°C	2–10kW th	Easy to operate	\$10–300 1–5years
Batch Kilns Portable/ transportable	Wet or dry wood & ag residues, 10–1000 kgs in 4–24 h	100–5000 ppm HHT 350-600°C	50–200kW th	Easy to operate, or needs 1–3 days of training	\$100–\$500,000 2–10years
Batch Kilns Fixed	Wet or dry wood & ag. residues 100–2000 kg/8–24h	100–5000 ppm HHT 350-700°C	50–200kW th	Load/Unloading hard. Requires skilled operator	\$2000–\$60000 2–10years
Continuous Kilns Portable/ transportable	Wet or dry wood & ag. residues 100–300 kg/h	100–1000 ppm HHT 350-600°C	200–500kW th 20–100kW el	Requires a fair degree of skill	\$60000–\$500000 3–10years
Continuous kilns fixed	Wet or dry wood & ag. residues 200–10,000 kg/h	50–1000 ppm HHT 350-800°C	200–4000kW th 50–1000 kW el	Requires a high degree of skill	\$350k–\$10m without electricity

PART 2: SIMPLE DIY METHODS FOR MAKING BIOCHAR

This section focuses on simple do-it-yourself (DIY) batch methods for making biochar, which if properly implemented are safe, effective, and low polluting. The chapter covers options for pyrolysing chunky or fine feedstocks, making biochar mineral complexes (modernising traditional methods), and making wood vinegar.

For an urban backyard, a simple and compact biochar maker is usually desired. An urban farm may require a larger and more expensive enclosed kiln for efficient production. The user needs to be aware of and comply with any specific requirements or limitations imposed by local authorities on the use of these devices. Don't make biochar when fire bans are in place. Safety measures include separating the burn area from flammable materials and having at hand fire-suppression means such as water or dirt, shovels, gloves, and assistance.

Open flame-cover methods

The most common kiln in use is a Kon-Tiki. The kiln is an advance on a Japanese method that has been used for over 200 years to produce biochar from wood and bamboo. Pyrolysis takes place inside the cone, while the combustion of emitted gases occurs above the biomass, forming a flame cap over the top of the cone. Biomass can be continually added through the flame cap until the kiln is full, which allows the container volume to be fully used. The kiln in use, and the principles of operation, are shown in Figure 3.1.

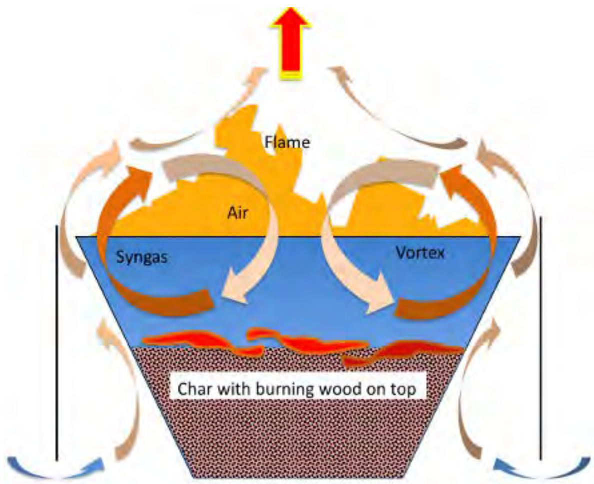


Figure 3.1 Left: The original 1.5 m diameter deep cone Kon-Tiki, developed at Ithaka Institute in Switzerland. The flame cap burns gases cleanly and protects the char from oxygen. **Right:** Convection dynamics of the Kon-Tiki. Updraft past the rim of the kiln entrains a rolling vortex inside the kiln. This pulls air down into the centre of the kiln, providing primary air for pyrolysis. Gases and smoke released from the pyrolysis zone are captured into the vortex and become mixed with air in the flame zone for cleaner combustion. A heat shield (optional) enclosing the kiln strengthens the natural vortex dynamic of the Kon-Tiki and makes the kiln more comfortable and efficient to operate. (Photo: Paul Taylor, Hans Peter Schmidt.)

A 1.2 metre rim diameter cone, with a volume of 375 litres, can be rolled from a single 1.2 m x 2.4 m (4 ft x 8 ft) sheet of steel. A larger cone can be created by rolling two half cones from two such sheets, which are then welded together to make a cone of up to 1.65 metres and volume of up to 1100 litres. The original Kon-Tiki design (Fig. 3.1) included a welded base (flat or slightly domed) with a short drainpipe and valve to allow for flooding from the bottom with quench water, or nutrient solutions, and for draining. However, flame cap kilns can be as simple as a drum (preferred greater than 0.7 m diameter), an open bottomed ring sitting on the ground, or a closed bottom firepit, or even a pit in the ground.

A study comparing emissions from various flame-cover kilns found the carbon monoxide, fine particles and nitrogen oxide emissions were significantly lower for these kilns than for retorts and traditional kilns.[1]

Operating the Kon-Tiki or flame cap kilns

Whatever form the kiln takes, it's the management of the fire that is crucial for high char yield, good productivity, and minimum pollution. The following operating instructions can be supplemented with online instructions such as www.youtube.com/user/TheBiocharRevolution

Preparation and Igniting the Fire:

- Gather biomass material with a moisture content under 20%. The Kon-Tiki works best with chunky material, such as brush, limb wood or carpentry off-cuts. Prepare 2–3 times the volume of the kiln.
- Set the kiln on a stable surface well clear of any flammable material.
- Ensure safety gear and tools, such as water, spades, gloves are on hand.
- In the kiln, make a pile of dry sticks with kindling on top.
- Light the kindling at the top to provide a cleaner start with less smoke.
- Feed kindling to the fire to build a complete flame cap and a strong fire bed.

Maintain the Flame Cap, feed the flames:

- Add material at a rate that keeps flames high and smoke low. Strong flames burn the smoke, aid fast drying and pyrolysis, and shield the char from O_2.
- Start with small material, add any big material in the middle of the run, and then taper to finish with small material. Tip: Allow about 20 min per cm of radius to fully carbonised wood.
- If flames are too small, feed dry thin material. If flames are large, feed your bigger or moister material. Do not quench the flames and create smoke.
- Do not leave the burn unattended. Keep the fire strong.

Finishing the Pyrolysis:

- After the last fuel is added, yellow flames die away as most pyrogas has evolved. Add small sticks, leaves, grass, or straw to keep the flame cap while finishing.
- A mist of water can be sprayed to generate steam and hydrogen, potentially activating the char and leading to cleaner combustion.

Quenching:

- Flood the hot char with water through a bottom drain. Steam that is flashed off and re-adsorbed cracks the char and activates surfaces. Alternatively, spray the hot char from above until cool, and check back every half hour for warmth or smoke.
- You can add nutrients to the quench water, including rock dust, manure, and acids (phosphoric or acetic or sulphur) to neutralise the pH.
- To preserve more of the microorganisms in manure, it can be stirred into the biochar slurry after its bulk has cooled.

Processing the Biochar:

- The Kon-Tiki can be drained overnight, or if quenched with nutrient-rich solution, it can be left overnight to charge the biochar.
- Collect the chemical-rich "smoke water" or nutrient water for reuse. Choose suitable dilutions and test before applying to plants.
- When cold, unload the kiln, and spread the char spread to dry for 2+ days.
- Wood biochar in the Kon-Tiki will mostly have a size of 10–30 mm. Crush the biochar to ≤ 2 mm-sized particles for soil application. A fast and thorough way to crush the biochar is in a hammer mill chipper.

Making biochar-organo-mineral complexes in the Kon-Tiki

There are a variety of easy ways to generate enhanced forms of biochar in the Kon-Tiki, including by adding nutrients and chemicals to the quench water as mentioned above. By firing a flame cap kiln with additional ingredients, biochar-organo-mineral complexes (BOMC, see Chapter 7) can be produced. The following are three methods the authors have used.

1. Extinguish the flames by covering with soil At the completion of the normal Kon-Tiki run the char was snuffed with layers of compost, soil, and red clay. A layer of biochar (not complete in the photo) was added to absorb any escaping smoke. The char continued to smoulder at 350°C for 3 days without smoke. (Note: Snuffing the fire with a thick layer of dirt is an alternative to water quenching, particularly for a kiln or pit fired in the field or forest with no water available.)	
2. Fire Ingredients directly in the Kon-Tiki Once a strongly flaming fire and ember bed were established, layers of wood chips, chicken manure and clay were added. Note: Unless very dry, wood chips are not ideal fuel for the Kon-Tiki because they require additional dry chunk wood to be added to maintain good flaming and burn the smoke.	
3. Fire ingredients in a retort, heated in the Kon-Tiki A mixture of ingredients (woodchips, straw, red clay, manure, and minerals) was blended in drums. The drums were loosely closed so that pyrogas could escape, and placed into a Kon-Tiki in the middle of its run where they baked at 500°C. Additions of wood chunks to the Kon-Tiki were continued till the drums were covered with char, resulting in 700 L/116 kg of Kon-Tiki biochar (mass yield 15% on dry basis) and 86 kg of retort BOMC.	

Top-lit open burn pyrolysis

Top-Lit open burn pyrolysis (or pile pyrolysis) is a technique that can be used in property management and forestry to deal with accumulated piles of slash from pruning or clearing, when a kiln is inconvenient or uneconomical. Referred to also as a "conservation burn", it has been taught to farmers and foresters in the Western US for reducing emissions from brush burning and creating valuable biochar. (www.kansasforests.org/forest_products/forest_product_docs/biochar_info/Small%20Scale%20Biochar%20Production.pdf)

In order to cleanly produce substantial biochar rather than mostly ash, the top-lit pyrolysis differs from a standard burn pile in four respects:

1. For pile pyrolysis, it is beneficial to stack the pile to make it more even, open, and contained.
2. The pile is lit at the top so that pyro gases are released below the flame. A regular burn pile lit from below can lead to copious smoke because the flames heat the material above, liberating gases that escape the flames.
3. Strategic water spray is used to cool any outlying char that is exposed to air and thus to ashing.
4. Once flames have died back the embers are quenched with water or dirt to preserve the char.

An alternative method to handle brush piles or scattered brush is to feed the material sequentially into an open fire. An advantage of this approach is that it can be managed to produce a steadier burn with less smoke. In these open burn methods, much of the carbon is converted to CO_2 and the yield of biochar is relatively small, although much higher than if a fire was initiated from the bottom of the pile.

A more controlled, clean, and carbon conserving approach with higher biochar yield and potential income is to light the fire in a pit and continue to feed it till the pit is full of biochar, managing the fire in the same manner as a Kon-Tiki kiln (Figure 3.2).

Figure 3.2 Top-lit open burn in a pit. The layering of sticks into the fire continues till the kiln is filled with char. (Photo: Pacific Biochar pacificbiochar.com/open-pit-biochar-production)

PART 3: BIOCHAR-MAKING STOVES

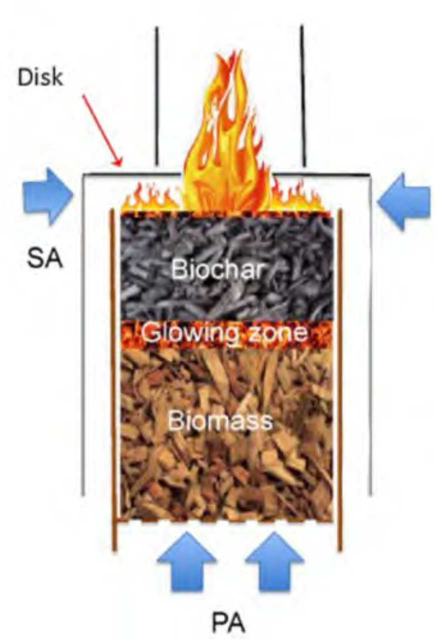
A large reliance on biomass for cooking and heating contributes to a range of negative impacts, including deforestation, indoor air pollution, and health problems, particularly for women and children who spend the most time in the kitchen. The use of more efficient and cleaner-burning stoves, which can be operated to make biochar, can help reduce these negative impacts while also providing carbon sequestration and promoting soil and food health through biochar production and application to soil.

The two main kinds of biochar-making stoves are TLUD gasifiers and retort stoves.

Top-lit updraft (TLUD) gasifier stove

A TLUD is designed to handle uniform particulate feedstock such as nutshells, wood pellets, rice husk, and dry wood chips. It is called a gasifier because primary air is fed to the pyrolysis front to gasify the biomass, and the gas is allowed to separate from the biomass and burn cleanly in excess air. The principles of operation are detailed below.

- Fire is ignited at the top of a column of biomass fuel in a vessel.
- A hot glowing zone moves down through the stationary fuel bed converting biomass to biochar and liberating pyrolysis gas.
- Primary air (PA) enters at the bottom of the fuel chamber and flows upward through the fuel bed. The flow volume is limited so only a portion of the liberated gas is combusted.
- The upward-moving hot gas mixture has little remaining oxygen to oxidise the char.
- Hot pyrolysis gases, smoke, and tars rising through the hot char are cracked into smaller molecules, emerging as combustible gas.
- Excess secondary air (SA) is introduced below a concentrator disc and blends with gases as they channel through the hole, resulting in a clean burning flame.
- A chimney creates a draft for PA and SA.
- Various more sophisticated "burner" arrangements have been developed to optimise clean combustion.



The TLUD principle has mainly been applied to small cook stoves and to 200 L drum biochar makers. TLUDs can be fabricated from recycled cans and drums using designs available online. TLUDS are also commercially available in many sizes for different biomass types and needs (Figure 3.3). If the available biomass is wood chips, nutshells, or other particulate biomass, then the larger TLUDs are good low-tech, low-cost candidates for making biochar. Once started, the TLUD often needs little attention till pyrolysis is complete, typically after 1–2 hours. A single person can start several 200 L drum TLUDs and manage their completion in sequence, producing nearly two cubic metres in a day.

Figure 3.3 Biochar-making gasifier cook stoves. 1. Champion TLUD Stove developed by Paul Anderson and manufactured by Servals in India. 2. FabStove, a fan driven advance on the Champion manufactured in South Africa and available online. 3–6. A range of gasifiers developed and photo'd by Paul Olivier in Vietnam: 3. Household stoves 250, 500, and 800 mm tall. 4. 800 mm tall, 500 mm diameter, 80 kW gasifier with multiple burners. 5. Nichrome wire burner on gasifier running on mesquite pellets. 6. 1200 mm tall bottom-lit downdraft gasifier with a run time of 8 hours

Retort stoves

In a retort stove, heat from a wood burner is utilised to trigger pyrolysis of feedstocks placed in a separate retort chamber. Gases liberated from the retort pass through holes into the burn chamber where they combust to provide heat to continue the pyrolysis and for cooking. High-temperature biochar is made in the burn chamber and at low temperature (around 450°C) in the retort. The arrangement has both feedstock flexibility and cooking flexibility. For instance, wood sticks or corncobs might be used in the burner, while other available feedstocks, such as mixtures of crop residues, manures, and minerals for making biochar mineral complexes, are used in the retort. After the retort has finished emitting gases, cooking can be continued if needed by simply adding further fuel sticks to the burner. The authors have developed several versions of rocket driven retorts, one of which is illustrated in Figure 3.4. Detailed schematics for these stoves can be obtained from the authors.

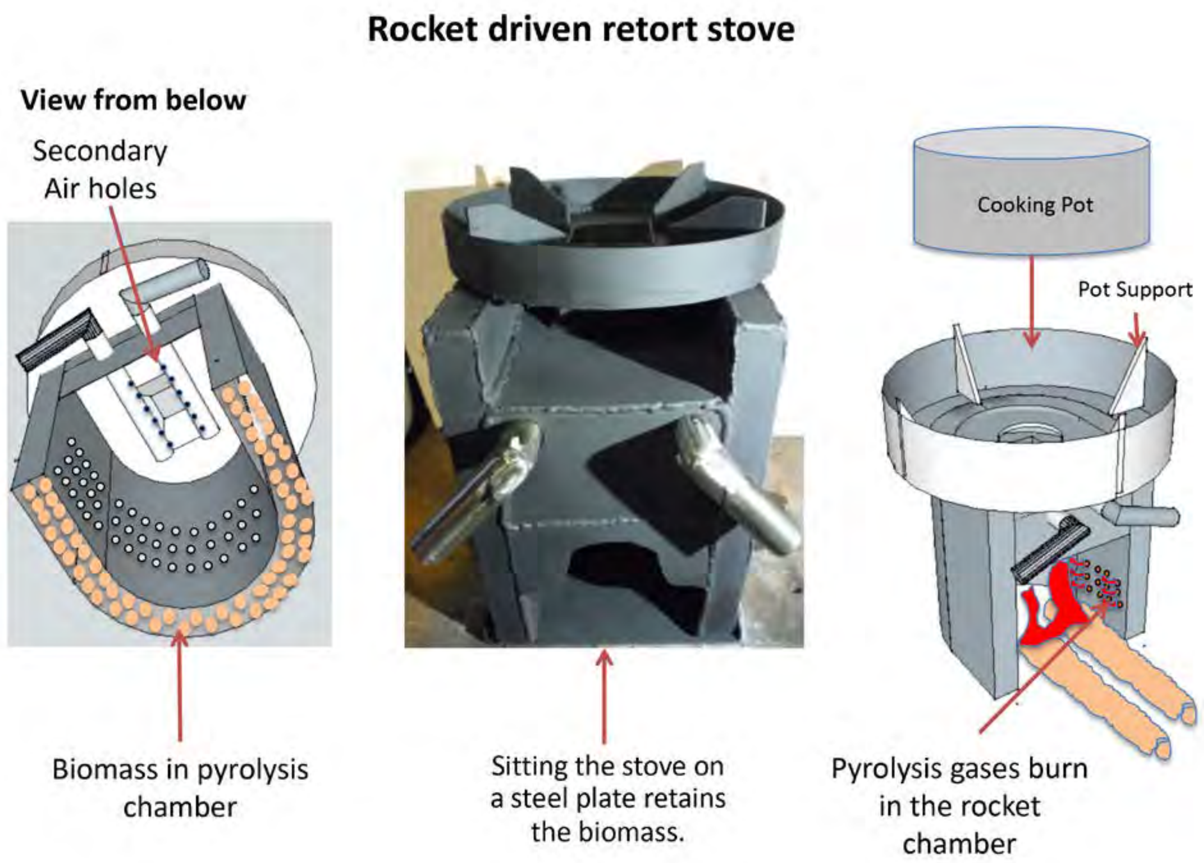


Figure 3.4 A rocket driven retort stove used for rice husk pyrolysis. (Photo Stephen Joseph)

PART 4: COMMERCIAL KILNS

Commercial batch kilns

Batch kilns have been produced and sold for production of biochar for over 100 years. There are at least three manufacturers in Australia. There are a number of other batch kilns operating in Australia that have been purchased overseas.

Visit biochar-us.org/suppliers-and-manufacturers for kilns produced in the US.
Visit www.energy-xprt.com/companies/keyword-biochar-15990/location-europe for Europe.

Many companies in China produce batch kilns and these can be accessed via the web. Little information is available on their in-service history.

Earth Systems – CharMaker

The Earth Systems CharMaker (Figure 3.5) is a transportable batch pyrolysis technology applicable to any log or stick-sized woody biomass – chipping of the biomass is not required. The CharMaker comes in two sizes: a 20 ft container and a 40 ft container, which have been sold in Australia and overseas. Over 20 feedstocks have been trialled, some with moisture contents over 50%. The technology can be used to make standard charcoal as well as biochar with >90% C content. A batch takes approximately 5 hours to complete depending on the size and moisture content of the wood.

Figure 3.5 Earth Systems batch kiln. www.esenergy.com.au/charmaker-2 for further information

Allthingsbiochar – The Big Roo

The Big Roo (Fig. 3.6) was designed for degraded straw, weeds, and other fibrous biomass as well as for wood. It can be either a fixed installation or towed by a utility vehicle. The cage is filled with biomass, the reactor is moved to cover the cage, and fire is ignited at the top. The blower provides a balance of air below and above the cage to maintain pyrolysis and burn volatiles (see Chapter 3 and Table 1).

Figure 3.6 The Big Roo 4 cum portable batch kiln designed for straw. (www.allthingsbiochar.com.au for further information)

Terra Preta Developments – Kon-Tiki

Terra Preta Developments manufactures the Stretched Kon-Tiki (Figure 3.7). With a volume of 1.85 m^2, in a tilting cradle for easy emptying, it is designed for farmers, contractors or landowners.

Figure 3.7 Commercial stretch Kon-Tiki Kiln, produced by Terra Preta Developments Pty, Ltd. (www.terrapretadevelopments.com.au/products/kon-tiki-tas deep-cone-kilns/kon-tiki-tas-stretch-deep-cone-kiln)

Ukraine Carbonization Furnace

The Ukraine Carbonization Furnace (Figure 3.8) is a retort-style kiln designed for processing of lump wood and briquetted plant residues. The kiln consists of two chambers connected to a furnace with an afterburner and chimney. Biomass is loaded into baskets on trolleys, which are rolled into the chambers. The chambers can alternate between drying and pyrolysis. Combustible gases released from the pyrolysis chamber are directed to the furnace, which partitions heat back to the chambers for drying (with steam released to the atmosphere) or for maintaining pyrolysis. A Ukraine kiln is being successfully used by Queensland Gidgee Brothers for producing Gidgee lump charcoal.

Figure 3.8
Ukraine Carbonization Furnace, Ekko -2

Commercial continuous kilns

There are a few manufacturers of continuous kilns in Australia, and there are also many kilns produced in Europe, North America, Japan, and China, some of which are being imported to Australia. A list of manufacturers and suppliers of biochar equipment can be obtained from ANZBIG. The following is a brief summary.

Trough pyrolyser

One of the first modern kilns for rice husk and sawdust was a trough pyrolysis kiln developed by Kansai Corporation in Japan in 1960 (www.kansai-sangyo.co.jp/en/products-page). Over 200 of these have been built and used in Japan (Figure 3.9). The company also makes rotary woodchip pyrolysis kilns.

●Main specification

Type	LM-900
Performance	900kg/h (Rice husk)
Capacity	220kg/h (charcoal)
Size	12,000(W)×7,000(L)×8,000(H) mm
Dry weight	16t
Power	13kW
Cooling Water	50 ℓ /min (※)
Option	Automatic bag-filling machine (baler)

Figure 3.9 Kansai continuous kiln for rice husk and sawdust

Open-source trough pyrolyser

An open-source design trough pyrolyser has been developed by one of the authors in collaboration with Cornell University (Figure 3.10). A number of companies, including Energy Farmers P/L, Allthingsbiochar, and Carbon Powered Minerals Technology and Products, manufacture, operate, and sell versions of this kiln.

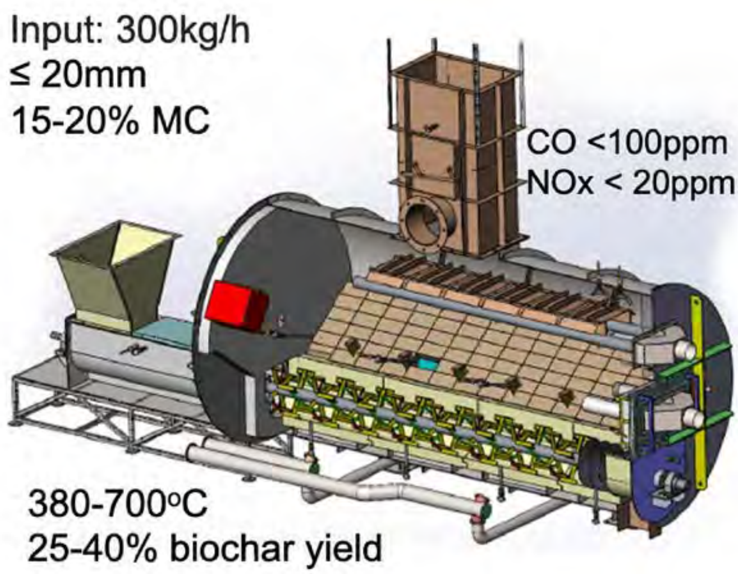


Figure 3.10 A trough pyrolyser designed by S and B Joseph

The method of operation is as follows:

A burner preheats the chamber, and the biomass is conveyed into the trough by a screw where it is ignited. Primary air (PA) enters through jets just above the troughs to start the pyrolysis process. Syngas from pyrolysing biomass rises, mixes with secondary and tertiary air, and combusts above the bed. Radiant flux over the bed dries and pyrolyses material as it moves along the trough. The pyrolysing biomass is continually turned and moved along the trough using a combined paddle and auger system. When the temperature of the kiln reaches 650°C, the primary air is turned off. When the temperature above the trough reaches 850°C, water is injected to give a translucent very clean flame. Changing the feed rate, amount of PA, and rate of water-mist onto the char bed controls the temperature of the biochar.

Earth Systems is now manufacturing externally fired continuous pyrolysis systems. The CharMaker Continuous Pyrolysis Plant (CPP) consists of a furnace, pyrolysis chamber, a thermal oxidiser emissions chamber, and a control panel (www.esenergy.com.au/continuous-charmaker-cpp).

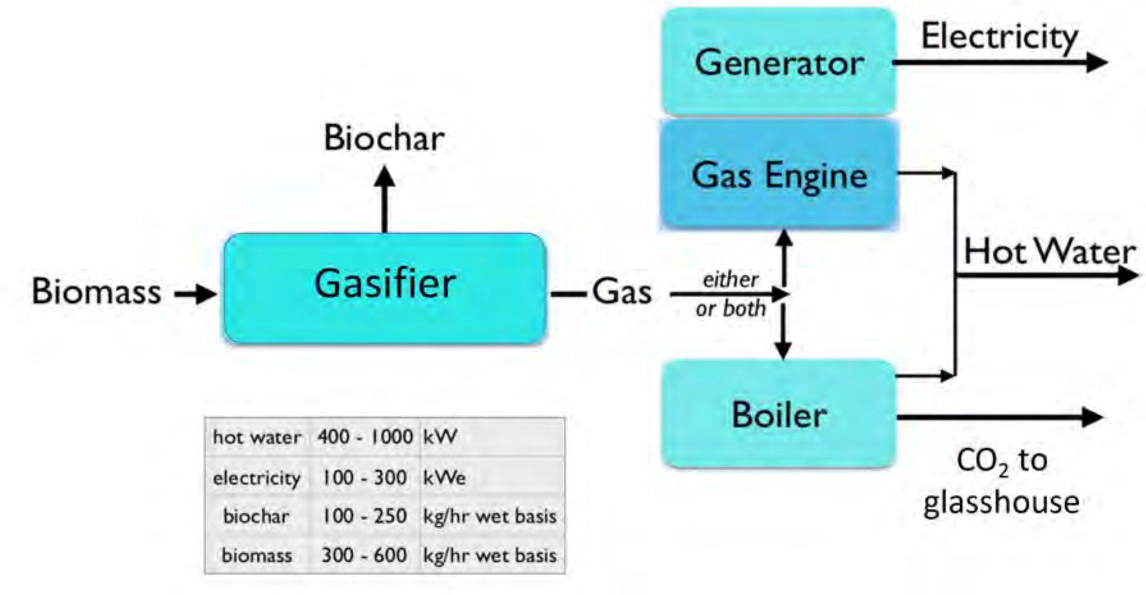
Pyrocal rotary hearth gasifier

Pyrocal produces a rotary hearth gasifier to provide heat and produce biochar. This technology has been sold in Australia and overseas. Recently a biosolids biochar plant has been commissioned at a sewage treatment works in Logan, Queensland, Australia (https://www.pyrocal.com.au/biosolids-to-energy-biochar). The basic design of the technology is given in Figure 3.11. Biomass enters the top deck where it contacts hot gas (1). Drying biomass is dragged across perforated decks. Biomass chars and breaks up, dropping through the decks (2). Larger pieces are dragged around to a larger hole, so have longer residence time (3). Residence time in a 3-deck hearth is approximately 120 s. Biochar exits from the lowest level and is quenched immediately (4). Air is drawn in at the bottom, constrained by the design of the ports (A). Pyrolysing biomass releases flammable gas, which consumes the oxygen (B). Rising hot, oxygen-depleted gases dry and pyrolyse the dragged and falling fuel (C). Residual flammable gases burn in a thermal oxidiser (D). Gas leakage is avoided by negative interior pressure, which is maintained by draft and process controls.

Figure 3.11 Early version of the Pyrocal rotary hearth gasifier

Rainbow Bee Eater screw gasifier

Rainbow Bee Eater manufactures a screw gasifier that produces a clean burning syngas either for providing waste heat for greenhouses or for other processes, electricity, and biochar production (Figure 3.12) (www.rainbowbeeeater.com.au).



hot water	400 - 1000	kW
electricity	100 - 300	kWe
biochar	100 - 250	kg/hr wet basis
biomass	300 - 600	kg/hr wet basis

Figure 3.12 Rainbow Bee Eater ECHO2 biomass to energy system for producing heat and electricity and, optionally, clean CO_2 rich boiler exhaust for greenhouse heating. www.rainbowbeeeater.com.au

Rotary pyrolysis and gasification kilns

Rotary pyrolysis and gasification kilns are being manufactured in Asia, North America, and Europe. The costs range from AU$350,000 to >$2,000,000 for kilns with a dry feed input of 0.25–2 tonnes/hr. Figure 3.13 shows the principles of operation, and a rotary kiln operating in Brazil by NetZero with an output of 250 kg/hr of biochar. In these kilns the biomass is turned in a slanted externally heated drum. Pyrogas, taken from the rotating drum, can be cleaned with water and the particulates and condensate recovered. Some of the cold syngas is burned to heat the kiln and the rest can be used for other applications such as heating greenhouses or generating electricity. The condensate can be separated into wood vinegar and tars, with the latter also burned for heating. The biochar is produced at about 450°C, or the kilns can run at higher temperatures. The recovered water from cleaning the pyrogas (with or without separating wood vinegar) can be used to quench the biochar.

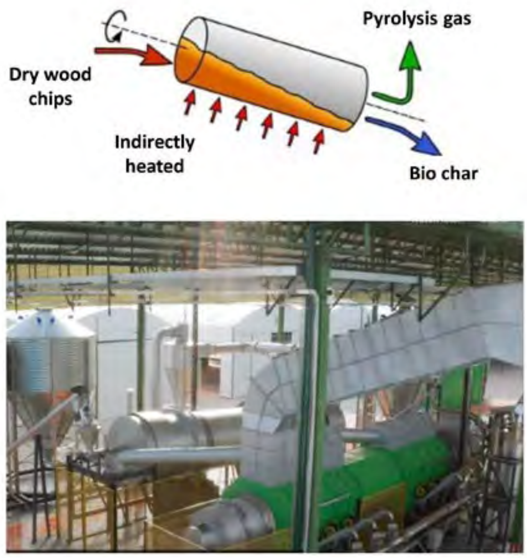


Figure 3.13 Schematic of the operation of a rotating drum pyrolyser, and a rotary kiln operating in Brazil

Air curtain burners

Air curtain burners modified to make biochar are a recent innovation. These transportable or mobile, skip-like burners, which have been developed in either batch or continuous versions, are taken to the waste or stranded biomass. The biomass is dropped into a fire in the burn chamber, while a high-velocity curtain of air is blown across the opening. This results in rapid incineration of the biomass, while it creates a barrier that prevents the release of harmful emissions and smoke into the environment. Some manufacturers have modified their designs and operating procedures to harvest biochar instead of burning to ash. Figure 3.14 is a photo of an air curtain burner, known as the Carbonator, which consumes 10 tonnes of biomass per hour. However, the biochar output is only 5% or 500 kg/hr. This is now operating in Queensland and the biochar is sold to a number of companies. The manufacturer is modifying the Carbonators to increase the quality and quantity of biochar, and to prevent them from dangerously emitting glowing embers.

Figure 3.14 Air curtain burnerThe Carbonator

PART 5: SPECIFYING A BIOCHAR REACTOR, AND SAFE OPERATION

There is a complex interplay between the inputs, outputs, kind of reactor, and control parameters of the reactor. The International Biochar Initiative (IBI) has published a thirty-page Guideline to assist in the development and testing of small pyrolysis plants.[2] Below we outline the most important points.

Considerations in specifying a biochar reactor

- Always consider:
  - Purpose of the reactor
  - Amount and type of biomass available
  - Current agriculture and waste management practices
  - Location and size of markets for products
  - Acceptance of small reactors is dependent on alignment with socio-economic context
  - Local or state regulations
- For industrial applications:
  - There must be no emissions of pyrogas to the atmosphere
  - The composition of the flue gas must meet local air emissions regulations
- Industrial-scale units must consider economic and regulatory environment, skills required to operate, reliability of feedstock supplies, and control system (manual or automated operation).
- Attend a workshop or work within an existing biochar plant before attempting to use a kiln if you have little to no experience working with biochar.
- Enlist the support of an engineer or a trained kiln operator who has designed or built and operated a kiln.
- For a continuous pyrolysis process, minimise the air entering with the feedstock by purging with low oxygen gas or vapour (e.g. with cooled flue gas) or specify an airlock system.
- Preheating the feed with steam, combustion gas, or exhaust gas from an engine helps to reduce air entering the feed, optimise energy use, and increase yield.

Important safety tips

- Even with simple kilns accidents can happen if correct operating procedures are not followed.
- Keep the biochar operation well clear of flammable materials.
- Flame cap kilns and TLUDs can emit hot cinders, which can start fires.
- Pyrogas can explode if air mixes with it in a closed vessel in the presence of an ignition source.
- Pyrolysis gas is toxic. Do not breathe it or allow it to contact your skin.
- Avoid breathing in biochar dust. Fine biochar particles are damaging to health and the environment. Take care when handling biochar during processing, storage, and shipment.
- Ensure that the biochar is fully cooled to ambient temperature in the absence of air, or filled with water, before standing in air. Biochar that is incorrectly produced (e.g. not fully pyrolysed), or insufficiently cooled or wetted can self-combust.
- For safety when storing or shipping, ensure that your biochar has at least 30% water in it when at ambient conditions. This will suppress dust particles and fire-risk.
- To measure the moisture content, weigh the biochar before and after it is heated at 140°C for 12 hours to drive out all of the moisture from the very small pores.

Photo credit: Pacific Biochar

References

1. Cornelissen G, Pandit NR, Taylor P et al. (2016) Emissions and char quality of flame-curtain "Kon-Tiki" Kilns for farmer-scale charcoal/biochar production. *PloS one* 11(5) p.e0154617 doi.org/10.1371/journal.pone.0154617
2. Guidelines for the Development and Testing of Pyrolysis Plants to Produce Biochar. biochar-international.org/wp-content/uploads/2018/04/IBI_Pyrolysis_Plant_Guidelines.pdf

Chapter 4

Introduction to basic biochar properties

Key Points

- Biochar can be made from almost any biomass, including many problem wastes.
- The suitability of a biochar for specific applications can be enhanced by strategically selecting feedstocks, and can be modified by preconditioning the feedstock, controlling the process, and post-conditioning the biochar.
- It is important to consider the physical, chemical, and electrical properties of biochar when designing a biochar to meet a specific application or constraint.
- Physical properties of biochar, including its porosity, surface area, and water-holding capacity impact its mobility in the environment, interaction with soil water, minerals, and nutrients, and suitability as an ecological niche for soil biota.
- Chemical properties of biochar include organic and mineral compounds in the biochar, their solubility into soil, and availability to plants. These affect biochar's pH and liming ability, cation and anion exchange capacities, and types and levels of functional groups on its surfaces — crucial in designing effective biochars.
- Electrical properties of biochar, its battery-like ability to store and donate electrons, enables biochar to drive nutrient cycles and change the soil's chemical composition and its oxidation-reduction status. This is part of how biochar affects bioavailability of nutrients, the pH, soil structure, and availability of water and air.
- The adsorption capacity of biochars, which can be enhanced by design, provides powerful environmental benefits for land, water, and agricultural remediation of heavy metals, pesticides, and other toxins.
- Levels of heavy metals, polycyclic aromatic hydrocarbons (PAH), and dioxins in biochars are typically within safe limits. The plant availability of these toxins is often less than 1% of the maximum tolerable risk to plants.
- Herbicides and pesticides may have reduced effectiveness if applied to soils where fresh biochar has been applied.

INTRODUCTION

This chapter introduces the key physical and chemical properties of biochar. We explore their relationships to the biomass feedstocks and the production conditions, and some roles they play in biochar applications.

It is important to note that the properties of biochar often change substantially when it is used in soil, compost, or animal feed. These changes may even override the significance of its original properties. Biochar properties can also be deliberately altered through pre-pyrolysis treatment with chemicals or minerals, or by post-pyrolysis treatment. This will be discussed in Chapter 7.

Overall, it's crucial to understand the properties of biochar to ensure its effective use as a soil amendment.

Biomass feedstocks

The most commonly used feedstocks for biochar are wood, straw, husks, bamboo, bagasse, manure, poultry litter, nutshells, hemp, and grasses such as *miscanthus*. Many other problem biomasses, such as gorse, lantana, privet, camphor laurel, prickly acacia, water hyacinth, dead fish, roadkill, diseased animals, animal waste, algal blooms, seaweed, and food waste make valuable biochars. European Biochar Certificate (EBC) has a list of permissible biochar feedstocks — www.european-biochar.org/media/doc/2/positivlist_en_2022_1_v10_1.pdf

While most biomass can be pyrolysed, environmental applications of biochar, including improving soil and water quality, increasing yields of food, and mitigating climate change, require that the feedstock be acquired sustainably. It is also crucial to exclude biomass with high levels of toxic organic and inorganic chemicals such as chromium, lead, arsenic, cadmium, and creosote when producing biochar for agricultural applications in soil, water, or animal feeds.

Finally, for a pyrolysis-biochar system to achieve effective net drawdown of CO_2 from the atmosphere, the feedstock must be derived from fast-growing biomass, or from wastes or residues that would otherwise be burned or quickly decompose sending their entire C to the atmosphere as CO_2. This is explained in in Figure 4.1.

Photo credit: Renewable Carbon Resources Australia

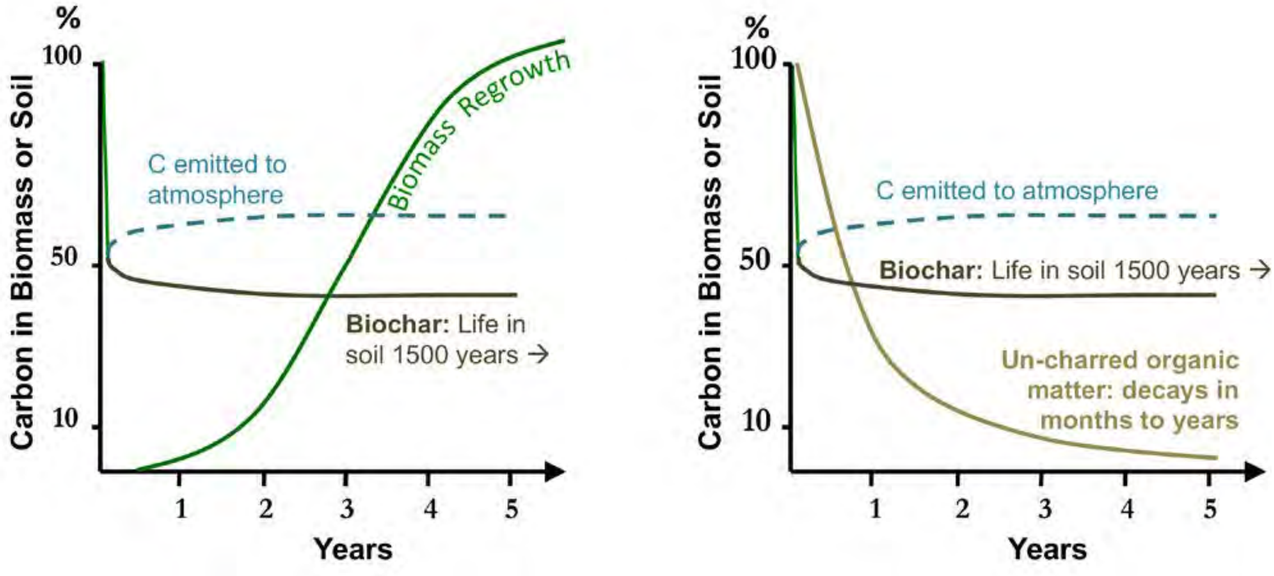


Figure 4.1 The carbon balance of the biochar production and use lifecycle when biochar is made from harvested biomass (left), or from decaying waste (right). Initially 100% of the C is in biomass. During pyrolysis about 50% of the C is emitted to the atmosphere as CO_2 (solid declining line) and 50% remains in the biochar. When applied to soil most of the C in the biochar remains sequestered for centuries, following initial decay of less stable C. Hence, the pyrolysis process results in an increase in atmospheric C levels (dashed blue curves). In the diagrams, we assume most of the regrowth or decay occurs within 5 years of converting the biomass. The initial release of C in the pyrolysis process is compensated for within three years by fast-growing biomass (left), or in only a year by the avoided emissions from the otherwise decaying waste (right). In either case, within 5 years the biochar process has resulted in a net increase in stored C of about 40% of the C in the original biomass.

Process conditions

The physical and chemical properties of biochar are primarily determined by the feedstock choice (especially the ash content of the biomass), and the process conditions such as rate of heating, time in the kiln, and final temperature. However, it is important to note that:

- The properties, as measured in the lab, of biochar made from clean biomass may differ from those of production biochar made from field residue or stored biomass that has been in contact with soil, manures, or fertilisers.
- The physical and chemical properties of biochar can be modified by conditioning, including post-treating the biochar with minerals, nutrients, or microorganisms.
- The properties of biochar will change as biochar interacts with microbes, plant roots, soil organic and mineral matter, or the animal gut after ingestion by fauna.

PHYSICAL PROPERTIES

The main physical properties that affect the efficacy of the biochar when it is first introduced into the soil or fed to animals are:

- Bulk density (mass of biochar per unit volume of its bulk)
- Particle density (mass of piece of biochar per unit volume)
- Particle size distribution (sizes of individual particles)
- Macro and micro-porosity (% of particle that is void)
- Surface area (total area of the internal surfaces of biochar)
- Hydrophobicity (tendency of a material to repel water)
- Water-holding capacity (gram of water held per gram of biochar)
- Grindability (ease of grinding, measured as specific energy used)

The mobility of biochar in the environment and its interaction with soil water, minerals, and nutrients are influenced by these interconnected characteristics. Biochar creates an ecological habitat for soil microbes and mycorrhizal fungi by offering surfaces, growth space, and protection from predators. The suitability of biochar as an ecological niche is also contingent on its physical properties.

Particle size

Biochars made from crop residues and small plants have an average particle size of less than 10 mm, although chunks of biochar made from block wood or bamboo may be larger, up to 50 mm. Typically, the processing of the biochar may include one or more of the following: chipping, cutting, crushing, milling, or grinding it to a uniform smaller size. Most biochar products that are applied to the soil or fed to animals have an average particle size of less than 1 mm. As a rule, the smaller the size the greater the beneficial effects of the biochar in terms of nutritional uptake, adsorption, and water-holding capacity. Larger pieces of biochar (1–5 mm) are used to improve soil structure, as mulch, or in the composting process, while still larger pieces (7–10 mm) are used as aggregate in roads and concrete.

Bulk density

Bulk density is the mass of a unit volume of a collection of particles or pieces. It is not an intrinsic property of a material, but depends on the size, shape, and compaction of the particles. Bulk density is an important factor to consider with respect to materials handling, production yield, and applications. The bulk density varies between 0.06–0.7 g/cm^3.

Porosity

The “pore volume” of a biochar refers to the void spaces inside the material, while the “porosity” is the percentage of the material volume that is void. The pore size and porosity of biochar reflect the cellular structure of the biomass it is made from and are also influenced by production conditions and ageing in soil (Figure 4.2).

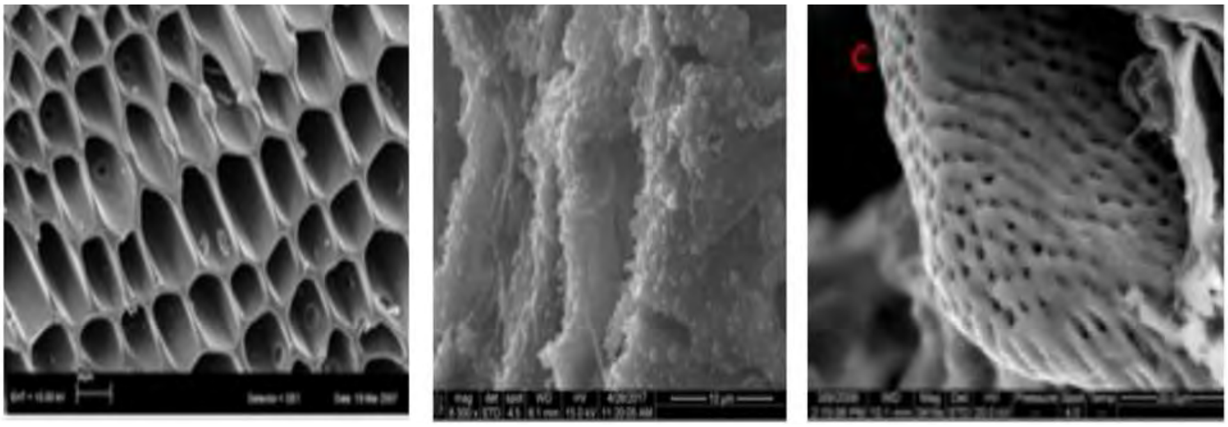


Figure 4.2 The pore structure of biochars. Left, fresh wood biochar. Middle, the dramatic changes occurring on the surfaces of biochar after 12 months in soil. Right, biochar made at 550°C from chicken litter shows lowered porosity due to melted minerals.

The pore size in biochar can range over six orders of magnitude from sub-nanometre slit-shaped pores between graphite-like “flakes” of aromatic carbon, to partially preserved cellular structures with pore size of tens of micrometres. Pores are typically characterised as micropores (or nanopores, smaller than 2 nm), mesopores (between 2 and 50 nm), and macropores (larger than 50 nm) (Figure 4.3). Micropores (found in materials such as zeolite, activated carbon, and some clays) hold gases and water very tightly. Mesopores provide a large surface area for chemical sorption processes. Plants cannot overcome the high capillary forces holding water in small pores, so plant-available water is restricted to macropores. Microorganisms reside in pores that have a diameter greater than approximately 1 micron, while root hairs and fine plant roots penetrate pores greater than 5 microns (see Chapter 5). Pores greater than 5 microns are optimal for microorganisms due to plant inputs (rhizodeposition) and simultaneous availability of both water and oxygen (Figure 4.3). While most pore volume (approximately 3 cm^3/g of biochar) is found in the pore size range from 1 to 100 µm important for microbial habitat, there are vastly more smaller-sized pores that contribute less to pore volume but are important for surface area and chemical sorption.

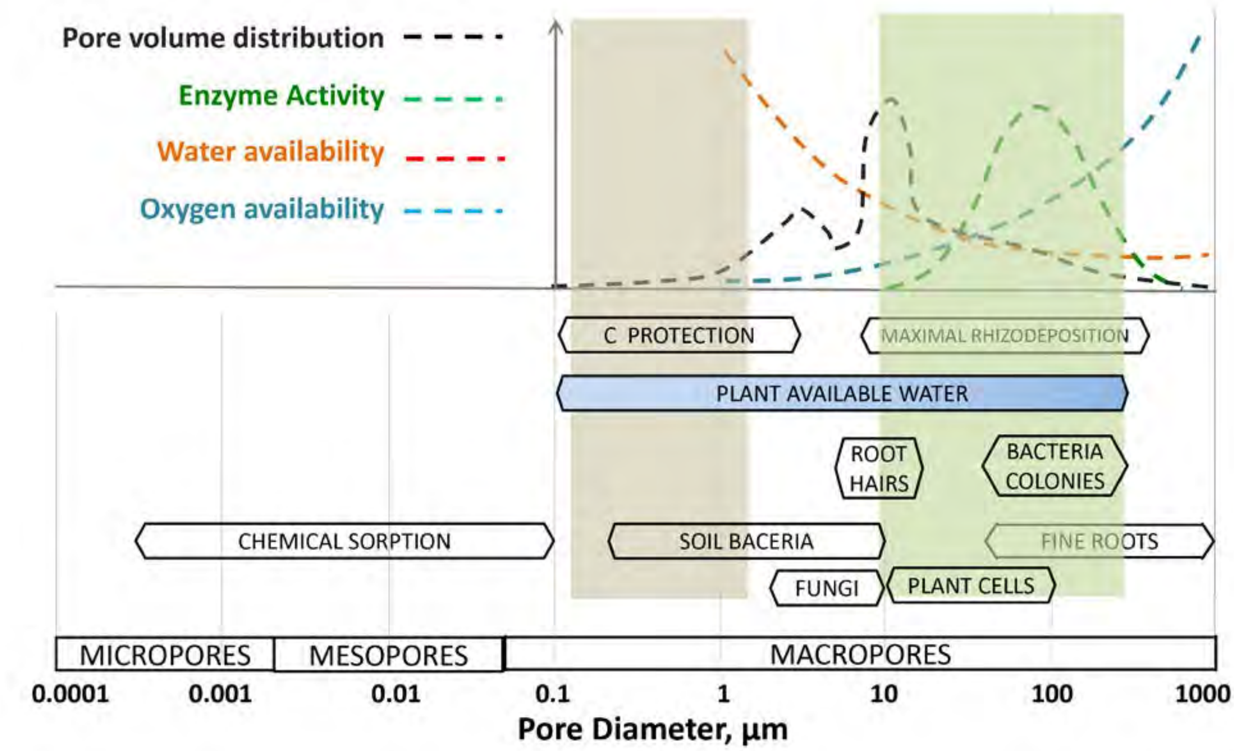


Figure 4.3 Pore size range and associated physical, chemical, and microbial phenomena in biochar and soils. The graphs show the water and oxygen availability, the enzyme activity in the soil, and a typical bimodal pore volume distribution found for plant biochars. Maximal rhizodeposition occurs where microorganisms interact with roots and root hairs. Plant-available water pore size range is extended down to the limit allowed by capillary forces (dashed line). (Modified from Brewer et al.[1] and Kravchenko et al.[2])

Surface area

Surface area is the measurement of surface per unit weight. The surface area varies from 5 to 600 m^2 per gram, typically increasing as the final pyrolysis temperature increases, and being high for wood biochars and low for high mineral ash biochars such as manures. For the high mineral content biochar, melting, and fusing can occur at high temperatures causing the surface area and porosity to decrease further (Figure 4.2). The surfaces and pore structure of the biochar may be open and regular, as in hardwood biochar, or complex and irregular, as in poultry litter biochar (Figure 4.2). Surface area and pore volume, whether low or high, may change as the mineral elements dissolve or are mined by roots and microorganisms, or conversely, as minerals are added by complexing with the surface of the biochar.

Hydrophobicity

A biochar has a high hydrophobicity if it repels or is difficult to mix with water. Conversely a biochar that attracts water is known as hydrophilic. Hydrophobicity is caused by tars (aliphatic compounds) condensing on the biochar surface during pyrolysis. Low-temperature biochars are strongly hydrophobic, but longer pyrolysis time, or washing biochar, can reduce hydrophobicity. As biochar reacts in soil, hydrophobicity may decrease.

Water-holding capacity (WHC)

Water-holding capacity is the amount of water that biochar can adsorb and is measured as:

$$\frac{\text{Mass of water held by the biochar}}{\text{Mass of biochar}} \%$$

Water-holding capacity is an important property of biochar, affecting its suitability as a soil amendment. Within its porous structure, biochar has the ability to both retain and release water. This quality makes applying biochar an effective approach to improve soil water retention and plant growth, and minimise water consumption. The water-holding capacity of a biochar depends on several factors, including its porosity, surface area, chemical composition, and particle properties.

Australian Scientists found that biochar products with mixed particle sizes, rough and irregular pores, and hydrophilic properties have higher WHC while biochars with smooth surfaces and hydrophobic properties have lower WHC.[3] Water was stored mostly in interpore spaces (between biochar particles) although intra-pore spaces were also significant for some biochars.

The variations of WHC with feedstock type and temperature are shown in Figure 4.4. Grasses and sugarcane waste exhibited the highest water-holding capacity – up to 700%; wood biochars hold up to 450%, and manure biochars around 300%. High ash biochars (including some grasses and manures along with papermill waste, food waste, and biosolids) can develop blocked pores in this temperature range, leading to low WHC. A wood biochar produced above 800°C had low WHC, likely due to fused pores.

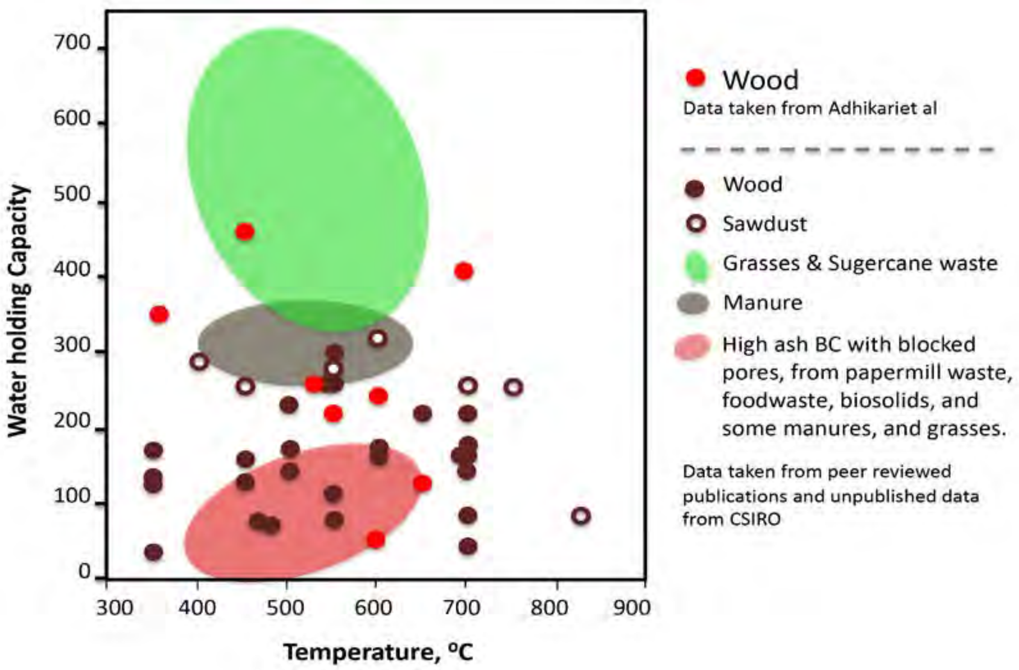


Figure 4.4 Water-Holding Capacities of over 60 biochars (BC) as a function of temperature. Individual data points are shown for wood and sawdust BCs produced between 350 and 830°C. Similar data points for biochars produced between 400 and 600°C from grasses, manures, and high ash feedstocks are indicated by their approximate ranges of WHC. (Data from an unpublished CSIRO study.)

Particle density and grindability

Particle density is the mass per unit volume displaced by the envelope of the particle, including internal pores. Biochar that is made from hardwood and nutshells can be very dense, from 500–900 kg/m^3. Longer pyrolysis time can increase the density and hardness, making these materials harder to grind and similar to coal. Most crop residues have a particle density between 250–300 kg/m^3 and are easy to grind. The exception is residues that have high silica content, such as biochar made from rice husks.

CHEMICAL PROPERTIES

Organic elements and compounds in biochar

The main organic elements in biochar are carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). The carbon content of biochar is either organic or a carbonate salt (inorganic). It may vary from 50–95% of the mass of the biochar and depends on the feedstock and the temperature at which the biochar is produced (Figure 4.5). Higher production temperatures result in biochars with a higher content of stable carbon. The hydrogen content varies from 1 to 5% of the mass of the biochar. Research has shown that the ratio of hydrogen to organic carbon molecules (the molar ratio, H/$C_{organic}$) is an indicator of how long the biochar will persist in the soil, as illustrated in Figure 4.6. For example, a biochar with 2% H and 60% $C_{organic}$ by weight has a molar ratio of H/$C_{organic}$ of 0.4. Most of the carbon in such a biochar can remain stable for a hundred years to many thousands of years.

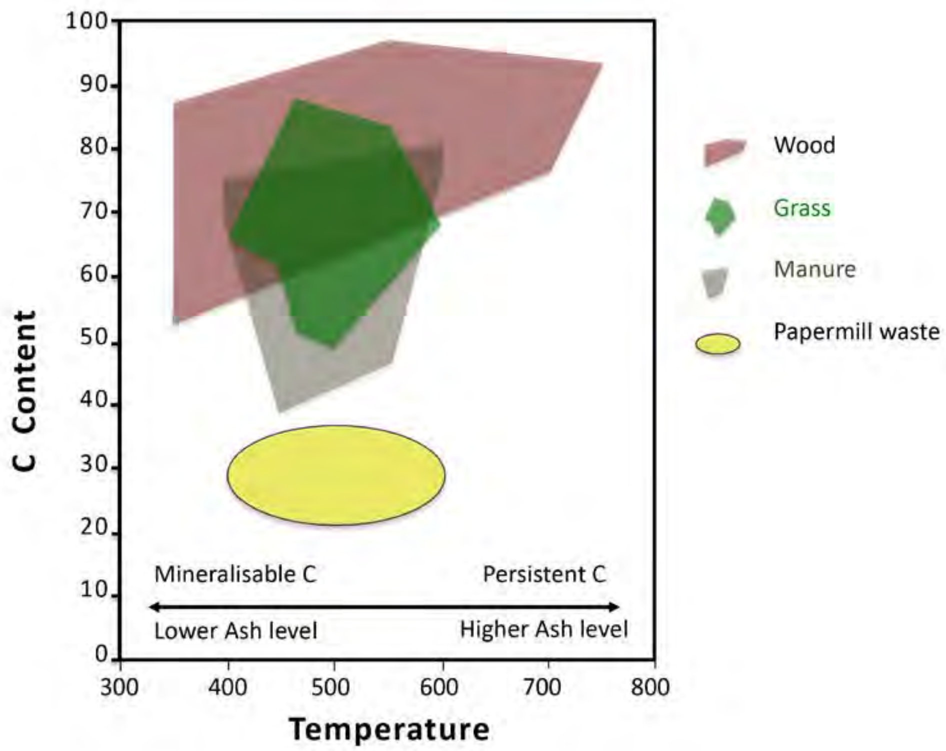


Figure 4.5 Carbon content of different biochars as a function of temperature.
(Data from an unpublished CSIRO study.)

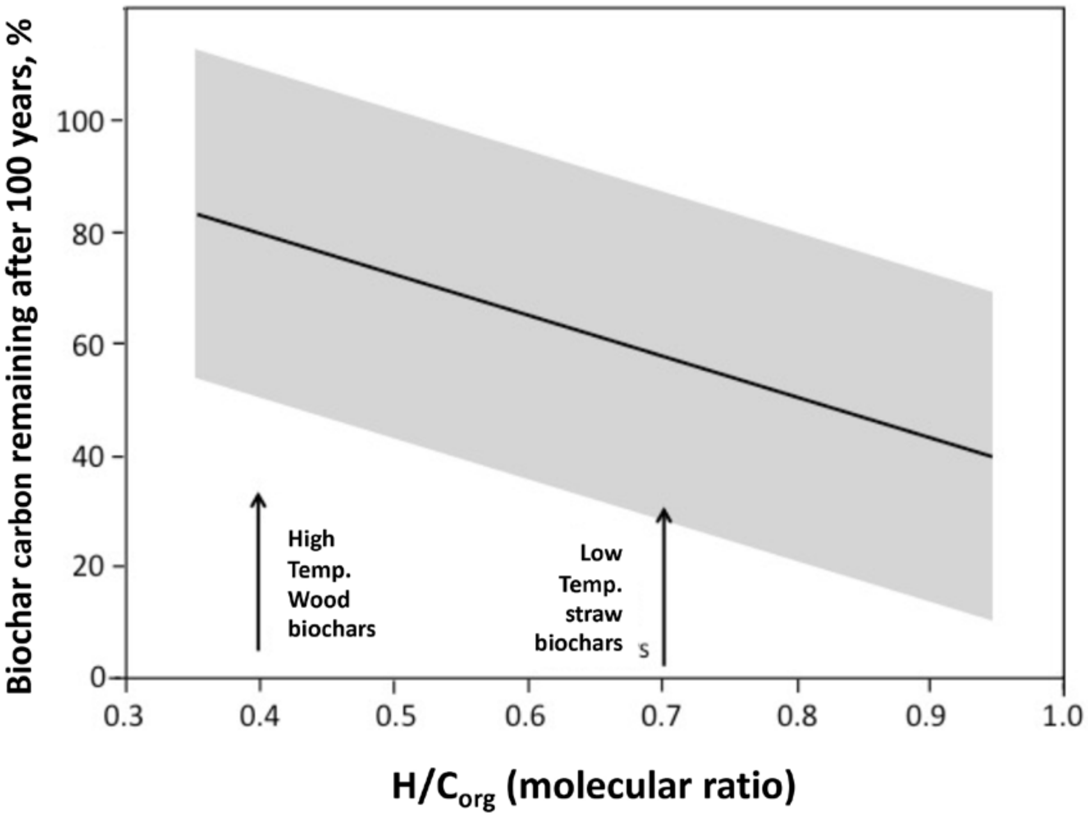


Figure 4.6 The percentage of the biochar carbon remaining in the soil after 100 years as a function of $H/C_{organic}$. The solid line represents the mean correlation of the biochars measured. The grey band represents the prediction interval within which 95% of future biochar measurements are expected to fall. (Modified from Budai et al.[4])

Biochars produced at temperatures below 450°C have a high content of water-soluble organic compounds, which are available as a food source for microorganisms. Some of these molecules are important for germinating plants and protecting them against disease, and some are responsible for helping plants take up nutrients.

Biochar, if not carefully produced, may also contain polycyclic aromatic hydrocarbons (PAH) and dioxins. These are toxic if applied at high concentrations. If a biochar smells of tar, then it likely has a high content of PAH and it should be sent to a certified laboratory for analysis. For properly made biochars, bioavailability of these toxic compounds is usually very low as discussed in the later section, Potential Toxic Properties of Biochar.

The nitrogen content of biochars may be as low as 0.1% and as high as 5% (Figure 4.7). Nitrogen can be over 5% for biochar produced from high protein content feedstocks like chicken feathers. There is less nitrogen in high-temperature biochar than in low-temperature biochar. Typically, biochar has 50–60% of the original nitrogen in the biomass when produced at 400°C–450°C, reducing to 30–40% in high-temperature biochars. In high-temperature biochars, the nitrogen is bound to the stable carbon lattice and is often not very plant-available, whereas in biochar produced at the temperature below 400°C, the nitrogen is loosely bound to the carbon lattice, often as ammonium N. Nitrogen is not only more concentrated but more plant-available in lower temperature biochars.

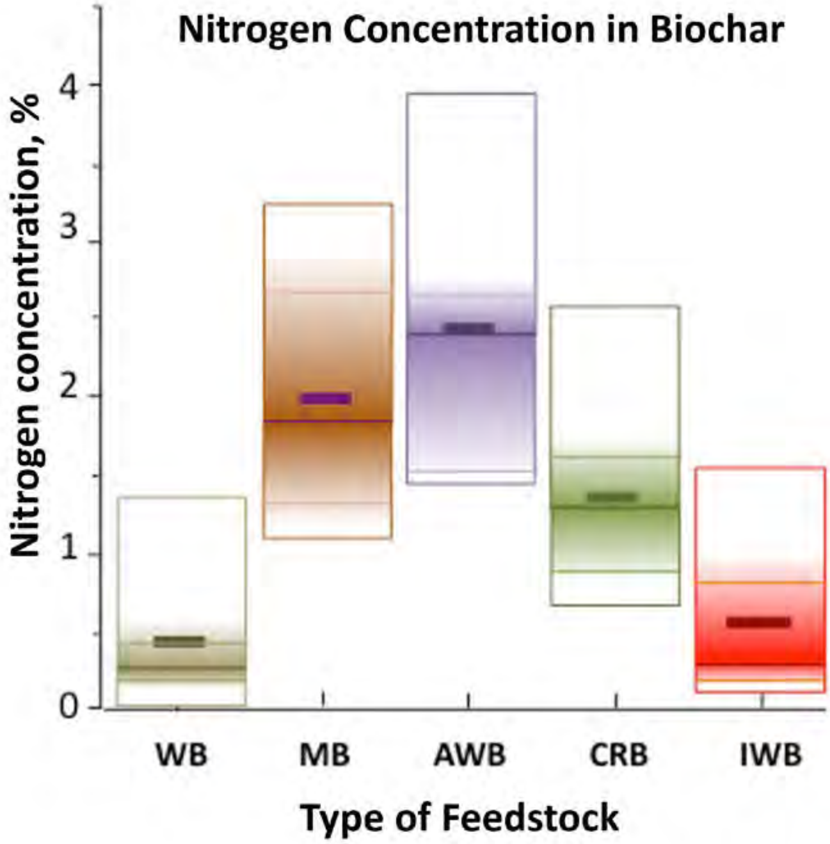


Figure 4.7 Percentage nitrogen concentration in biochars made from different feedstocks: WB woody biochar, MB manure biochar, AWB animal waste biochar, CRB crop residues biochar, IWB industrial waste biochar. The data are from a meta-analysis of 37 studies including 146 average values. The outer box covers the entire range of reported averages, while the short thick bar is the overall average for each feedstock. For further details on the boxes see footnote[a]. (Modified from Ahmad et al.[5])

Inorganic elements (ash)

The inorganic component of biochar, often referred to as ash, consists mainly of what soil scientists refer to as macro-nutrients P, K, Ca, Mg, and N, and micronutrients including Fe, Si, Mn, Se, B, Zn, Cu, Mo, Cl, Ni, and S. Some of these elements are attached to carbon atoms and some exist as very small mineral particles (e.g. sodium chloride, iron oxide, clay, silicon dioxide). Some of the salts and minerals are crystalline, while others do not have a crystalline structure and are termed amorphous. Crystalline minerals in biochar include rock phosphate ($CaPO_4$), salt (NaCl), sylvite (KCl), struvite ($NH_4MgPO_4.6H_2O$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), anatase (TiO_2), silica (SiO_2), clays ($Al_2O_3.SiO_2.H_2O$), iron sulphide (FeS), hematite (Fe_2O_3), or magnetite (Fe_3O_4). The inorganic elements also include heavy metals, such as mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb). Some heavy metals and metalloids, such as copper and zinc, are required in small quantities by plants. A typical analysis of a wood and a straw biochar is given in Table 4.1. For more detailed information on minerals see [6] in the reference list.

a. For each feedstock, the outer box covers the entire range of reported averages for a given biochar, while the inner shaded box captures the inner 50% of the values. The central solid line represents the median, and the short thick bar is the overall average for the category.

Table 4.1 Composition of wood and straw biochars. (Data from author SJ.)

Element	*Acacia saligna* 400°C mg/kg	Wheat straw 480°C mg/kg	Element	*Acacia saligna* 400°C mg/kg	Wheat straw 480°C mg/kg
Ca	245,000	195,000	Ba	125	123
Mg	16,400	51,500	Ti	334	778
Si	19,000	447,000	Mn	102	382
Cl	7,540	135,000	Li	76	17
Na	6,100	8,680	I	32	24
Fe	1,595	11,300	Ni	34	0
Al	3,150	8,260	Rb	30	91
P	2,540	4,000	B	28	9
Sr	1,350	763			

pH and liming value of biochars

The pH of biochar is its H^+ or proton activity. Biochars can have alkaline or acidic pH. It is found that the pH ranges from below 5 for low-temperature wood biochars to 11 for food waste biochars produced at 600°C (see Figure 4.8).

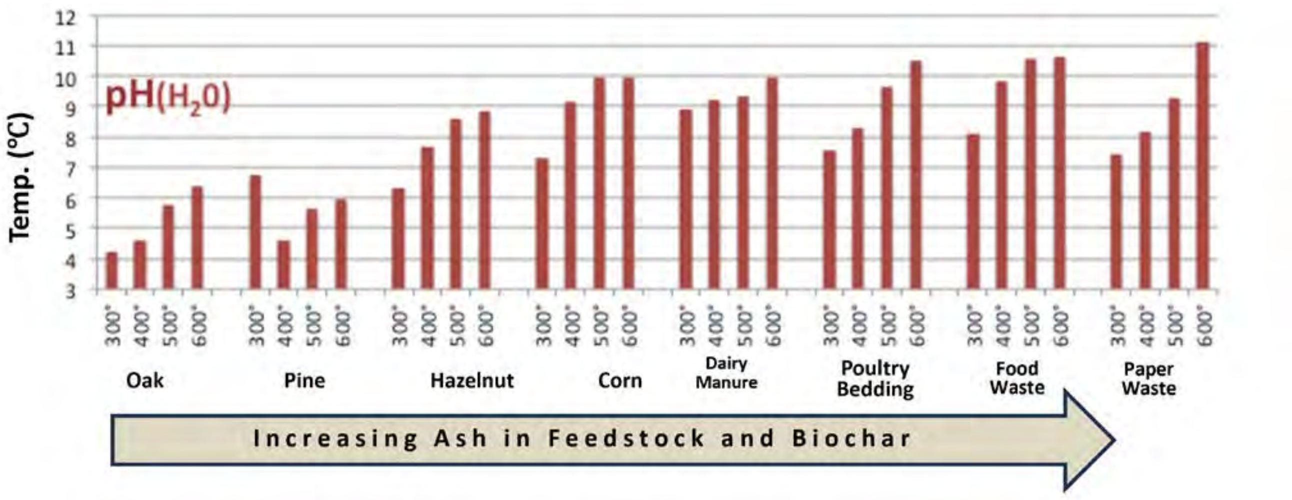


Figure 4.8 pH of a range of biochars produced at different temperatures (data from Rajkovich[7]).

The liming value of an amendment is its ability to neutralise acid soils relative to the ability of pure $CaCO_3$ (lime), which is indexed as 100%. The liming effect of biochars can improve mineral nutrient supply for plant growth and alleviate Al and P stress for better crop health in acid tropical soils. The liming value of biochar increases with its ash content. The ash content generally increases with temperature whereas pH doesn't always follow this trend, as can be seen in Figure 4.8. Liming values for biochars made from selected feedstocks are shown in Table 4.2. The liming value of corn biochar is over ten times that of the wood biochars. Some very high ash biochars, such as those from paper waste, could substitute for lime as a liming amendment.

Table 4.2 pH, ash content, and liming values as a function of highest heating temperature.[8]

Feedstock	HHT, °C	pH	Ash, %	$CaCO_3$, Equ %
Eucalyptus	400	6.9	3.6	-0.9
Pine	400	6.9	3.7	0.7
Pine	550	7.9	4.1	1.0
Corn	350	8.9	9.1	11
Manure and chips	450	10.0	30.4	9.5
Paper waste	700	9.2	45.4	40.9

Electrical conductivity

When biochar is placed in water some of its salts will be dissolved and the water will be able to conduct electricity. Electrical conductivity (EC) is a measure of total dissolved salts (TDS) and gives an indication of the availability of nutrients or presence of excess ash or salts. When added to soil, biochars made from high ash biomass like manure, paper waste, and biosolids are likely to increase soil EC and TDS (Figure 4.9).

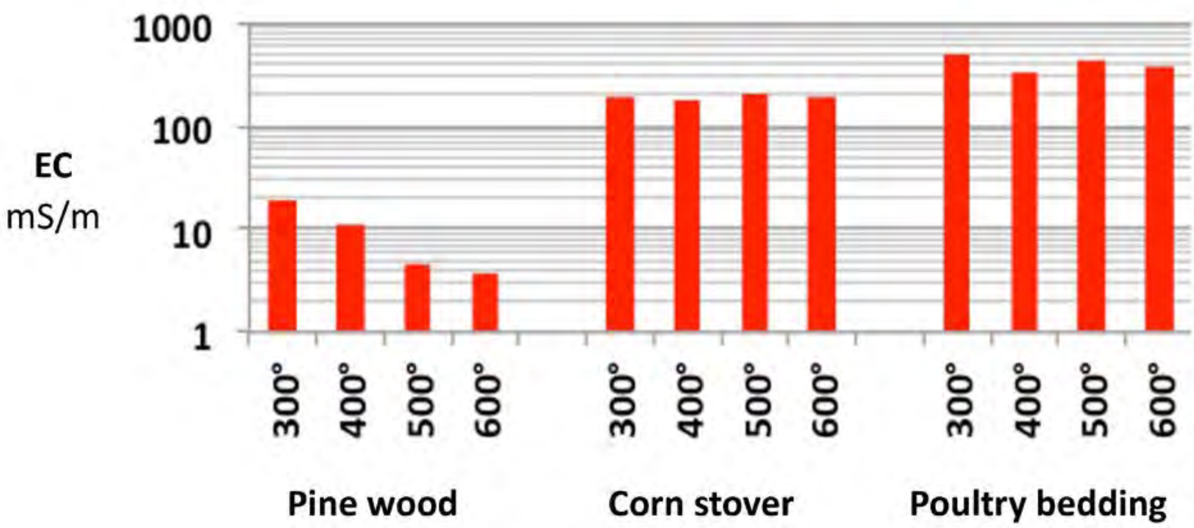


Figure 4.9 EC for three different biochars, plotted on a log scale, as a function of temperature. The ECs of biochars from corn stover (stalks) are 10 to 50 times higher than those of the wood biochars, while the ECs of manure biochars are 1.5 to 2.5 times higher than those of the corn stover. (Data from Rajkovich.[7])

Soluble cations and anions

Comprehending the composition and release rates of biochar's soluble cations and anions at different soil pH levels is necessary for assessing the appropriate amount of biochar needed to fulfil plant nutrient needs. It is noteworthy that following the initial release of soluble nutrients, the biochar surface adsorbs organic matter and minerals, leading to the formation of organo-mineral clusters (as discussed in the subsequent chapter). These clusters, in turn, have the capacity to bind surplus cations and anions present in the soil.

In a lab in Canada, investigators shook 36 biochars with water and analysed the separated liquids.[9] The feedstocks for biochar preparation included corncobs, corn stover, cocoa husk, cotton seed husk, wheat straw, spent hops, switchgrass, pine mulch and bark, poultry and cattle manures, and mushroom soils. Overall, the amount of nutrients released was much greater in acidic water with a pH < 6.5 than in alkaline water with pH > 7.5. No significant differences were observed between low-temperature (300°C) and high-temperature (600°C) biochars from the same feedstock in terms of release of NO_3^-, Cl^-, Na^+, Ca^{2+}, Fe, Cu, PO_4^- P, NH_3^- N, and K^+ in water. Manure-based biochar released significantly more concentrations of Cl^-, Na^+, Mn, Ca^{2+}, and K^+ compared to biochars from agricultural residues. Additionally, manure-based biochar had a greater concentration of nitrates than woody biochars.

Functional groups and cation and anion exchange capacities

Functional groups, consisting of oxygen, nitrogen, and hydrogen atoms are crucial components on the surface of biochars, playing a pivotal role in various biochar functions. These functional groups bind cations (e.g. K^+) and anions (e.g. PO_4^{3-}) when introduced into soil or water, making the cations potentially available to plants. The concentration of functional groups on the biochar surface, and consequently the performance of the biochar, may increase as the biochar ages or undergoes chemical treatments.

Figure 4.10 illustrates the diverse ways in which metallic compounds, cations, and anions, including heavy metals and nutrients, bind to the biochar surface through functional groups and other mechanisms. This binding is a complex process involving interactions with the carbon matrix.

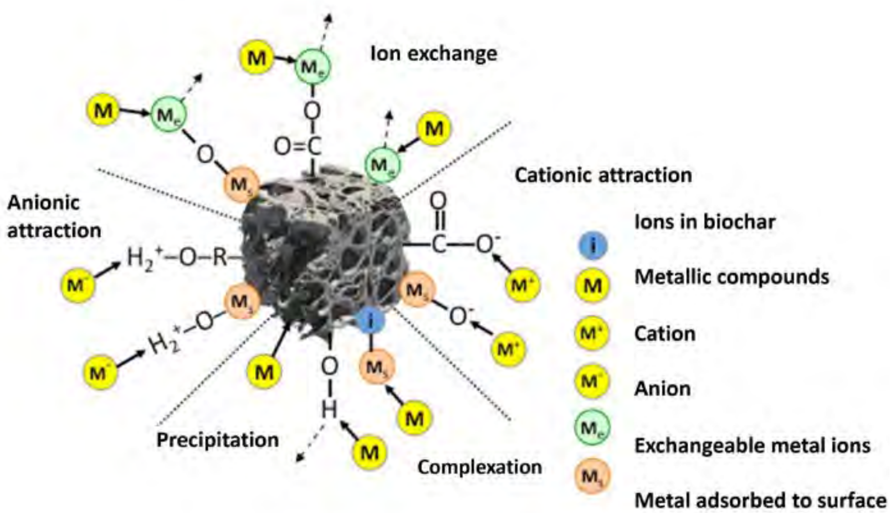


Figure 4.10 Some of the ways that cations and anions bind via different functional groups on the surface of biochar or metals that are embedded in the carbon matrix. Note: R stands for an organic molecule. (Adapted from Ahmad et al.[10])

Cation exchange capacity (CEC) and anion exchange capacity (AEC) are key measures of a biochar's ability to hold exchangeable cations and anions, respectively. The CEC is primarily influenced by the concentration of oxygen functional groups on the biochar surface, as shown in Figure 4.11. The AEC is linked to the presence of positively charged minerals on the surface. Notably, straw biochars produced at low temperatures often exhibit the highest CEC, as depicted in Figure 4.11. Conversely, high-temperature biochars demonstrate the highest AEC, as illustrated in Figure 4.12.

Find further information on CEC and AEC in a readable online article, Biochar, and the Mechanisms of Nutrient Retention and Exchange in the Soil[11]

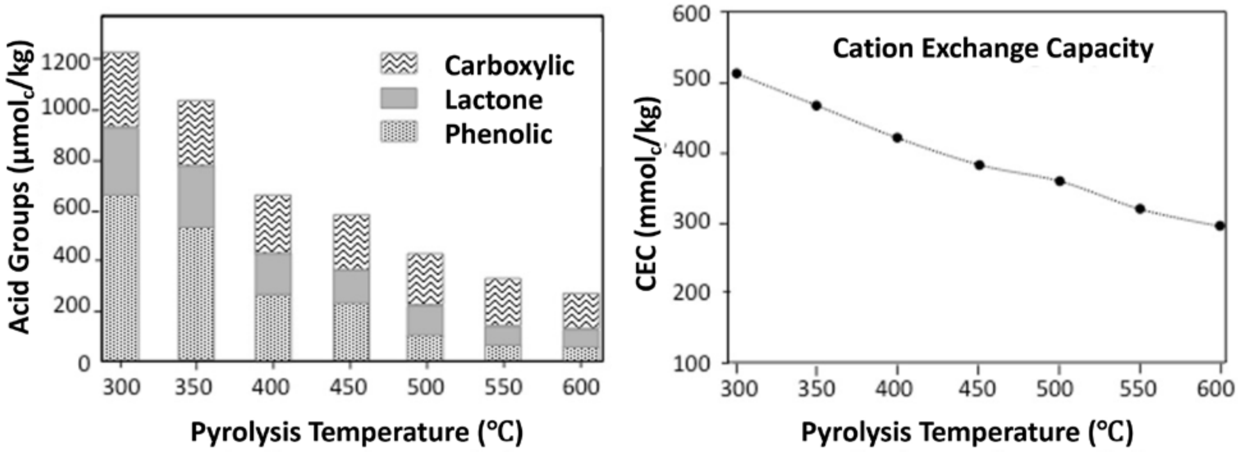


Figure 4.11 Acidic functional groups (phenolic, lactone, and carboxylic) and cation exchange capacity (CEC) of poultry litter biochars generated at different pyrolysis temperatures. (Redrawn from Song & Guo 2011.[12])

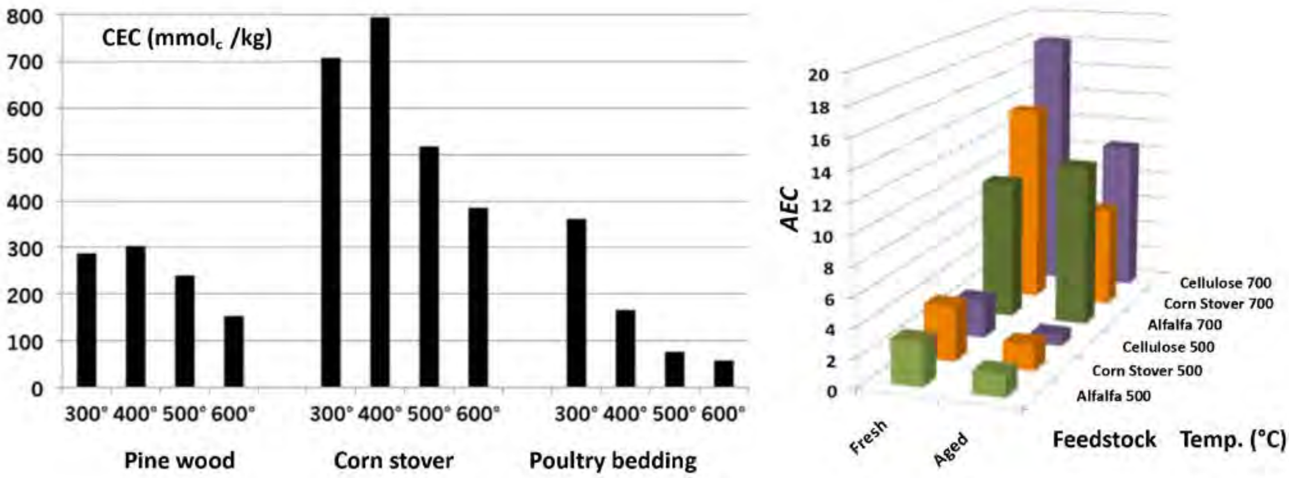


Figure 4.12 Left: Available CEC for biochars at different feedstocks and temperatures (adapted from Rajkovich[7]). Right: Anion exchange capacity of fresh and 4-month aged biochars from different feedstocks and biochar production temperatures. (Adapted from Lawrinenko.[13])

Adsorption and binding of toxic elements

Biochar's unique properties make it an effective adsorbent for contaminants due to its high specific surface area and reactive surface. For remediation of soils or water, high concentrations of suitable biochar (>10 tonnes/ha in soil) will be most effective. However, small amounts of biochar concentrated in the plant rhizosphere will enhance the adsorption of contaminants like heavy metals or polycyclic aromatic hydrocarbons (PAH), reducing their bioavailability to plants and various soil organisms.

Heavy metals

The adsorption of heavy metals involves multiple mechanisms: complexation, ion exchange, precipitation, electrostatic interactions, and chemical reduction, most of which are illustrated in Figure 4.10. Different mechanisms dominate for adsorption of different heavy metals, resulting in the sorption capacity of biochars for specific heavy metals having a complex relationship with factors such as feedstock and temperature.[14] High-temperature biochars (550°C–700°C) characterised by elevated pH, surface area, and pore volume exhibit greater adsorption for certain heavy metals. Conversely, biochars made at low temperatures with a substantial content of carbon and oxygen functional groups can exhibit a high sorption capacity for other heavy metals. Li et al[14]. found that a peppertree biochar produced at a temperature of 300°C had the highest adsorption of Hg, and coconut coir biochar produced at 250°C and then acidified had the highest adsorption for Cr(VI). Sorption of both biochars decreased with higher temperatures — see Figure 4.13. In contrast, a sludge biochar produced at 550°C had a high adsorption for lead.

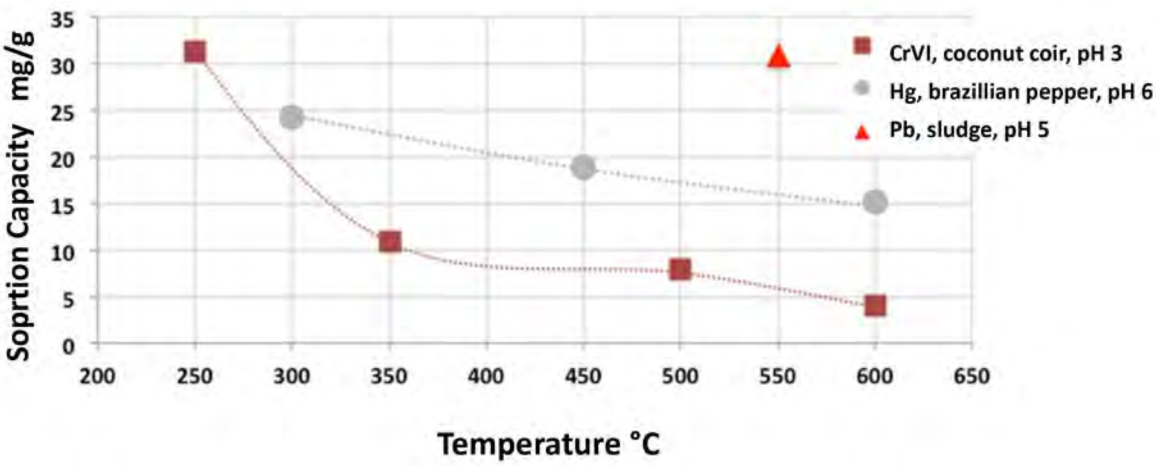


Figure 4.13 Capacity of selected biochars produced at different temperatures for metal sorption from aqueous solutions. The legend lists in order: Heavy metal species, feedstock, biochar pH. (Data from Li et al. 2017.[14])

Toxic organic compounds

Both high- and low-temperature biochars adsorb toxic organic compounds (e.g. naphthalene and trichlorobenzene),[15] microplastics, residual antibiotics, pesticides, and herbicides.[16] The mechanisms for adsorption are the same as those for heavy metals. The mechanisms that dominate depend on feedstock and temperature of production. Once adsorbed onto some types of biochar, the toxicity of these chemicals may be reduced or eliminated through redox reactions and by certain microorganisms that live in the pores of the biochar. This is especially true for biochars that have a high concentration of Fe and Mn oxide nanoparticles.

Biochar can also adsorb and trap microplastics in water. A study set in the UK found that corn stalk biochar produced at 500°C and a hardwood biochar from a charcoal kiln were the most effective at capturing microplastics in a water filter.[17] An international group found that adding livestock manure biochar to compost at 10% enhanced the degradation of microplastics during composting through increasing the abundance of specific microorganisms that degrade plastics. Oxidation reactions also degraded the plastics.[18]

Certain types of biochar and engineered biochars have been found to adsorb residual glyphosate that moves from the soil to water. A team of chemists in Cameroon found that a clay and wood biochar composite was more efficient at removing glyphosate from water than a straight wood biochar.[19]

Application of biochar to agricultural soils may reduce the contamination of underground water, by decreasing the leaching of applied nutrients or pesticides, and reduce runoff into neighbouring lakes or bodies of water. It must be considered that herbicides and pesticides may have reduced effectiveness if applied to soils containing fresh biochar.

Potential toxic properties of biochar

Biochar may itself contain toxic substances derived from contamination in the feedstock from which the biochar is made or from the production process.

Heavy metals

Biochars made from feedstock containing heavy metals will retain these metals, as they are not volatilised during the production process. Feedstocks of concern include sewage sludge, urban commercial and industrial wood, and residues taken from contaminated land. Metals present in biochar may include arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), and zinc (Zn). Most countries have regulations prohibiting the land application of materials, including biochar, with excessive total heavy metal contents, even though research indicates that most of these metals are often immobilised within the biochar. Biochar-certifying organisations such as The International Biochar Initiative (IBI) have also established maximum allowable standards. In some jurisdictions, exemptions may be possible if the amendment contains only small amounts of heavy metals exceeding permissible concentrations or if it is proven that the heavy metals are mostly not bioavailable. An aqueous leaching test may provide acceptable evidence.

For context, investigation of heavy metal contamination of biochar in Poland found that biochars derived from plant, compost, and municipal solid waste had heavy metal levels well below the limits set by the IBI for biochar. These levels were also lower than those found in compost and sewage sludge, which are permitted additions to soil in many countries. Although some biochars contained higher levels of specific heavy metals (Ni, Cu, Pb) compared to certain soils, leaching tests indicated concentrations in aqueous extracts of biochar were less than 1/100 of prescribed norms for available Cr, Ni, As, and Pb, and less than 1/4 for Cd.[20] Nonetheless, since biochar may be applied over multiple years, caution is advised when producing biochar from waste contaminated with heavy metals.

PAH and dioxins

Depending on the production process, polycyclic aromatic hydrocarbons (PAHs) and dioxins may be produced within the structure of the biochar. Numerous studies, including one that measured the total and bioavailable PAHs in 60 biochars found that the contents of total PAHs were generally well within the limits set by regulatory standards for application of materials to soils. Gasification chars had the highest PAHs, sometimes above regulatory requirements for soil amendments, although the PAH contents of Top-Lit UpDraft (TLUD) gasifier chars (see Chapter 3) were low (<10% of the allowed standard). However, biochars bind PAHs as much as 400 times more strongly than do soils. The levels of water extractable PAHs, a measure of the bioavailable toxicity, were generally less than 1% of the maximum tolerable risk. For dioxins, researchers found food waste biochars with high salt content, and therefore high chlorine content, had the highest levels of dioxins. However, total dioxin levels were all lower than the maximum specified in guidelines for non-sensitive soils, and bioavailable concentrations were below the analytical limit of detection.[21]

Basic properties of wood vinegar (WV)

WV is a dark red-brown to clear reddish brown translucent liquid that is a complex mixture of water and several hundred organic and inorganic compounds, minerals, and very tiny pieces of biochar. It normally has a pH of less than 5, as its main chemical compound is acetic acid (vinegar). The concentration of heavy metals and polycyclic aromatic compounds in refined wood vinegar is below the level specified in most regulations related to application of waste to soils. If uncertain about the purity or if there is no analysis on the label, conduct pot trials or send it to a laboratory before applying to soil. For more information on wood vinegar, contact the authors.[b]

ELECTROCHEMICAL AND ELECTRICAL PROPERTIES

The movement of electrons in soil, known as electron activity, plays a pivotal role in influencing soil health, fertility, and its capacity to sustain plant growth. This activity is instrumental in driving essential nutrient cycles, including those of carbon, nitrogen, and phosphorus. Electron activity alters the chemical composition of soil by transforming ionic species from one form to another, thereby impacting the bioavailability of nutrients. Additionally, electron activity exerts influence on other soil properties, such as soil structure, pH levels, water and air availability, and the overall oxidation-reduction status of the soil.

Biochar consists of a high content of porous carbon, mineral phases, and organic molecules that contain a range of functional groups, which can store and release electrons, acting as a battery in the soil (Figure 4.14). This biochar capability facilitates redox (electron transfer) processes and could explain many of the beneficial effects of biochar. If soils have little organic carbon and have a high potential (i.e. if they are oxidised), then plants have to expend more energy to take up nutrients. The plants are also more stressed, encouraging a greater abundance of pathogens. Biochar reduces the soil potential and the content of oxidised species. Sitting next to or on the roots of the plant, biochar can increase the voltage difference between the inside and outside of the root, reducing the energy the plant has to expend to take up nutrients. These effects provide energy for nutrient uptake and growth of beneficial microorganisms (Fig. 4.15).

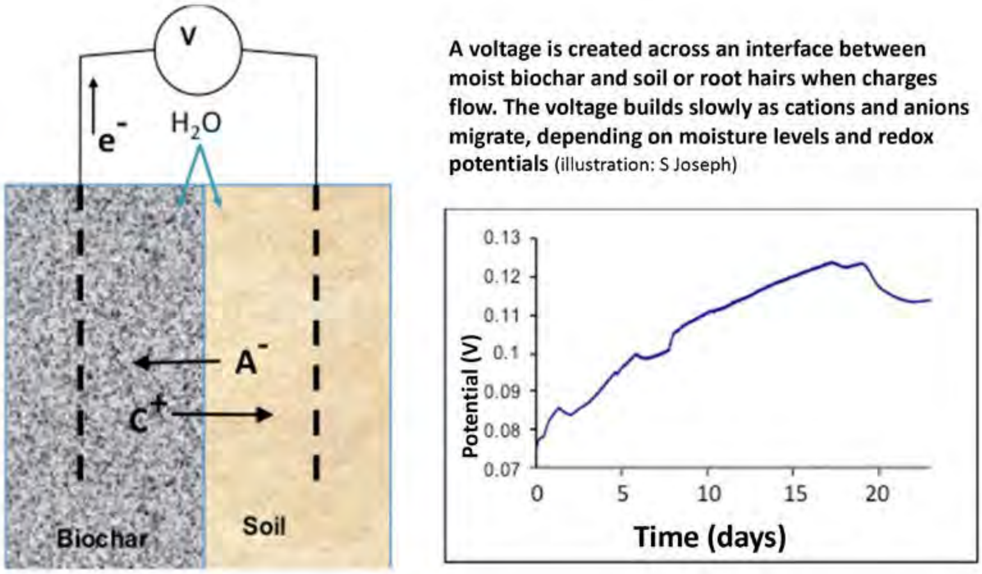


Figure 4.14 Biochar with water in its pores can store and donate electrons and ions like a battery. In the soil, it creates a potential difference between biochar and the soil, affecting electron activity. C^+ represents the positively charged cations such as potassium and A^- represents negatively charged anions such as nitrates.

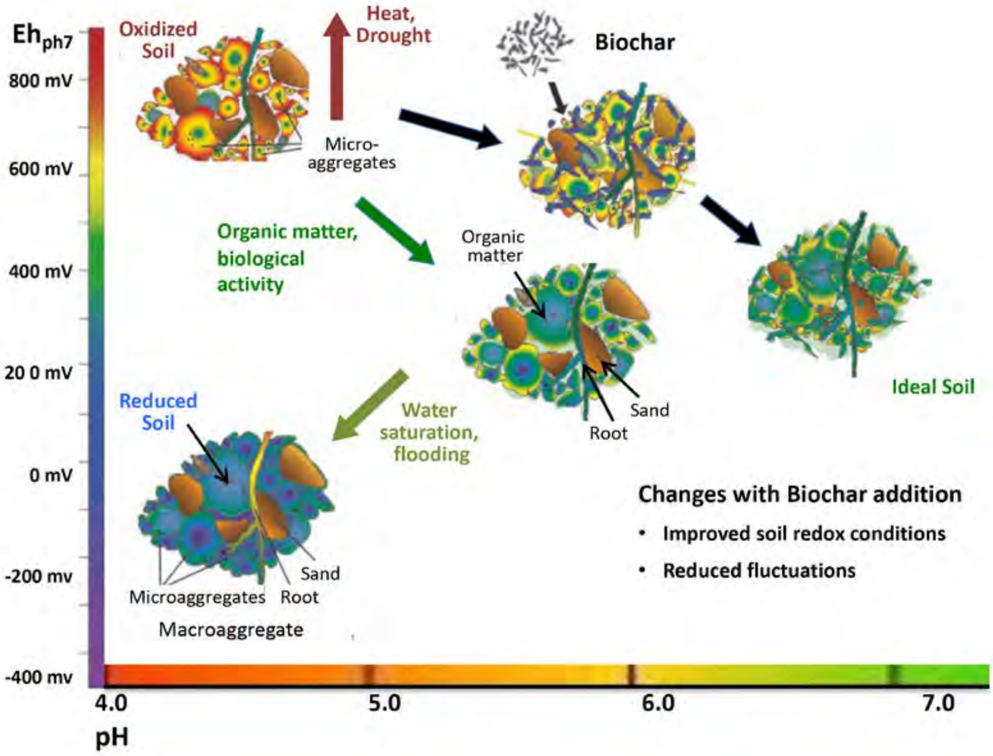


Fig. 4.15 Effect of biochar and other drivers on Eh and pH. Drought oxidises soil and flooding reduces soil. Biochar can enhance the ability of organic matter to bring the soil back to balance and make it more resilient and ideal for plant growth. (Modified from Husson.[22])

There are multiple measures of soil and biochar that provide insight into the electron activity within the soil and the capacity of biochar to influence it:

Redox potential (Eh) is a measure of the soil's oxidation-reduction status, which is its tendency to gain or lose electrons, and is expressed in millivolts with values ranging from negative (more reduced) to positive (more oxidised or a higher content of oxidised species).

Electron activity (pE) relates to the actual flow of electrons in the soil, and (like pH) it is expressed as the negative logarithm of the concentration of electrons.[23]

Electron Exchange Capacity (EEC) is defined as the sum of the Electron Acceptor Capacity (EAC) and Electron Donor Capacity (EDC) and is a quantifiable and stable property of biochars. Up to several millimoles, or over a billion trillion electrons, can be stored and exchanged by a single gram of biochar, depending on the biomass source and pyrolysis conditions.

Poise is the resistance to change in Eh when an oxidant removes electrons from a system or a reductant adds electrons. Consider this as similar to the relationship between "buffer capacity" and pH in soils, where buffer capacity quantifies the ability to resist change in pH by absorbing or desorbing H^+ and OH^- ions. By acting as a rechargeable battery, accepting, storing, and releasing electrons, biochar has a high capacity to keep the Eh poised in an optimum range for soil, microorganisms, and plants.

Footnotes

b. Author contacts (via website) **INSERT THIS INFO**

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Chapter 5

Changes in properties of biochar after interaction with soils, compost, or animals

Key Points

- The properties of a biochar change when it is aged in soil, compost, or animal feed.
    - Organo-mineral microaggregates form on the surface of the biochar as it interacts with soil organic and mineral matter. This results in changes in the biochar's pH, surface area, cation and anion exchange capacities, electron acceptor and donor abilities, and the ability to adsorb and release nutrients.
    - Biochar in compost undergoes similar changes, more rapidly, which enhances the biochar, the compost, and the composting process itself.
    - Biochar fed to animals (chickens, fish, cows, dung beetles, earthworms) or used in animal bedding promotes animal health and product quality. A cascade of benefits follows as the biochar moves through the animal's gut, or bedding, and into the soil as aged and enhanced biochar.
    - The rate at which a particular biochar ages, the changes in its properties, and the effects on soil and plants are complex and will depend on many external factors, such as environment, soil, crop, and agronomic practice.
- Ageing enhances the biochar's agricultural and environmental benefits. Aged biochars can improve the yield and nutrient value of crops and pasture, soil water-holding capacity, and ability to stabilise heavy metals, and can adsorb and oxidise methane and nitrous oxide.
- Understanding the changes in biochar with ageing helps when designing enhanced biochars for specific applications.

INTRODUCTION

Once biochar is introduced to soil, compost, or animals, it undergoes a dynamic process of change that enhances its properties. In this chapter, we introduce how biochar ages and the ways in which this maturing process improves its efficacy.

AGEING IN SOILS

A complex series of changes can occur over time when biochar is added to soils, as illustrated schematically in Figure 5.1.

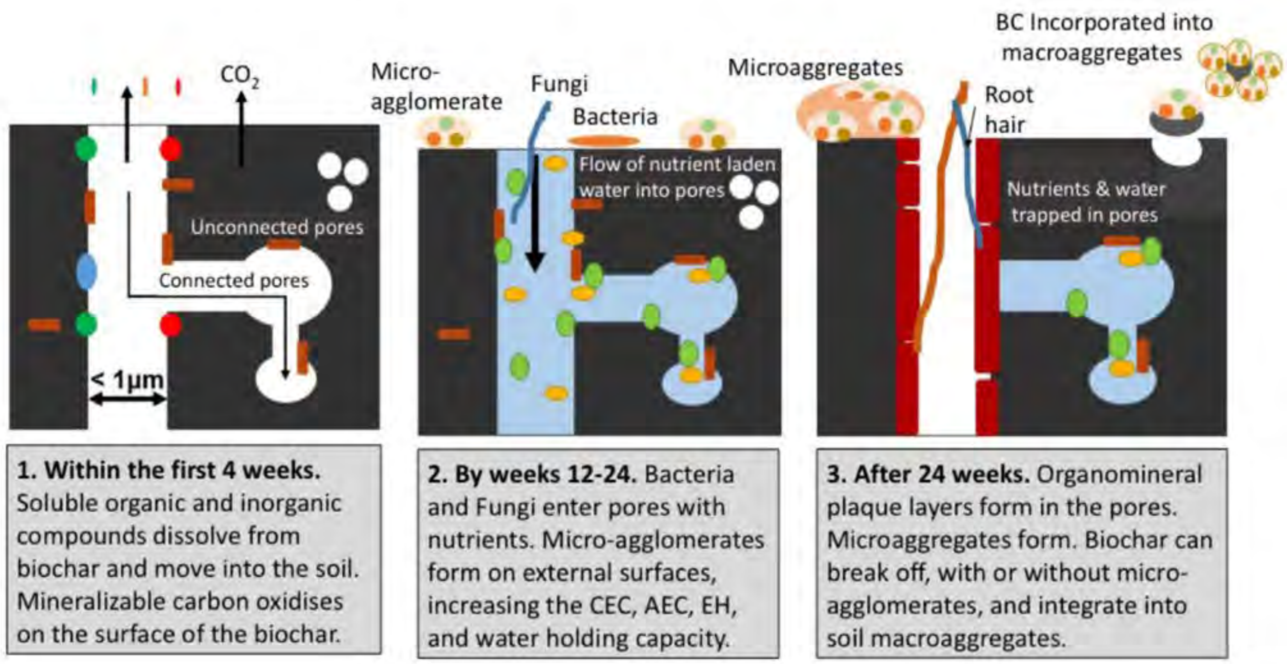


Figure 5.1 Schematic illustration of the ageing process on the surfaces and in shallow and deep pores in biochar (BC) added to soil. The time periods for the three stages are approximate, depending on rain, temperature, soil type, soil disturbance and agronomic practices. (CEC/AEC = cation/anion exchange capacity, Eh = reduction potential.)

When water infiltrates the pores of biochar, soluble organic and mineral compounds on the pore surfaces dissolve. This increases the concentration of dissolved organic carbon (DOC), cations, and anions in the soil solution, thus increasing the electrical conductivity and pH, as well as reducing the redox potential (Eh) of the soil. The release of DOC and nutrients from the biochar is most rapid during the first week and gradually slows in the following weeks. The release of nutrients is most rapid in acidic soils. Some of the dissolved organic compounds will promote seed germination and help combat pathogens.

After this initial phase, the surface of the biochar is coated with organic matter from the soil. The organic matter combines with minerals, cations, and anions from the soil water, forming small, porous clusters of organo-mineral complexes on the biochar surface, as well as within the biochar pores (as shown in Figures 5.1 and 5.2). The clusters are rich in oxygen, nitrogen, and hydrogen functional groups, which enable the clusters to capture nutrients from the soil or added fertilisers.

Plants and fungi interact with available activated nutrient-rich surface regions of the biochar. Plant root hairs enter the biochar pores gaining access to the nutrients in the biochar or organo-mineral clusters. They also exude organic compounds and gases that adsorb into the pores of the biochar. Organic molecules from dead microorganisms and plant exudates can also bind to the aged biochar surface. Much of the carbon becomes protected, which leads to an increase in the long-term carbon stored in the soil, and hence enhances the carbon sequestration benefit of the biochar.

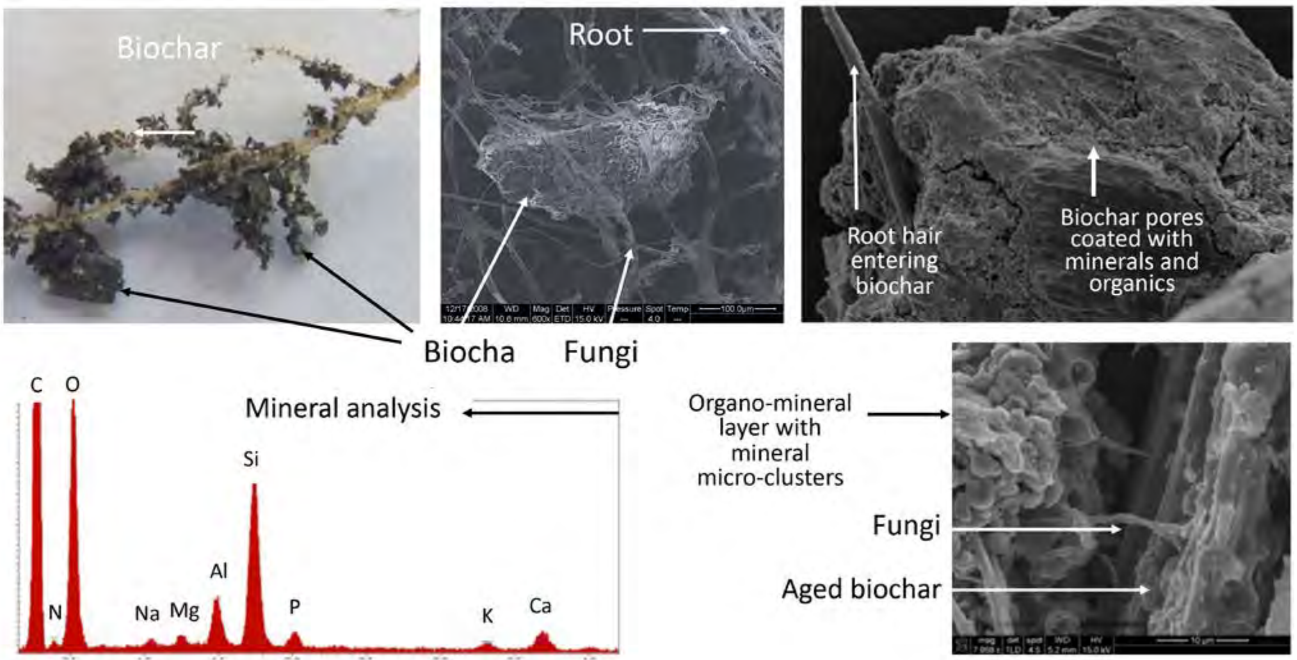
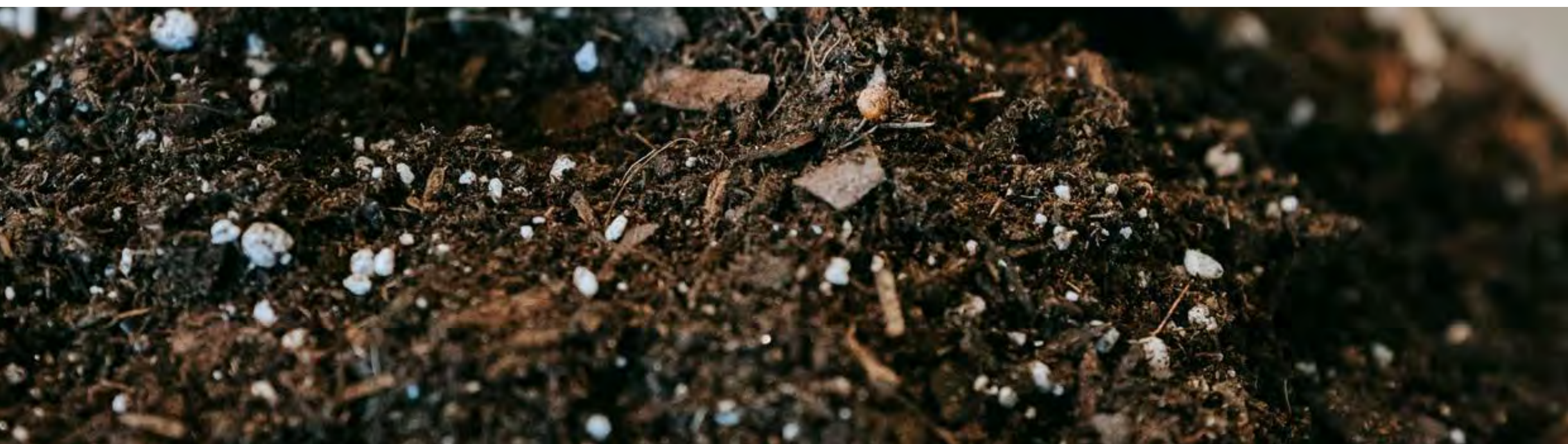


Figure 5.2 Top row: Fungi and root hairs entangling and entering pores of an organo-mineral coated wood biochar after 6 months in the soil. **Bottom:** High magnification image of the organo-mineral microaggregates that have formed on the surface of the biochar (right), with an X-ray spectrum showing the mineral elements (left).

Over time, biochar particles are broken down further by the actions of microorganisms and soil fauna, which disrupt and ingest the biochar. Root disturbance through cultivation, and exposure to wet–dry and freeze–thaw cycles also break down the biochar. This enables further interaction of fresh surfaces of the biochar fragments with the soil to form more organo-mineral micro-agglomerates. As biochar particles age and shrink in size, they become more mobile in the soil. Unless intercepted and bound by roots or root hairs, they can move into the subsoil, which increases its carbon and mineral content and sequester carbon.



AGEING IN COMPOST

When biochar is included with the biomass in the composting process, the biochar, the compost, and the composting process itself are all enhanced. Biochar provides a habitat for composting microbes, increasing the rate of composting. The composting process reduces the pH of the biochar and increases the CEC. For improving the quality and profitability of both the biochar and compost, the optimal addition of biochar to the biomass ranges between 5 and 10% of total dry weight of the biomass being composted.

When biochar is present during composting, it undergoes similar changes to those that occur in soil, but in a shorter time frame due to the elevated temperatures (>50°C), nutrient availability, and microorganism activity. The biochar gains and retains nutrients during composting due to the high nutrient content of the biomass used in composting, particularly when manures or grasses are included.

An organic layer of hydrophilic organic compounds coats the surface of biochar, then highly permeable organo-mineral clusters form on this organic layer. This helps to increase the biochar's porosity, CEC, and the electron acceptor/donor ability. The concentrations of N (especially nitrate), Ca, K, Al, Si, and Fe increase (see Figure 5.3). Biochar also changes the abundance of specific microorganisms. These changes on the surfaces of the biochar can significantly reduce the emissions of methane and nitrous oxide during the composting process.

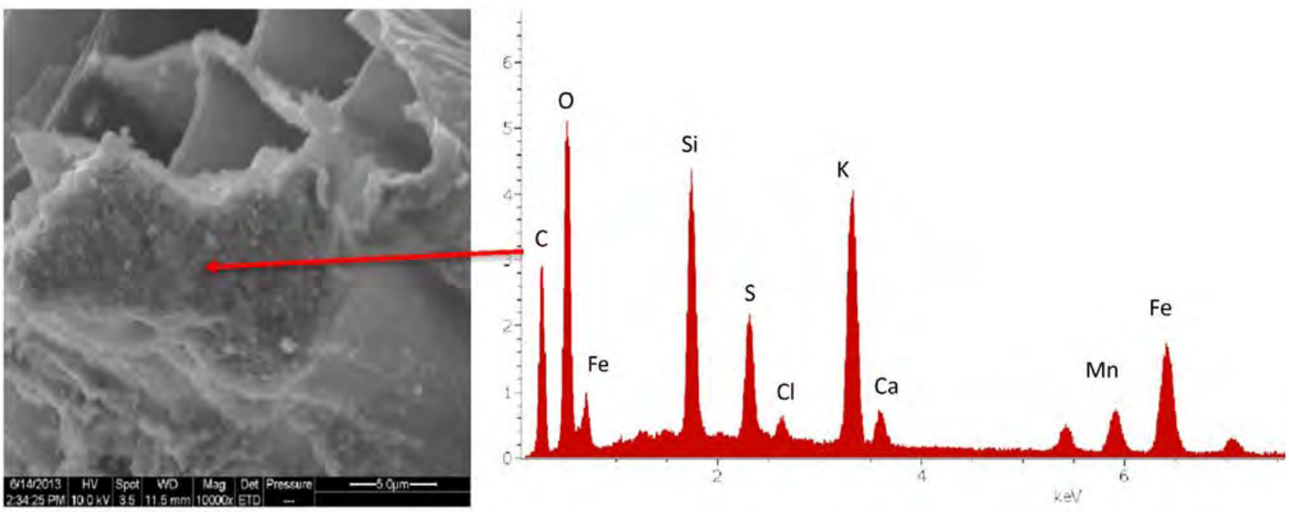


Figure 5.3 High-temperature wood biochar after composting, showing formation of organo-mineral clusters on the surface of a macropore. The X-Ray dispersive analysis shows high concentrations of K (potassium), S (sulphur), Si (Silica), Fe (iron) and small concentrations of Mn, Cl, and Ca

AGEING IN ANIMALS

Incorporating fit-for-purpose biochars into animal feed have been found to improve feed digestion and gut microflora, and reduce gut inflammation. Biochars that are sold as animal supplements include biochars made from hardwoods, straw, nutshell, and bamboo. After ingestion, soluble minerals in the biochar dissolve in the acidic environment of the stomach. The activated biochar surfaces then adsorb a variety of gut nutrients, in a process similar to that described earlier for composting. Beneficial bacteria and fungi also grow on the biochar in this phase. Studies found that when this animal-gut enhanced biochar is excreted and then incorporated into soil by a rain event or by dung beetles, it improved the yield and nutrient value of pasture within a few months. Similar changes occur in the worm gut (Figure 5.4), resulting in improved properties of vermicast.

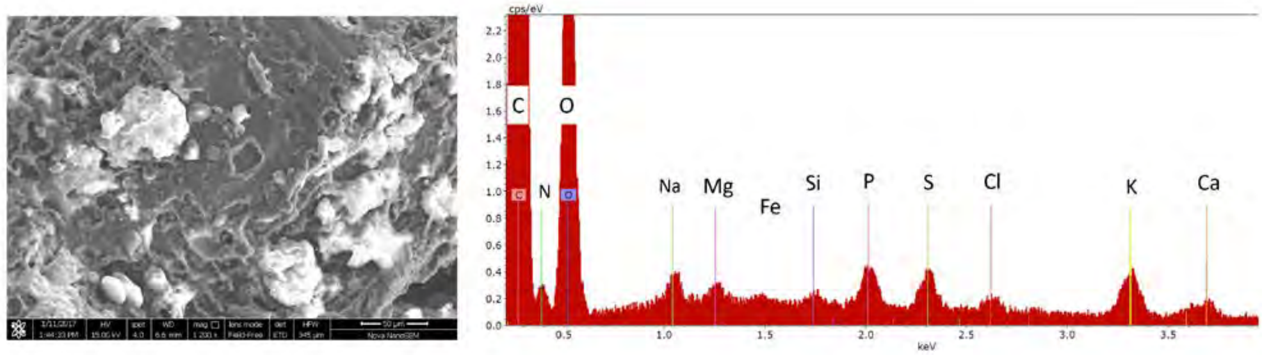


Figure 5.4 Organo-mineral clusters on a high-temperature wood biochar taken from the gut of a worm. Note the relatively high nitrogen (N), potassium (K) and phosphorus (P) contents in the X-ray spectrum

CONCLUSION

Biochars will often form organo-mineral microaggregates through interactions with soils, composting, and animals. This process enhances its properties including surface area, cation exchange capacity (CEC), anion exchange capacity (AEC), electron acceptor/donor ability, and the capacity to adsorb and release nutrients. These modified biochars demonstrate increased effectiveness in boosting crop and pasture yield, improving nutrient value, enhancing soil water-holding capacity, stabilising heavy metals, and adsorbing and oxidising methane and nitrous oxide. Understanding how biochar properties change after interacting with these environments is essential for planning and enhancing biochars for specific applications. It should be recognised that the rate at which a particular biochar ages, the changes in its properties, and the effects on soil and plants are complex and will depend on many external factors, such as environment, soil, crop, and agronomic practice.

Chapter 6

Effects of biochar on crop production and soil properties

Key Points

- Each farm has specific soil and environmental constraints. This chapter provides guidelines to help you meet these constraints by using combinations of biochars and additional nutrients. The findings and guidelines in this chapter will not apply to every farm. On-farm experimentation is recommended to optimise the benefits.
- To get the maximum potential of biochar-based amendments over the years, the biochar ageing process and the nutritional uptake of the biochar, soil, soil biota, and plants all have to be considered.
- If the biochar amendment and its rate and method of application are designed to meet the applicable constraints and nutritional dynamics, it can be maximally effective for specific constraints, or across a broader range of constraints.
- Biochars that are produced at low temperatures often produce greater crop yield, resistance to disease, and abundance of beneficial soil microorganisms than biochars produced at higher temperatures.
- High-temperature biochars have better water-holding capacity than low-temperature biochars.
- Biochars from nutrient rich grasses, straw, or manures, and woody biochars that are loaded with nutrients (especially N and P) produce greater yields than straight woody biochars.
- Biochar added at 5 t/ha or less to poor soils (that is, acidic, sandy, clayey, leached, oxidised, or low organic soils, or those with low cation exchange capacity) improves the yield relatively more than when added to fertile soils.
- Biochar applied at high application rates can improve the water-holding capacity and aggregate stability of degraded soils.
- Biochars that are aged before applying to soil are more effective than fresh biochars at increasing yield; however, as the fresh biochars age, the difference diminishes over 2–3 years.
- The effects of biochar on photosynthesis can differ in different types of plants, especially if their photosynthetic mechanism also differs.
- In terms of plant response (and return on the investment), a biochar or biochar–fertiliser combination is most effective if applied in the root-zone of the plant.
- Applying smaller amounts of biochar every crop cycle is not only more affordable but can be as effective in improving crop performance, and even more effective in building soil carbon, than one-off applications of a larger amount.
- To ensure continuous immobilisation of heavy metals, biochar should be added at least every two years.

INTRODUCTION

This chapter delves into the diverse effects of soil and foliar application of biochar on crop production and soil properties, synthesising findings from research literature, farmer practices, and personal experiences.

Different biochars have different effects on:

- Soil properties, crop growth, and resistance to disease
- Quality and yield of the crop (grain, fruit, vegetables, pasture, nuts)
- Abundance of specific microorganisms, especially in the root-zone (rhizosphere)
- Greenhouse gas reduction

The efficacy of biochar in increasing yields, plant resistance to disease, food quality, and soil health changes as biochar ages. The rate of change is a function of biochar type, soil properties, agronomic practices, and environmental factors.

BIOCHAR EFFECTS ON CROP YIELD

Biochar works best combined with fertiliser

Ye et al. (2019)[1] conducted a meta-analysis of literature published between 1998 and 2017, comparing the yield benefits of adding biochar without or with fertiliser against both non-fertilised controls (NFC) and fertilised controls (FC). The worldwide study encompassed data across different climates, soils, biochars, and management practices. Bai et al. (2022)[2] published a similar comprehensive meta-analysis using data from 2014 to 2019.

Separately examining the yield effects of biochar-based amendments when applied to unfertilised and fertilised soils is useful. Farmers in least-developed countries often cannot afford fertiliser and will value the potential of affordable biochar to enhance their yields. In countries where fertilisation is standard practice, further yield increases along with reduced fertiliser use are desired. Hence, understanding the optimal way to use biochar in both fertilised and unfertilised soils is important.

The effects of applying biochar (BC), inorganic fertiliser (IF), or a combination (BC+IF) on crop yields after one year are shown in Figure 6.1, separated according to the type of control, i.e. comparing with unamended soil (NFC) or standard fertiliser practise (FC). Notably, both studies show that biochar plus fertiliser was substantially more effective than fertiliser alone or biochar alone, against either baseline. The Bai (2022) results vary a bit from the those of the Ye (2019) analysis, probably owing to the use of different (more recent) data sets. We delve into the different effects of biochar amendment in unfertilised and fertilised soils by referring to the simple average of the two data sets, which we plotted in Figure 6.1.

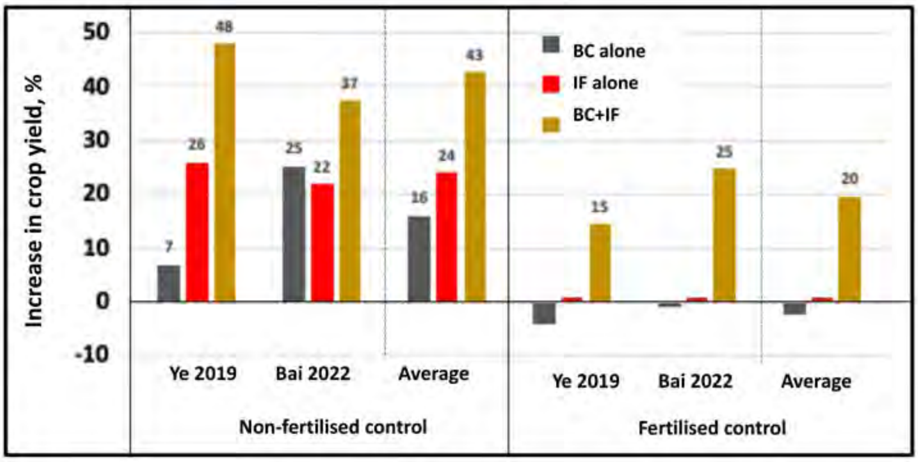


Figure 6.1 Average increases in crop yields relative to fertilised and non-fertilised soil controls after applications of biochar (BC), fertiliser (IF), or a combination (BC+IF). Data were combined from two meta-analyses each of over 55 studies (Ye et al.[1] and Bai et al.[2]) Each data bar represents the overall average from many comparisons of all kinds of biochar, for all application rates, all crops, all soils, and all climate conditions. The average of the results from the two studies is also shown.

Biochar yield effects in unfertilised soils

- In unfertilised soils, across all the studies, biochar alone gave an average 16% increase in yield compared with 24% for fertiliser. Combining biochar with fertiliser boosted yield to 43%.
- The Ye (2019) study found biochar was much less effective than fertiliser in unfertilised soils, whereas Bai (2022) found about the same effectiveness for both BC and IF. The improvement in the effectiveness of biochar reported in the more recent dataset could in part be attributed to researchers finding better ways to target biochar to the soil constraints and conditions.

Key Point

- When no, or limited, fertiliser is available biochar, can be a substancial help to yields.

Biochar yield effects in fertilised soils

- Ye et al. found biochar alone had a small negative average effect on yield when applied to fertilised soils. This can be expected because many untreated biochars are low in nutrients and deliver little yield increase; moreover, fresh biochar could be detrimental if it adsorbed nutrients provided by the fertiliser .
- Relative to fertilised controls, BC+IF gave average increases in yield, across all comparisons, of 15% according to Ye (2019) and 25% according to Bai (2022).
- Note that the average effect of applying industrial fertiliser (IF) when compared to fertilised controls (FC) was zero, since the fertilised control *is* industrial fertiliser (FC = IF).
- The overall average yield effect of the two studies against FC (20%) was less than half of the overall average yield effect against NFC (43%). This is aligned with the finding, from all the studies, that the average fertiliser effect in unfertilised soils was 24%.

Key Points

- In countries where fertiliser amendment is standard practise, successful application of biochar for yield increases generally requires employing the synergistic effects of biochar combined with fertiliser. When this was done, the overall mean yield boost of BC+IF against the fertilised control was 20%.
- More substantial increases will be obtained by designing optimally effective biochars to meet the soil constraints and conditions.

Biochar yield effects over time

Ye et al. also studied the effects of biochar application over time, drawing data from those studies that reported follow-on crop yields for 3–4 years after a single application of biochar.[1] A single application of biochar, with or without fertiliser, produced the greatest yield increase relative to a non-fertilised control in the second year after application (105%; range 59% to 177%; Figure 6.2). The mean effect in the first year was less than half (48%), and no significant effect was observed after the second year. In contrast, a significant effect in crop yields relative to fertilised controls was only observed after the second year, with a mean effect of 30% at 3+ years.

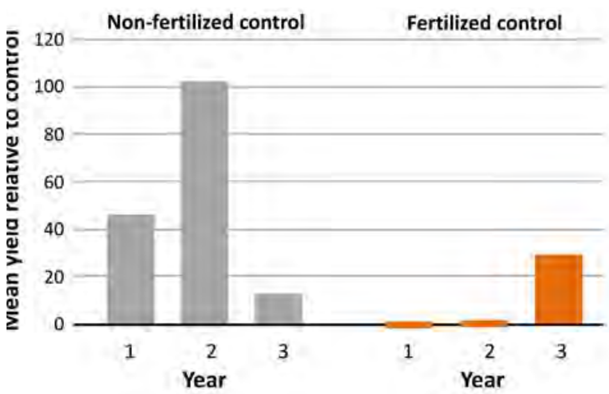


Figure 6.2 Changes in crop yield over years since a single application of biochar (combining all trials with and without the use of fertiliser) relative to non-fertilised controls and fertilised controls. The error bars contain 95% of the variation. The mean effect sizes were computed from the total number of pairwise comparisons (170 and 69). (Modified from Ye et al.[1])

The increase in yield over time after a single application of biochar comes from properties that develop with biochar ageing. Biochar that has aged in the soil for one or two years can be more effective than was the fresh biochar (i.e. in its first year). However, the biochar yield effect can decline again after two or more years, depending on conditions. The few multi-year studies available indicate that wood biochars may not have positive yield benefits beyond 2–4 years, but in some soils, high mineral-ash biochars, especially those from poultry litter and certain straws, may have positive effects on yield and soil health over ten years.

Biochar yield effects by categories of biochar, soil, and environment

The crop-yield increases caused by biochar additions (combining results from biochar and Biochar+Fertiliser) are shown in categories defined by biochar type, crop type, soil properties, and climate, in Figure 6.3. The yield increases relative to non-fertilised controls (blue data points) are much greater in most categories than those relative to fertilised controls (red data points), as was the case for the overall yields already discussed. The variables that had the greatest influence on crop yields were related to biochar properties (including feedstock and highest treatment temperature—HTT), initial soil properties, and the amount of N fertiliser added in Biochar+Fertiliser applications. Our comments on the significance for each category are listed on the right of Figure 6.3.

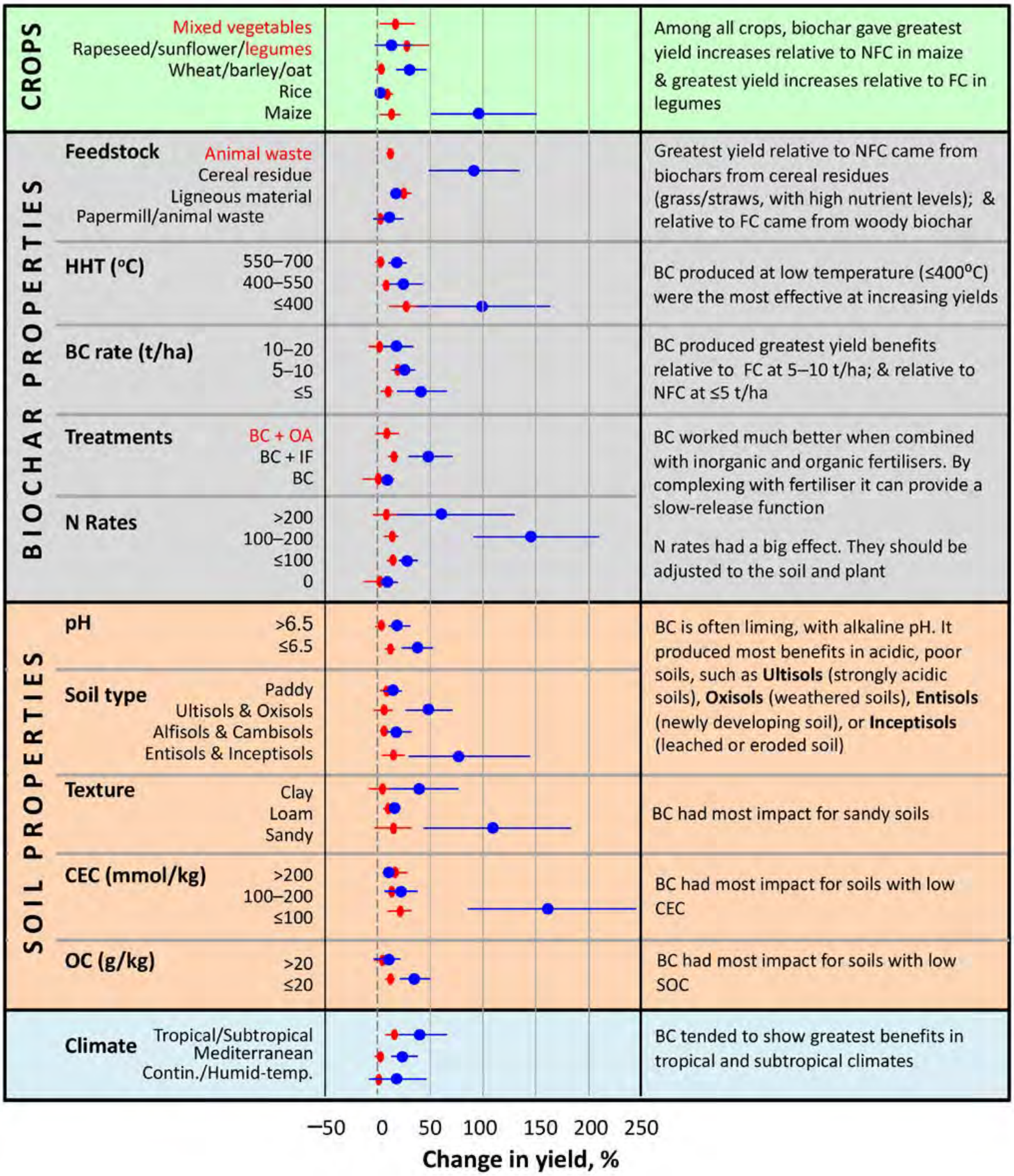


Figure 6.3 Proportional changes in crop yields (relative to controls) caused by adding biochar (BC), for crops, biochars, soils, and climates listed on the left. Blue dots represent changes in yields relative to those of non-fertilised controls. Red dots represent changes in yields relative to those of fertilised controls. Each data point is the average of many trials from many studies. Error bars encompass 95% of the data in each category. Comments by the present authors are listed on the right. (Modified from Ye et al.[1])

Key Points

- Biochars that are produced at low temperatures from cereal residues have higher nutrient content, producing greater yield increase.
- Using a combination of biochar and chemical fertilisers produced slighter higher yields than did using biochar alone or with organic fertilisers.
- Acidic, sandy, clayey, leached, oxidised, low organic, or low cation exchange capacity soils had higher yields when biochar was added at 5 t/ha or less, compared to yields from non-fertilised controls.
- Effects of biochar application relative to fertilised controls showed similar trends but much smaller effects than those relative to non-fertilised controls.
- The Ye et al. study only examined trials where biochar had been applied at greater than 2 t/ha and did not consider trials where small amounts of biochar (less than 200 kg/ha) were incorporated into or with fertiliser. The latter have been found to be very effective.
- The results shown in Figures 6.1 to 6.3 represent broad averages over a wide range of biochar, soil, crop and climate other than the category being examined. Much better average results could be obtained from trials using designer biochars optimised to meet specific soil, plant, and environmental constraints, as outlined in Chapter 7.

BIOCHAR EFFECTS ON PLANTS

In addition to yield increases, biochar can have a range of effects on root and leaf characteristics, photosynthesis, abundance of growth-promoting microorganisms that live in the root-zone and inside the plants, resistance to disease, and food quality. The effects depend on the type of biochar that is applied and its application rate. To be effective, the biochar should be applied in the root-zone of the plant.

Biochar impacts root characteristics

Biochar can have a significant effect on root properties:[3]

- Increases were measured in root biomass, volume, surface area, length, number of root tips, number of nodules for legumes, root phosphorus concentration, and fungal root colonisation, compared to a control without biochar.
- There were greater increases in root biomass and length in annuals (especially legumes) than in perennials.
- Overall root biomass increases were greatest in sandy soil followed by clay and then loam (especially soils with pH higher than 7).
- Biochars from fast pyrolysis with treatment temperatures between 450°C and 600°C, produced the greatest increase in the root length. This could be due to the high content of organic compounds that condense on the pore surfaces of the biochar.

Apply biochar in the root-zone of plants

Biochar concentrated in the root-zone has a much greater effect on plants than biochar that is dispersed throughout the soil profile. Biochar particles on or near roots can have the following benefits for plants:

- Plant root hairs enter the biochar particle and take up nutrients and water from the biochar.
- Root hairs stabilise the biochar on the root surface, reducing transport of biochar away from the rhizosphere.
- Organic molecules exuded by the plant can be adsorbed on the biochar surfaces and into the pores. This helps retain organic carbon close to the roots, where it provides food for microbes. If pores subsequently become blocked with clay, or the carbon complexes with clay, the carbon can add to the long-term store of carbon sequestered in the soil.
- In rice cultivation where the soils are flooded, biochar can be embedded in a plaque layer that forms on the root (Figure 6.4).[4]

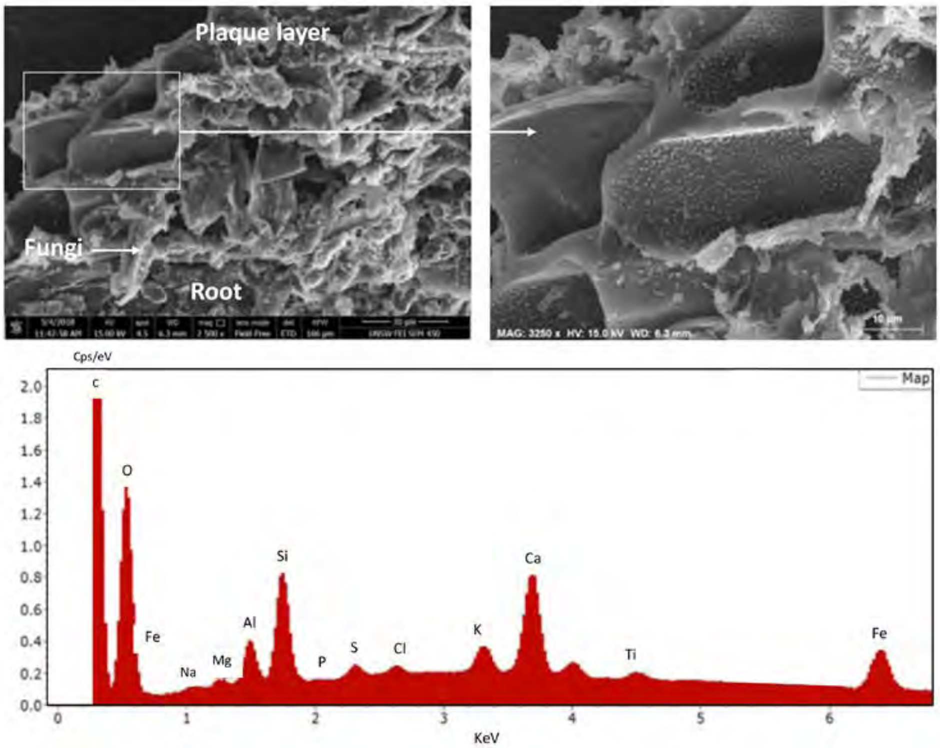


Figure 6.4 Top Left: A piece of wheat straw biochar embedded in the soil layer that forms on rice roots. **Top Right:** A magnified image of the embedded biochar particle. Fine mineral-nanoparticles coat the biochar pore surfaces. **Bottom:** X-ray analysis of the magnified area showing high contents of some nutrients on the surface of the biochar. The nutrients can be available for uptake by the plant

- Biochar can increase the abundance of growth-promoting microbes both outside and inside the root, which assist in making nutrients more available for the plant (Figure 6.5)[4].
- The biochar on the root surface can increase the voltage difference between the root surface and inside the root cell. This can reduce the amount of energy that a plant needs to expend to take up nutrients, promoting more rapid nutrient uptake (see Figure 6.5 and Chapter 4: Electrochemical and electrical properties).

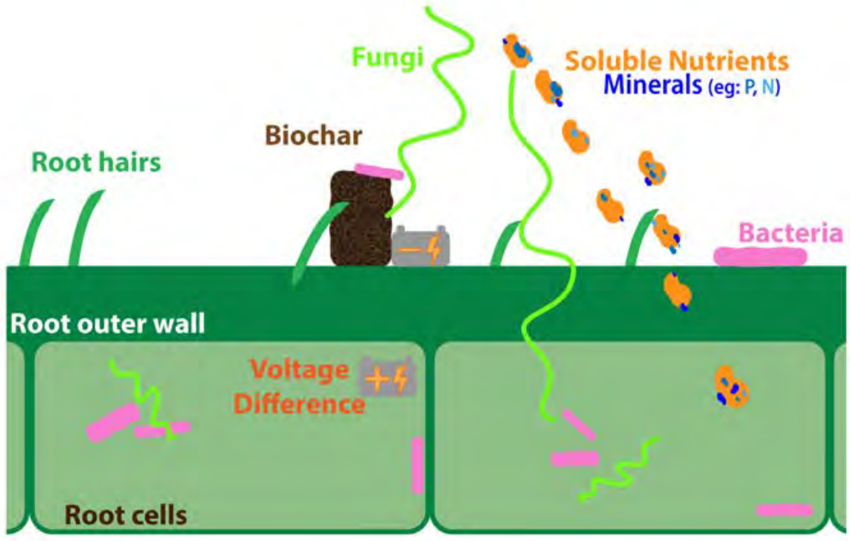


Figure 6.5 Schematic of bacterial and fungal interactions on the surface of a root near a biochar particle

- Biochar around the roots can capture heavy metals and other toxins and prevent their uptake by the plant.

Important Point

Too much biochar in the rhizosphere can reduce above- and below-ground biomass and crop yield and reduce the ability of the plant to resist disease and environmental stresses.

Biochar boosts leaves and photosynthesis

A global meta-analysis published in 2020 found that biochar amendment increased photosynthetic rate, transpiration rate, and water use efficiency by around 27% each. Stomatal conductance and chlorophyll concentration improved by 20% and 16%, respectively. Plant total biomass improved 25% (shoot biomass 22%, root biomass 34%).[5]

Biochar amendment largely boosted photosynthesis and biomass on C3 plants (adapted to cool season establishment, e.g. wheat), but had limited effect on C4 plants (adapted to warmer climates e.g. maize) (see Figure 6.6). The study authors recommend that biochar with higher pH (liming) and lower carbon content would be a good option for C3 plant-dominated systems. The results enable the design of effective strategies for extensive application of biochar for agricultural production management, including for increasing biomass for carbon sequestration and global warming mitigation.

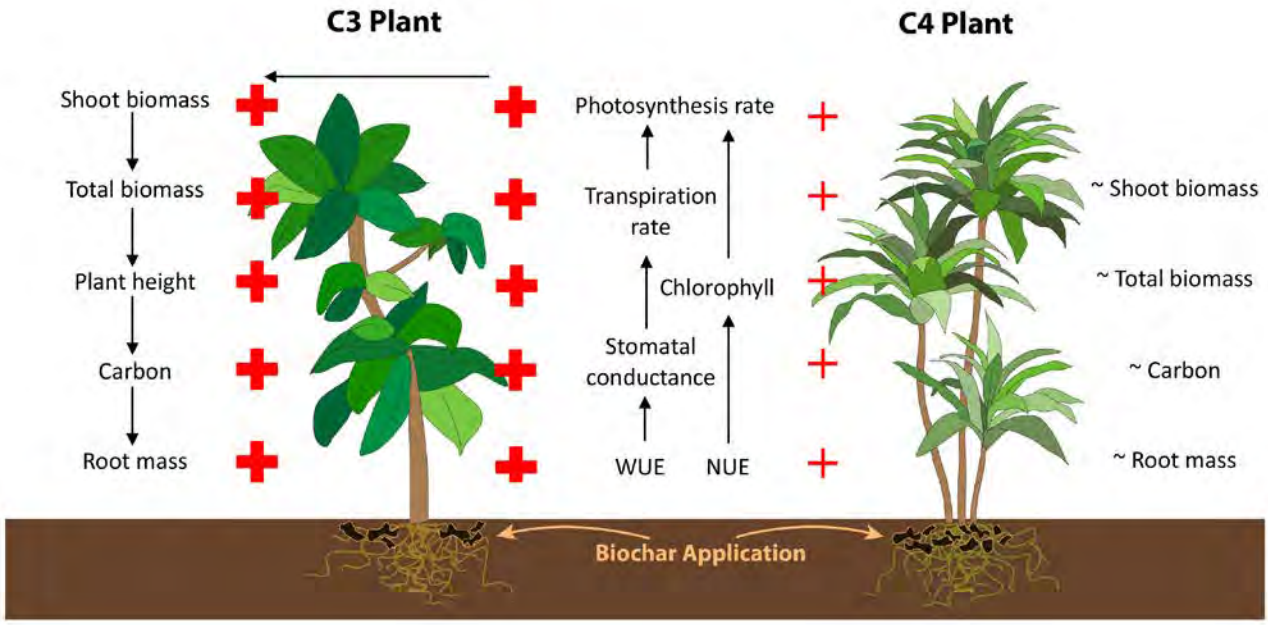


Figure 6.6 Effects of biochar amendment on plant photosynthesis rate, and thence on biomass and other properties, varied with C3 and C4 plants. Biochar improved water use efficiency (WUE) and nitrogen use efficiency (NUE), which enhanced plant function along a chain of causation indicated by the black arrows (centre). The boldness of the red plusses indicates that the positive responses were greater for C3 plants than for C4. This in turn led to increases in biomass and carbon supply to the roots in C3 plants (causation arrows and plusses down left side) but did not have significant effects on plant biomass in C4 plants (right side, ~ represents non-significant effect). (Modified from He et al.[5])

Biochar can improve disease resistance

Many studies have demonstrated that biochar can improve plant resistance to attack by insects and pathogenic bacteria and fungi. The ability to protect a plant from attack is a function of the properties of the biochar, the amount of biochar that has been applied, the changes in the biochar's properties as it ages, and the type of pathogen. The increase in the plant's resistance to disease could be due to some or all of the following:

- More favourable soil Eh and pH, which increases nutrient supply and availability, reduces pathogenic microorganisms, and increases beneficial microorganisms.
- Organic molecules released by biochar that have antimicrobial properties.
- Dissolution of silicon from biochars into the root-zone and uptake by the plant thereby making leaves and stalks tougher and more resistant.
- Biochar's ability to adsorb specific compounds from pathogens, decreasing disease severity.
- Biochar acting as an antioxidant and reducing reactive oxygen species, thereby reducing stress from pathogens.
- Stored electrons in biochar, which help destroy pathogens that inhabit the biochar.

BIOCHAR AND WOOD VINEGAR CAN IMPROVE FOOD QUALITY

In addition to bolstering food yield and disease resistance, biochar and wood vinegar can positively influence the nutritional profile, taste, and shelf-life of crops. No comprehensive review or meta-analysis of the effects of biochar and wood vinegar on food quality has been published, to our knowledge. Nonetheless, individual studies have explored the impacts of these interventions on various quality parameters of vegetables, fruit trees, and grains.

Effects of biochar on food

The following is a summary of some of the research on the effect of solid biochar amendment on food quality:

- Maize and wheat plants grown under optimum biochar-enhanced integrated-nutrient management not only increased yield, but also produced food with higher protein, carbohydrate, and nutrition. Better results were obtained with 75 or 100% of the recommended NPK along with 5 t/ha of cotton stalk biochar, relative to treatments with 25% or 50% NPK+Biochar, or 100% NPK with no biochar. Relative to the control (no biochar, no NPK), the uptake of macronutrient (N, P, K, Ca, Mg, and Zn) increased. The increase ranged from 67% for N to 26% for Zn in both maize and wheat, and was 71% for P and K in wheat.[6]
- Carbohydrate, protein content, and nutrients (N, P, K, Ca, Mg, Zn) of maize increased when biochar from cotton-stick biomass, produced at 400°C, was applied to it.[6]
- Rice straw biochar produced by fast pyrolysis at 500°C–550°C applied at 10 t/ha before sowing sunflower seeds, followed at 30 and 55 days by silicon amendment, increased the quality and yield of sunflower oil grown under water deficit stress.[7]
- Several papers report biochars increasing total sugars, soluble solids, titratable acidity, sugar-acid ratios, vitamin C, and/or lycopene in tomato fruit.[8]
- Biochar-based fertiliser applied at a rate near 2500 kg/ha, increased fertiliser efficiency, as well as the yield, vitamin C content, soluble sugar, output value, and net income of eggplant fruit, and tomato.[9,10]
- Wood biochar produced at 450°C and applied at 2% or 3% increased shoot and root biomass, and enhanced root morphology and soil enzyme activity thereby increasing chlorophyll content, total sugar and flavonoids in sweet basil relative to control plants.[11]
- When cassava straw biochar was applied with fertiliser to rice, the protein content, amylose content, and brown rice yield were higher by 16%, 28%, and 4.6%, respectively, in both early and late season harvests.[12]
- A study on the effect of biochar on lettuce growth showed the total chlorophyll and carotenoid contents improved with increasing levels of biochar (Figure 6.7), with a 3% biochar treatment increasing them by 43% and 51% respectively compared with the control.[13] The higher 3% application also produced the largest improvements in leaf and root growth factors and soil enzymes, while 2% and 3% biochar amendment produced equal germination rates.

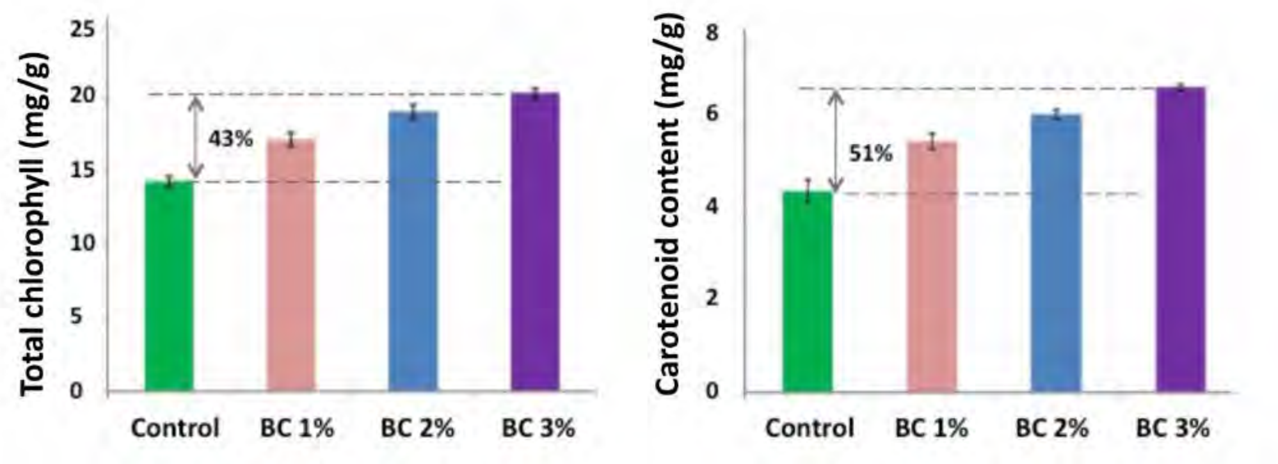


Figure 6.7 Effects of biochar (BC) amendments (1%, 2%, 3%) on the total chlorophyll content (left) and carotenoid contents (right) of lettuce. (Adapted from Jabborova et al.[13])

- Biochar can reduce the levels of heavy metals in plants, but the extent of reduction is a function of the heavy metal, the plant, and biochar type. A recent paper reported that most biochars reduced Pb, Cd, and Zn in plants by 10–40%.[14] Some biochars increased uptake of Cu by plants slightly, others reduced Cu uptake. Sewage sludge biochar increased heavy metal uptake, but this depended on soil properties and the specific plants that were grown. Manure biochars resulted in the lowest levels of Pb, Cd, and Cu in plants. The adsorption of heavy metals by biochars is outlined in Chapter 4.

Effects of biochar foliar sprays

A study reported that liquid from both wheat and maize straw biochar applied at dilutions of 50 or 100 times significantly increased the yield, vitamin C content, and soluble protein content of cabbage while decreasing the nitrate content. The spray was applied ten times during the growing season.[15]

Low-dose foliar application of aqueous extracts from organomineral-activated biochars produced from pine wood/clay/sand and wheat straw/bird-manure increased the growth of lettuce.[16] The carbon-coated mineral and biochar nanoparticles diffused through the stomata (Figure 6.8) and increased the contents of photosynthetic pigments (carotenoids and anthocyanins). Photosynthetic pigments can increase plant growth, and they also act as antioxidants, strengthening plant resilience against stressors such as salinity, drought, and heavy metals. These benefits were achieved by foliar application at much lower biochar applications rates than typically reported for macro-biochar application to soil.

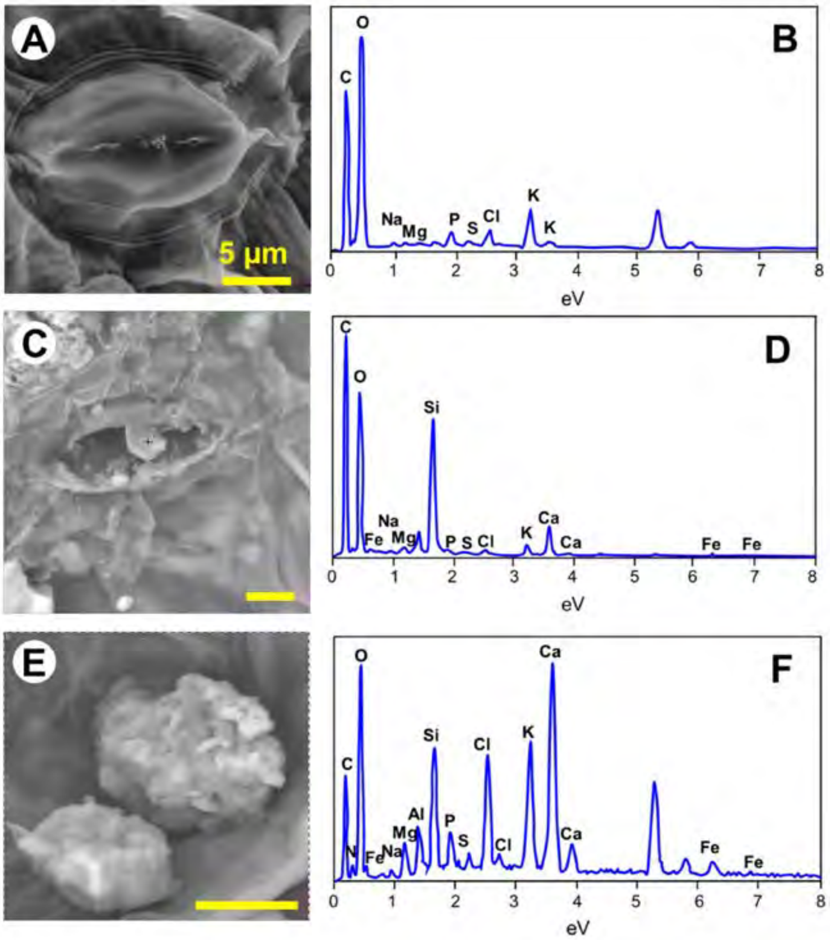


Figure 6.8 Scanning electron microscopy images and elemental analysis of biochar and carbon-coated minerals inside and around stomata. **Top:** Stomata. **Middle:** Biochar-treated leaf with stomata and organo-mineral complexes. **Bottom:** High-resolution image of organo-minerals inside the stomata[16]

Effects of wood vinegar on plants

Refined wood vinegar (WV) produced from the condensation of volatiles at early stages of biomass pyrolysis (180°C to 250°C) is rich in biologically active substances like polyphenols, alcohols, acids, and esters. In Asia, most WV comes from the pyrolysis of bamboo, certain hardwoods, or crop straw. Wood vinegar applied as a foliar spray at suitable dilutions and application rates improved both crop yield and quality, or increased disease resistance, or both. Wood vinegar applied to the soil increased dissolved organic C, nutrient availability, and microbial activity; while foliar spray increased leaf growth, number of pods, flower development, and fruit production.[17]

Wood vinegar produced from sweet chestnuts applied to lettuce seedlings as a foliar application at 0.25% and 0.5% was found to enhance chlorophyll (50%), biomass (49%), starch (double), sugar content, caffeic acid, and quercetin contents and antioxidant power.[18,19] The same wood vinegar applied to chickpea seeds, lead to an increase in diameter (11%), weight (33%), starch content (46%), total soluble protein (13%), total polyphenol (16%), and antioxidant potential (28%) of the chick peas. Most of the essential amino acids and mineral elements also increased.[20]

In field experiments exploring the effect of bamboo biochar and wood vinegar on yield and quality of sweet potatoes, it was found that the biochar application increased the number of tubercles, while the wood vinegar increased weight yield. Biochar and wood vinegar combined enhanced the sugar content, appearance, and marketability of sweet potatoes.[21]

BIOCHAR EFFECTS ON SOILS

The effects of biochar on physical and chemical properties of soils are very dependent on feedstocks, pyrolysis temperatures, and application rates.

Biochar modifies soil pH and Eh

Adding biochar can change both the pH and Eh of the soil. If soils are lacking carbon, and are acidic and oxidised, then adding biochar can increase the pH and decrease the Eh into a favourable zone that will allow the release of specific nutrients and the growth of beneficial microorganisms (Figure 6.9). If too much biochar is added, then the Eh and pH of the soil can overshoot this sweet spot and cause unwanted negative effects.[22,23]

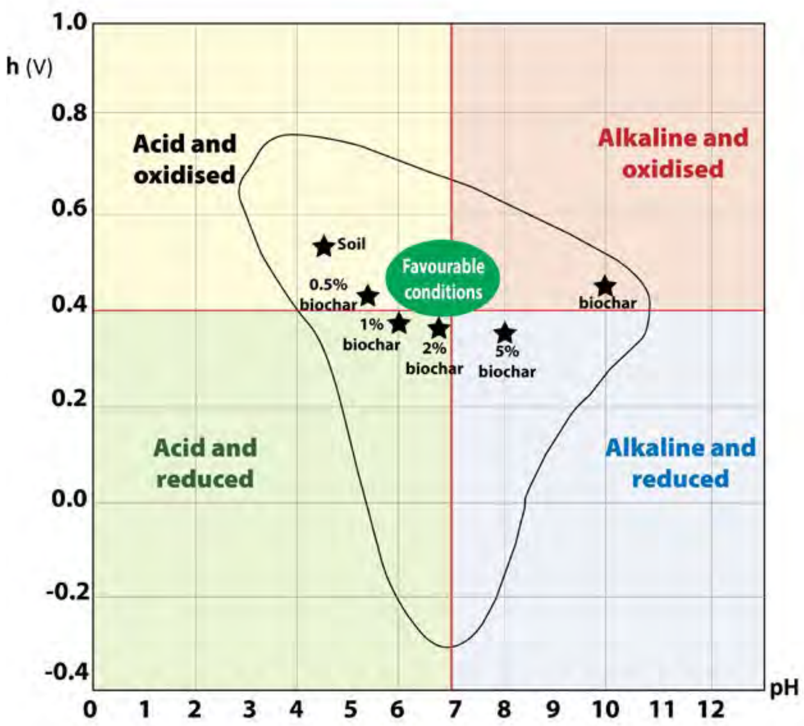


Figure 6.9 The full range of Eh and pH in soils and the relationship with extreme soil conditions, showing also the normal range in soils and the limited favourable conditions for plant growth. Biochar can reduce Eh and increase pH, bringing soil to more favourable conditions for plant growth. Too much biochar can result in the pH increasing above the favourable range. (Modified from Husson et al.[22] and Joseph et al.[23])

Biochar improves soil hydrological properties

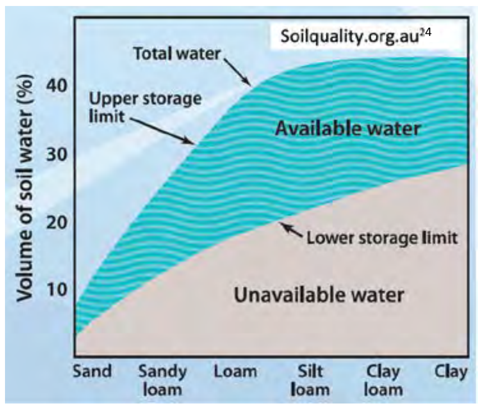
Soil-water terminology:

Water-holding capacity or Field capacity (FC) is the maximum amount of water the soil can hold, measured after excess water has drained.

Wilting Point (WP) is the water left after the plant can no longer extract water from the soil.

Available Water Capacity (AWC) = FC – WP

Sandy soils can hold least water since they drain well. Clay, with its fine pores, can hold most water.



A meta-analysis by Edeh et al. (2020) assessed the effects of biochar on various soil hydraulic properties for the first time.[25] The impacts on hydraulic properties depended strongly on the application rate, and on the soil type and texture.

Across all types of soils, feedstocks, pyrolysis conditions, and application rates, biochar improved all hydraulic properties, as shown in Figure 6.10. At application rates >30 t/ha, improvements in available water-holding capacity (AWC), field capacity (FC), permanent wilting point (PWP), and saturated conductivity (K_{sat}) were all substantially greater than those shown in Figure 6.10). The improvements were greater still when the biochar and its application rate were optimised for the soil. For example, while bulk density was not much reduced (–0.8%) when averaged over all conditions, biochar application at the optimal rate substantially decreased the bulk density of clay soils. The main parameters influencing soil-water dynamics were physical characteristics of biochar, including particle size, specific surface area, and porosity (Figure 6.10), underscoring the importance of the soil and biochar interparticle pores as well as intraparticle pores within the biochar.

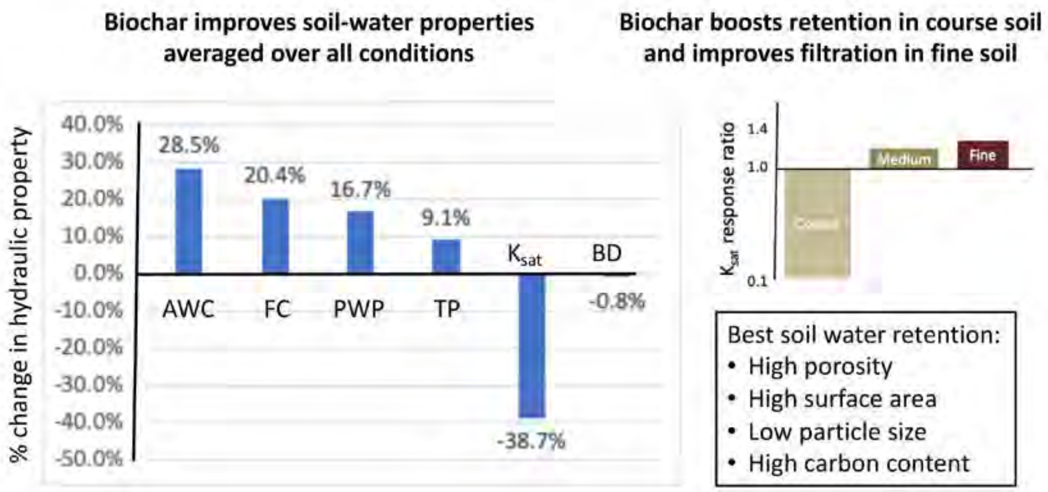


Figure 6.10 Effects of biochar on hydraulic properties.[24] AWC = water-holding capacity, FC = field capacity, PWP = permanent witing point, TP = total porosity, K_{sat} = saturated conductivity, BD = bulk density. (Adapted from Edeh at al.[25])

The effects of biochar on soil-water properties were most pronounced in coarse-textured sandy soils, in which biochar increased soil water retention and decreased saturated hydraulic conductivity. For these coarse, sandy soils, biochar with small particle sizes (<2 mm), high specific surface area, and applied at rates exceeding 30 t/ha up to 70 t/ha was found to be most effective. By contrast, biochar had considerably less impact on most water properties in clayey soils (excepting on soil bulk density and porosity). It did, however, increase hydraulic conductivity and decrease bulk density, which are beneficial for decreasing runoff in clayey soils. The application rates needed for improvement of water properties were lower (<30 t/ha) in coarse sandy soils than in fine-textured clayey soils. As illustrated in Figure 6.11, a large addition of biochar can fill the pores of coarse-textured soils, trapping much more water. Fine-textured soils with much smaller pores, are less responsive to biochar amendment and require less biochar to get the maximum response.

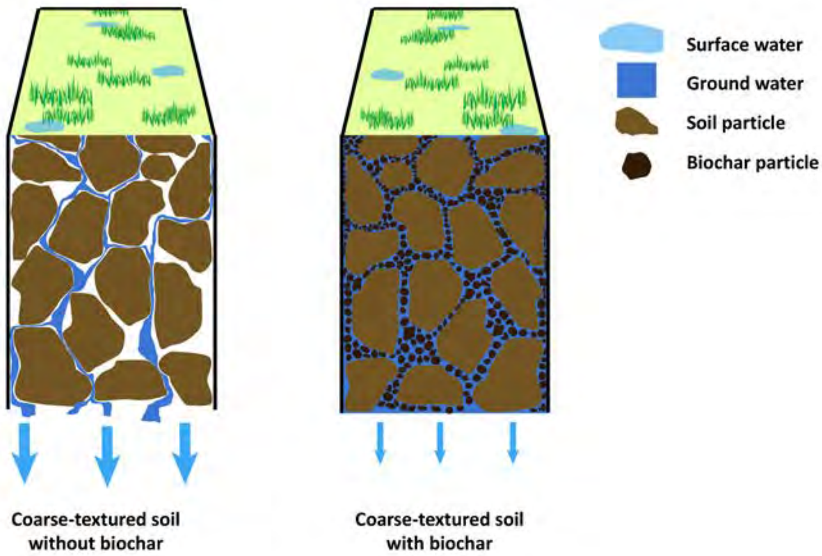


Figure 6.11 Schematic illustration of the effect of biochar on hydraulic conductivity of coarse-textured soil. A large addition of fine biochar can fill the pores of coarse-textured soils, trapping much more water. (Adapted from Edeh et a l.[25])

The authors concluded that the agronomic benefits would be relatively limited at the low application rates of 0.5–2 tons per hectare typically used in arable farming, even if practised annually. However, with concentrated root-zone application, and/or intensive horticulture, higher localised application rates could be achieved. This could provide higher water availability to the roots, particularly during the vulnerable early stages of plant growth when drought and other stresses pose greatest risk.

Wu et al. (2022) conducted a more recent meta-analysis encompassing 681 observations, which showed that biochar application increased water-holding capacity (AWC) by 27% and water use efficiency (WUE) by 4.7%, on average.[26] It also led to a 36% increase in soil organic carbon (SOC). Causal analysis highlighted that SOC was a crucial driver for AWC improvement, both directly, and also indirectly by affecting permanent wilting point (–1.0%) and mean weighted aggregate diameter (+11%). The grand mean soil porosity (SP) and water content (WC) increased by 7% and 11% respectively under biochar amendment, thus improving the WUE. The greatest benefits in both SP and WC were obtained for application rates of 30–40 t/ha, using crop residue feedstock, in soils with (10–20%) clay content (Figure 6.12).

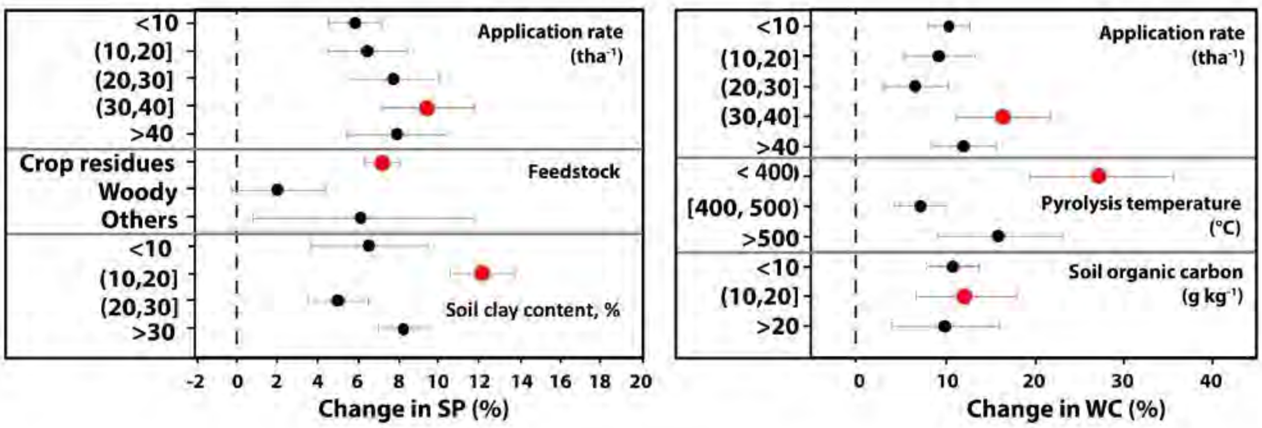


Figure 6.12 Changes in soil porosity (SP) (left), and soil water content (WC) (right), after biochar application. Changes are characterised by the values of the following attributes, listed on the Y axis: application rate (t/ha), feedstock, soil clay content (%), pyrolysis temperature, and SOC content. The error bars represent a 95% confidence interval. The greatest effects are shown in red. (Modified from Wu et al.[26])

Biochar develops soil aggregate stability

A meta-analysis in 2021 covering 641 paired comparisons from 119 published articles found that biochar application significantly improved soil aggregation by 16.4 ± 2.5%, regardless of biochar, experimental, and soil conditions.[27] The soil-aggregation response to biochar amendment, relative to soil attributes and field conditions, is shown in Figure 6.13.

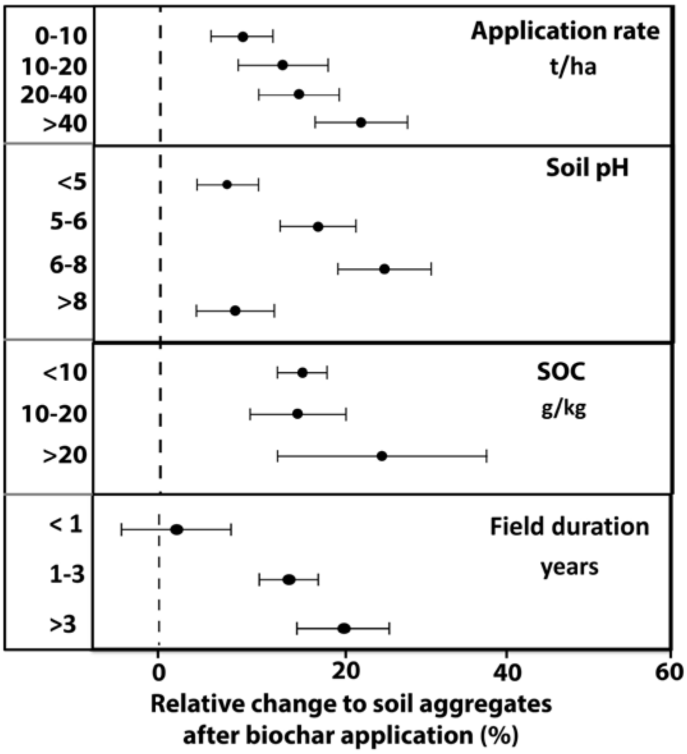


Figure 6.13 Changes in soil aggregation in response to biochar application rate, soil pH, soil organic carbon percentage (SOC), and field duration. (Modified from Islam et al.[27])

The response:

- increased linearly with biochar application rate to beyond 40 t/ha;
- was maximal for soil pH in the range of 6 to 8;
- improved more in loam-textured soils (+20%) than in sandy soils (+13%);
- strengthened over time, from insignificant effect in the short term (<1 year), to over 20% at >3 years.

There were also indications, though non-significant, that greater benefits to aggregate stability came from biochars made from woods (relative to straws, manures, grain residues, and others), at higher pyrolysis temperatures (>600°C), with biochar pH less than 8. Wood biochars, with porous structures, high CEC, surface areas, and levels of Fe^{3+}, can adsorb minerals and organic matter, which serve as binding sites for organising and aggregating soil structure. Also, wood biochar has a relatively higher C:N ratio, which is likely to provide favourable conditions for growth of fungi, which in turn promote formation of macro aggregates.

Overall, the meta-analysis demonstrated that biochar amendment to soils improved soil aggregation through application of suitable biochars chosen for the soil properties and field conditions.

Biochar can boost nitrogen in soils

A 2021 meta-analysis[28] examined the potentialities of biochar to affect (positively or negatively) the complex nitrogen cycle in soils. Depending on its properties and application rates, biochar may play roles in either enhancing or reducing the availability of N and uptake efficiency for plants. Biochars from biomass with low N content (e.g. wood) applied at application rates above approximately 5 t/ha without fertilisers can compete for the nitrogen in the soil and reduce N availability for plants. Other biochars especially those made at low temperatures from manures (e.g. poultry litter) applied at high application rates can supply nitrogen and enhance plant growth (see Figure 4.7 in Chapter 4). High rate (30 t/ha) pine woodchip biochar added with fertiliser increased soil inorganic N (NO_3^- N) at 12 and 24 months following the initial application of biochar. This indicates that the pine wood biochar adsorbed the fertiliser and released it over a period of two years.[29]

Additionally, some biochars can indirectly enable higher N availability by reducing the N losses and stimulating supply. Biochar can reduce losses due to volatilisation and emissions, and from runoff and leaching. It can increase N supply from symbiotic and non-symbiotic biological nitrogen fixation, and by N mineralisation and retention. Aged biochar (that has a fine surface-layer of organic matter) can adsorb the N from fertilisers, reducing loss through leaching by 26% on average. Present research indicates that biochar produced above 400°C reduces nitrous oxide emissions from dryland soil, especially at high application rates (>10 t/ha). Ammonia volatilisation increases at high application rates of biochar (>40 t/ha) and with biochar pH >9. However, pre-treating biomass before pyrolysis, or post-treating the biochar to reduce the C:N ratio, can result in greater N availability and use efficiency when applying biochar at high application rates.[30] The enhancement of biochars to meet N constraints will be discussed further in Chapter 7.

Some biochars enhance the abundance of nitrogen-fixing bacteria as well as other bacteria and fungi that can make N available to plants, either through increasing root nodules (symbiotic nitrogen fixing) or through increasing the abundance of non-nodularising microorganisms such as the non-symbiotic Azospirillium. Such processes can increase the nitrogen fixation by up to 60%, and by an average of 35% across all biochars.[28]

Nitrogen use efficiency (NUE) is defined as the ratio of N uptake by plants to the total applied N fertiliser, and it is dependent not only upon the N supply potential of soil but also on the subsequent transport, mobilisation, and storage of N by plants.[28] Figure 6.14 shows the dependence of NUE on application rate and pyrolysis temperature of biochar. The NUE changes can range from +40% to –35%, depending on the feedstock and the amount of biochar that is added, with an average null effect across all biochar trials, indicating the importance of strategically selecting or enhancing the biochar to help it meet N constraints.

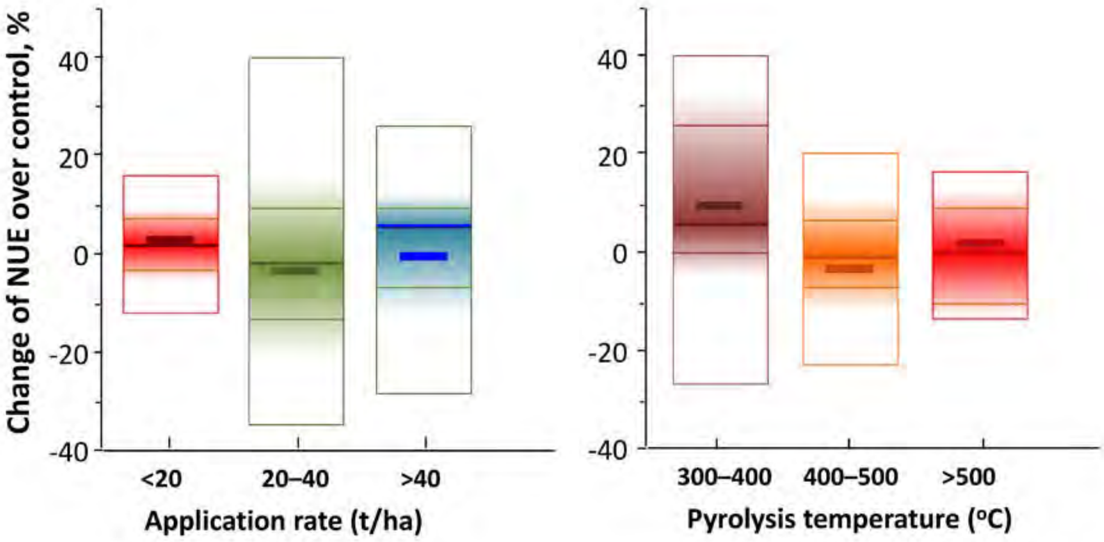


Figure 6.14 The range of nitrogen use efficiency (NUE) found in 22 studies, expressed as percentages of that of the control, for three application rate ranges and three pyrolysis temperature ranges. For each category the outer box covers the entire range of reported changes, while the inner shaded box captures the inner 50% of the values. The solid line represents the median and the short, thick bar is the overall average. (Modified from Ahmad et al.[28])

Key Point

- Large applications of biochar can increase the C:N ratio, reducing the availability of nitrogen and increasing N loss through volatilisation of ammonia.
- Add an additional source of N to bring the C:N ratio to around 30:1 and limit application rates to below 10 t/ha.

Biochar increases availability of phosphorus in soils

A meta-analysis found that, averaged across all biochar feedstocks and conditions, the addition of biochar increased the P availability in agricultural soil by a factor of 3.4 to 5.9.[31] Both the biochar and the control had no phosphorus fertiliser added. As can be seen in Figure 6.15, bigger effects were found when results were analysed within categories. Manures and wastewater sludges, followed by biowaste and crop residues, gave the greatest increases in P availability. Wood biochars (without combining with fertiliser) were relatively ineffective. The highest increases (up to 10x) came at application rates above 40 t/ha. Biochars produced at temperatures of less than 450°C and applied to acid soils (pH >7.5) were most effective. Biochars made at temperatures above 450°C or applied in soils with pH >6.5 were less effective. However, the limitations of straight biochar made from wood, or at higher temperatures, or applied in alkaline soils can be overcome by designing the biochar by combining with nutrients or adjusting its pH (e.g. by fermenting it—see Chapter 8) to overcome these constraints).

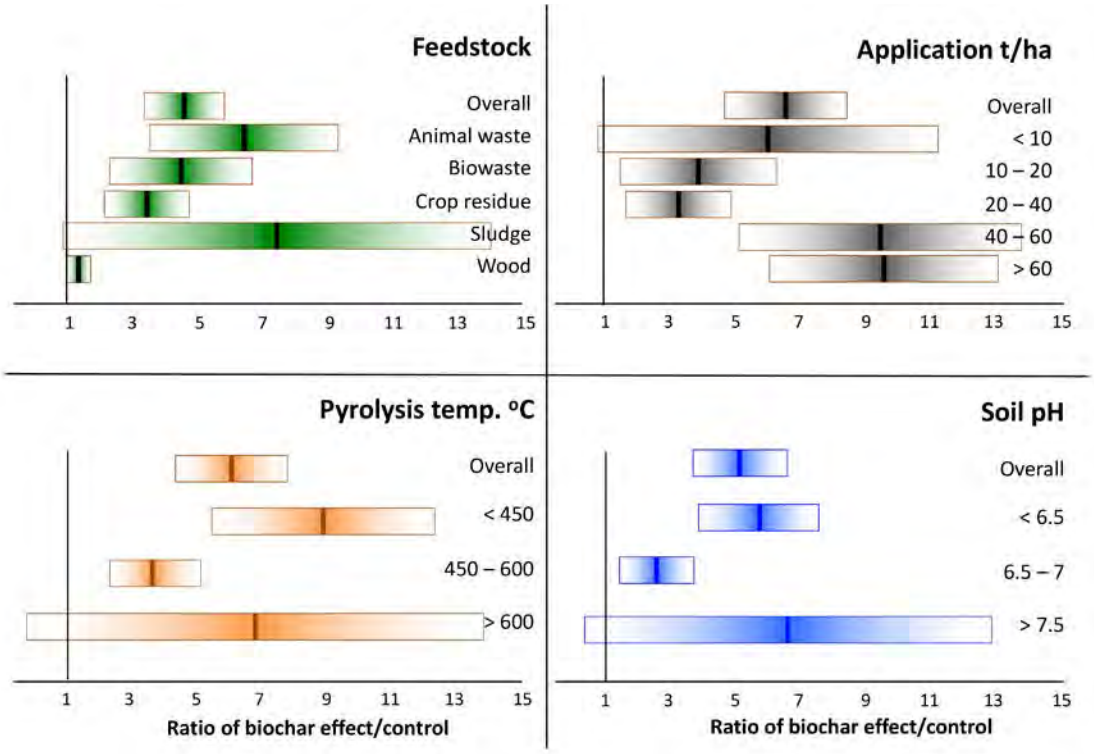


Figure 6.15 The effect of biochar amendments on phosphorus availability in agricultural soils as influenced by feedstocks, application rates, pyrolysis temperatures, and soil pH. The average for each category is indicated by a dark line in a shaded box that represents the 95% confidence range. (Modified from Glaser et al.[31])

In low P soils, arbuscular mycorrhizal fungi (AMF) invade the pores of biochar, especially biochars with high P content on the pore surface, and this process can increase P uptake by plants. In the presence of high mineral-ash biochars, root colonisation by AMF can increase by up to 75% compared with the increase observed 20% in the presence of mineral fertiliser. Other studies have shown that very small applications of biochar (less than 200 kg/ha) along with phosphorus-rich fertilisers can also increase phosphorus availability.

Biochar reduces bioavailability of heavy metals in soils

Biochar in the soil can bind with heavy metals through various mechanisms, as explained in Chapter 4. As biochar ages (discussed in Chapter 5), its initial ability to bind heavy metals improves because of the formation of active organo-mineral clusters on its surface.[32] These clusters are very porous and redox active and contain many carbon and oxygen functional groups that have a high affinity to bind heavy metals, resulting in increased ability to bind heavy metals. As the biochar particles continue to age in the soil they are encased in soil aggregates, which further immobilises the heavy metals, but also considerably reduces the effectiveness of the biochar in binding heavy metals. Consequently, multiple applications of biochar may be necessary for extended heavy metal remediation. Different heavy metals may require different biochars to achieve the most effective immobilisation.

Results from field and pot experiments indicate that biochar amendments produced at both low (<400°C) and high (500°C–600°C) temperatures, when applied to acidic soils, may exhibit greater efficacy in immobilising certain heavy metals over an extended duration when compared with biochar produced within the temperature range of 400°C to 500°C. Engineered biochars, particularly lower temperature biochars enriched with iron oxides and other minerals, can significantly enhance the immobilisation of heavy metals. Biochars enhanced with Fe_2O_3 were most effective when produced at 350°C. Applied at a dosage of 1.0%, this biochar immobilised Cu, Cd, and Pb in contaminated soils by up to 62%, 46%, and 43%, respectively. Precipitation and complexation of the heavy metals converted them into more stable forms. Iron-enhanced biochar also indirectly influenced heavy metal by improving soil pH and CEC, reducing the bioavailability of heavy metals, while significant improving soil health by promoting the abundance and community structure of microorganisms and altering soil fertility.[33]

Biochar captures toxic organics

A recent meta-analysis of the effects of pure biochars versus engineered biochars[34] concluded that:

- Most biochars will adsorb organic pollutants including pesticides, herbicides, phthalates, per- and poly-fluoroalkyl substances (PFAS), and polyaromatic hydrocarbons (PAH).
- The extent and mechanisms of reducing bioavailability of toxic organic pollutants are affected by many internal and external factors. Internal factors of biochar, such as type of raw materials, specific surface area, preparation methods, pyrolysis temperature, pore structure, functional groups, and nutrient composition, will affect its sorption capacities and influence the fixation of pollutants.
- High-temperature biochars can be more effective at reducing bioavailability, while low-temperature biochar can indirectly reduce pollutants accumulation through providing nutrients for microorganisms that can degrade the pollutants.
- Engineered biochars, especially those where metal oxides are coated on the biomass before pyrolysis, usually capture toxic organic pollutants more effective than do untreated biochars.

Biochar proliferates abundance and diversity of soil microorganisms

Biochar can improve the abundance of beneficial microorganisms and can change the bacteria-to-fungal ratio. Biochar has a complex effect on microbial communities, with the changes being a function of the type and amount of biochar added, the properties of the soil, and the crops grown.

Some general observations can be made from Figure 6.16 , which is derived from a meta-analysis of 59 studies:[35]

- Herbaceous feedstocks (green waste, lentil stalks, maize stover, straws, switchgrass) had the biggest impact on increasing bacterial diversity.
- Biochars made from lignocellulosic waste (including rice husks, rice hulls, shells of nuts, coffee husks, corncobs, vineyard pruning, and pine sawdust) had the biggest effect on fungal diversity.
- For bacteria and fungi diversity, biochar application rates below 40 t/ha were more effective, particularly for fungal diversity.
- Biochars made at lower temperature (<500°C) were most effective at promoting microbial diversity (bacterial and fungal).
- Biochar most significantly increased bacterial diversity only in coarse and medium textured soils. Conversely, fungal diversity was significantly increased in fine-textured soils.

- In flooded rice production, or in soils in tropical areas, biochar can increase fungi/bacteria ratios probably because fungi were the dominant decomposers of increased recalcitrant carbon from biochar and rice biomass.

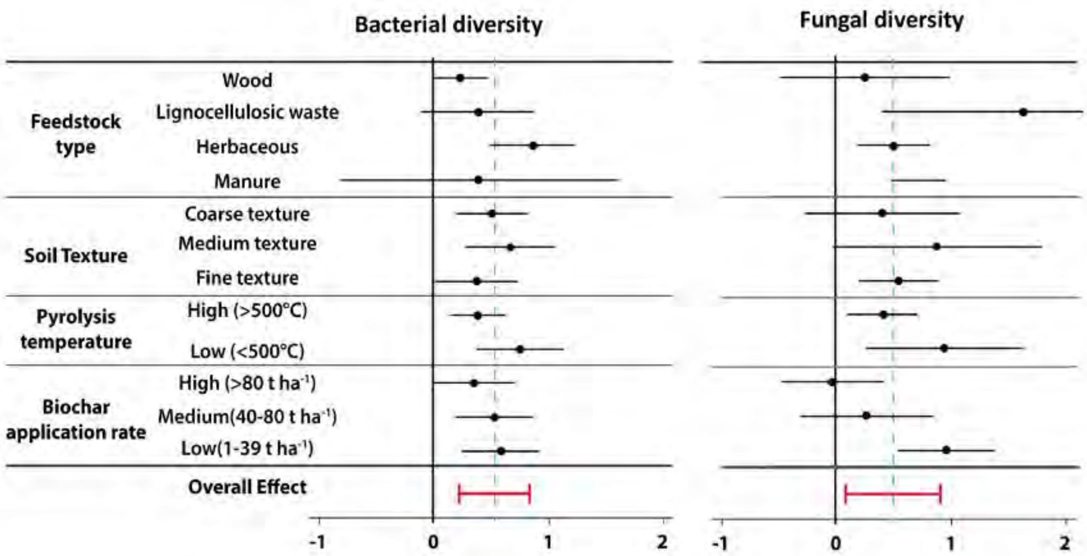


Figure 6.16 Changes in bacterial (left) and fungal (right) diversity due to biochar addition to soil, for different biochar feedstock types, soil textures, pyrolysis temperatures, and application rates. Bars represent 95% confidence intervals. The red bars and dashed lines show the overall grand mean effects. (Modified from Singh et al.[35])

On the whole, the application of biochar increases the diversity and abundance of both fungi and bacteria, with beneficial outcomes owing to the effects of many factors that are summarised in Figure 6.17.[36]

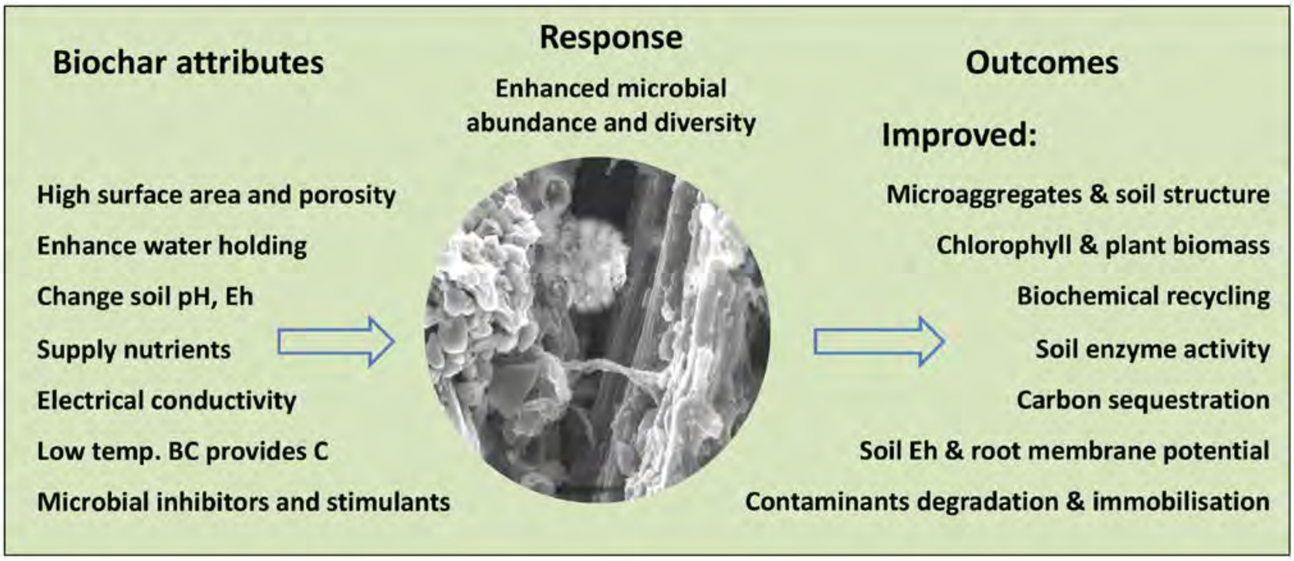


Figure 6.17 Schematic showing the microbial response and outcomes following biochar application. **Centre:** Electron microscope image of fungi and bacteria on surfaces of biochar. BC = Biochar, Eh = redox potential. (Modified from Palansooriya et al.[36])

Biochar increases soil carbon and mitigates climate change

The long-term persistence of biochar C in the soil means that biochar can be used to mitigate climate change. Biochar systems have been reported to show life-cycle climate change impacts equivalent to net emission reduction in the range of 0.4–1.2 tonne CO_2-equivalent per tonne of dry feedstock (due to C storage plus the avoided CO_2 and non-CO_2 emissions from the diversion of biomass and use of pyrogas energy).[37] However, over time biochar can support the soil microbial community in sequestering and protecting additional soil organic carbon in the soil, beyond the carbon in the biochar. The responsible mechanisms which protect the SOC from decay, can raise the natural limit of how much C can be stored in the soil.

The amount of additional non-biochar carbon increase depends on many factors. A long-term field experiment at Wollongbar Primary Industries Institute in NSW was started in 2006 by applying ten t/ha (1% w/w) of Eucalyptus saligna biochar produced at 550°C into the top 100 mm of replicated plots of Rhodic Ferralsol soil under managed pasture. The study found that at the end of eight years, following a single application of 10 t/ha of a hardwood biochar to the Ferralsol soil, increases in SOC (not including the biochar) were observed comparable with the amount of BC itself. There were around 10 t of SOC increase for 10 t of BC added.[38] The increase in SOC was more than the C added by the BC itself, which was only 76% C. After eight years from the first application, a second application of BC kicked off another round of SOC increase, demonstrating that multiple additions of BC can continue to increase the limit to which soil can grow SOC.

Biochar can also build soil inorganic carbon, as calcium and magnesium carbonates, in high-pH calcareous soils, creating an additional 0.5–0.8 tonnes of soil inorganic carbon over ten years for the application of one tonne of biochar.[39]

The possible effects of biochar on soil carbon compared with those of compost or leaf litter are illustrated in Figure 6.18.[40] Here, the biomass C is 57% decomposed in 1 year and 90% decomposed in 6 years, whereas the BC loses only 10% of its C. After eight additions, biomass C has accumulated to about 10% of all its C additions, whereas BC carbon has accumulated to 90% of all its additions. Moreover, the BC has stimulated microbial, soil, and plant processes that accumulate more C from the atmosphere (similar to those depicted in Figure 6.17). The actual total soil C increase from biochar or compost or leaf litter can vary considerably, depending on feedstock properties, pyrolysis process conditions, and soil and environmental factors.

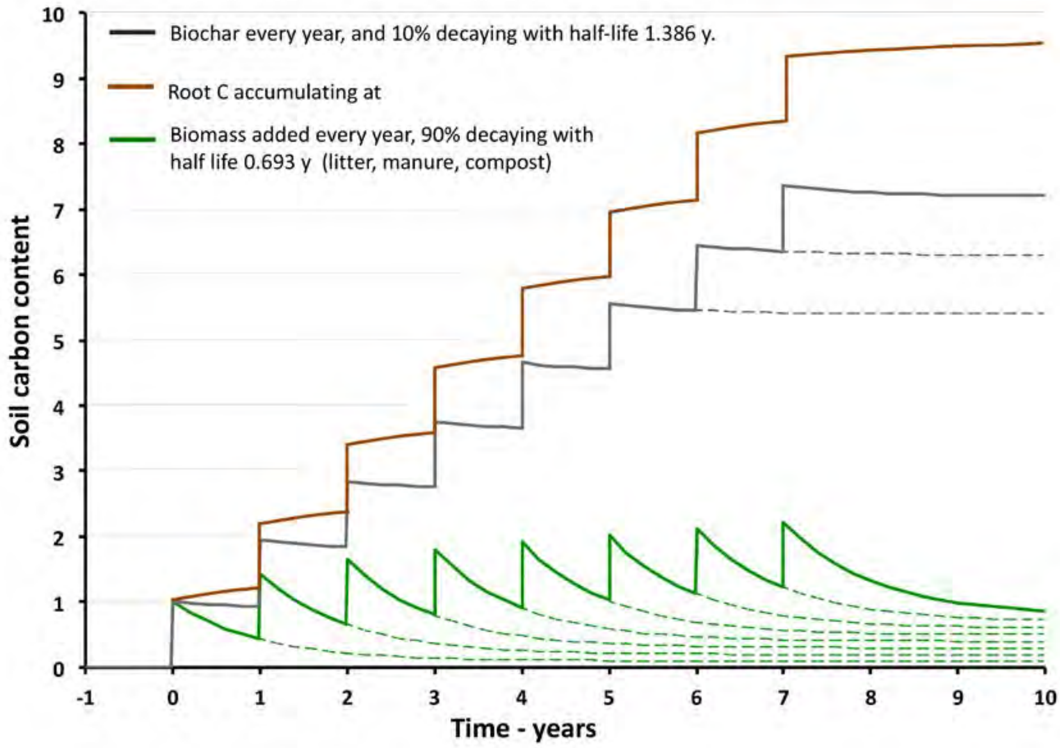


Figure 6.18 Schematic of changes in soil carbon as a function of time, when a unit of biochar or biomass carbon is added every year for eight years. Each increment of biomass or biochar accumulates on the residual of the previous amendment. In this model, all the biomass C (such as in litter, manure, or compost) decays with a half-life of near 0.7 y, whereas only 10% of the biochar C decays with a half-life of 1.4 y. In addition, the biochar has stimulated microbial, soil, and plant processes that accumulate more C from the atmosphere (illustrated here at about ¼ of the biochar increment in C per year). (Adapted from Joseph et al.[40])

Key Points

- Applying biochar every crop cycle can result in a much quicker build-up of soil than a one-off application.
- *Terra preta soils* can have up to 15% total carbon in the top 500 mm of soil (equating to 750 tonnes/ha) and high carbon contents have been measured to 2 m depths.

Biochar can reduce release of nitrous oxide and methane from soils

A number of meta analyses have been published on the effects of biochar on greenhouse gas (ghg) emissions using different biochars. A meta-analysis published in 2022 reviewing the effect of biochar on ghg emissions from soils in three different environments (upland soils, rice paddies, and wetland) found that cross all soil types, biochar supressed N_2O emissions by 31% and methane by 7% (relative to the control of no biochar).[41]

The effect of biochar varied greatly with the soil environment (Table 6.1): N_2O was suppressed the most in upland soils at –62%, while methane was suppressed most on compost. CO_2 was supressed the most in rice paddies and wetlands, but in upland soils, biochar triggered the release of CO_2 in the first 3 to 6 months of application. The greenhouse gas potential of N_20 is about 310x the potential of CO_2, while that of methane is 85x on a 20 year time scale, so biochar's impact on reducing them is important.

Soil Environment	CO_2	CH_4	N_2O
Upland soils	+9%	–3%	–62%
Rice paddy and wetlands	–10%	–6%	–20%
Composting sites	–2%	–15%	–10%

Table 6.1 Comparison of the suppression effects of biochar in different environmental systems. (From Lyu et al.[40])

Soil pH is an important parameter to control soil CH_4 emission rates because the biochemical activities of most methanogens are very sensitive to changes in soil pH. In wetlands and rice paddy biochar from straw, with its higher pH, mineral composition, high Eh and higher porosity, suppressed CH_4 emissions by 16% while biochar from wood significantly increased CH_4 emissions by 34%. Poultry manure supressed methane emissions in composting by over 20%. Straw and herbaceous biochar were most effective for supressing N_2O emissions. Generally application rates at < 10 t/ha of biochars made with pyrolysis temperatures over 500°C were found more effective.

Recent trials with engineered biochars are showing significant reductions in emissions of both CH_4 and N_2O, especially when engineered biochars are applied as biochar–mineral compound fertilisers. This will be discussed in the next chapter.

FURTHER INFORMATION

For a more detailed summary of the effects of biochars on soils and crop productivity, the reader can download a paper **"**How biochar works, and when it doesn't"[24] onlinelibrary.wiley.com/doi/pdf/10.1111/gcbb.12885

Other informative papers include:
Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls (from which the data in Figure 10.1 to 10.3 was drawn).[1]

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Chapter 7

Choosing and enhancing biochars to meet specific soil constraints

Key Points

- It is important to list your constraints and understand how biochars can meet them, so that suitable biochars can be chosen.
- The ability of biochar to meet soil constraints and increase the efficiency of nutrient uptake can be enhanced by any of the following, or a combination of them:
  - mixing different feedstock and pyrolysing over a range of temperatures,
  - pre-treating the biomass with minerals (including those rich in P and K),
  - post-treating with chemicals, minerals, or organic matter rich in nutrients (especially N).
- Minerals added to biomass are carbon-coated during pyrolysis. This carbon coating provides food for microbes that will make the minerals plant-available and increase the cation and anion exchange capacities (CEC and AEC).
- Post-treating the hot biochar as it comes from the kiln allows nutrients to diffuse more effectively into the pores of the biochar. Nutrients in the larger pores will be released quickly, while those in the small pores will be released slowly.
- The cheapest and simplest methods to enhance biochar (and in some cases to apply it) are to:
  - feed biochar to animals and increase the population of dung beetles that will bury the resultant manure that contains biochar,
  - add the biochar to biomass then compost the mix aerobically, anaerobically, or both,
  - add the biochar to nutrient-rich water (e.g. ponds or pits that contain manure on dairy farms).
- For certain applications (e.g. applying to pasture or under trees), a liquid biochar fertiliser that is produced from pre-treated biomass followed by post-treatment with nutrients and wood vinegar can result in a greater increase in plant yield than that from applying a solid biochar fertiliser.
- Filtering such a liquid biochar fertiliser and diluting it so that the biochar to water ratio is approximately 1 to 100, then applying the liquid as a foliar spray at 10 kg/ha can cost effectively increase crop yields.
- Repeating applications each season of nutrient-enhanced biochars to the rhizosphere at low application rates may be optimal for improving the economic feasibility of biochar amendments.

INTRODUCTION

To meet soil constraints, strategically choose an untreated biochar with properties that target the constraints. Alternatively, enhance biochar to make it more effective in meeting a given constraint, or a greater variety of constraints. In this chapter we introduce common constraints and provide some general guidelines to help you to choose suitable types of biochar amendments. This is followed by details of which biochars might meet specific constraints, and how the biochars can be modified or incorporated with other fertilisers or amendments to meet a given constraint at lower application rates, ensuring a return on your investment.

Methods for enhancing biochar include treating biomass before pyrolysis (pre-treating) or treating biochar after pyrolysis (post-treating), with one or more of a wide range of physical, chemical, and biological processes. Simple post-treatments can be carried out on the farm to enhance the properties of the biochar. More complex pre- and post-treatments can be carried out at a biochar-producing facility, which may or may not be located on the farm.

SOIL CONSTRAINTS

When choosing or formulating a biochar or biochar-based amendment, it is important to consider the soil, financial, and environmental constraints that you want the biochar to address, and then develop a strategy to amend the soil with an appropriate biochar, enhanced biochar, or biochar–fertiliser combination. Figure 7.1 outlines constraints that may challenge a farmer's productivity under categories chemical, physical, biological, environmental, and financial. List all that apply to your situation to guide your choice of appropriate biochar(s) and enhancement strategies.

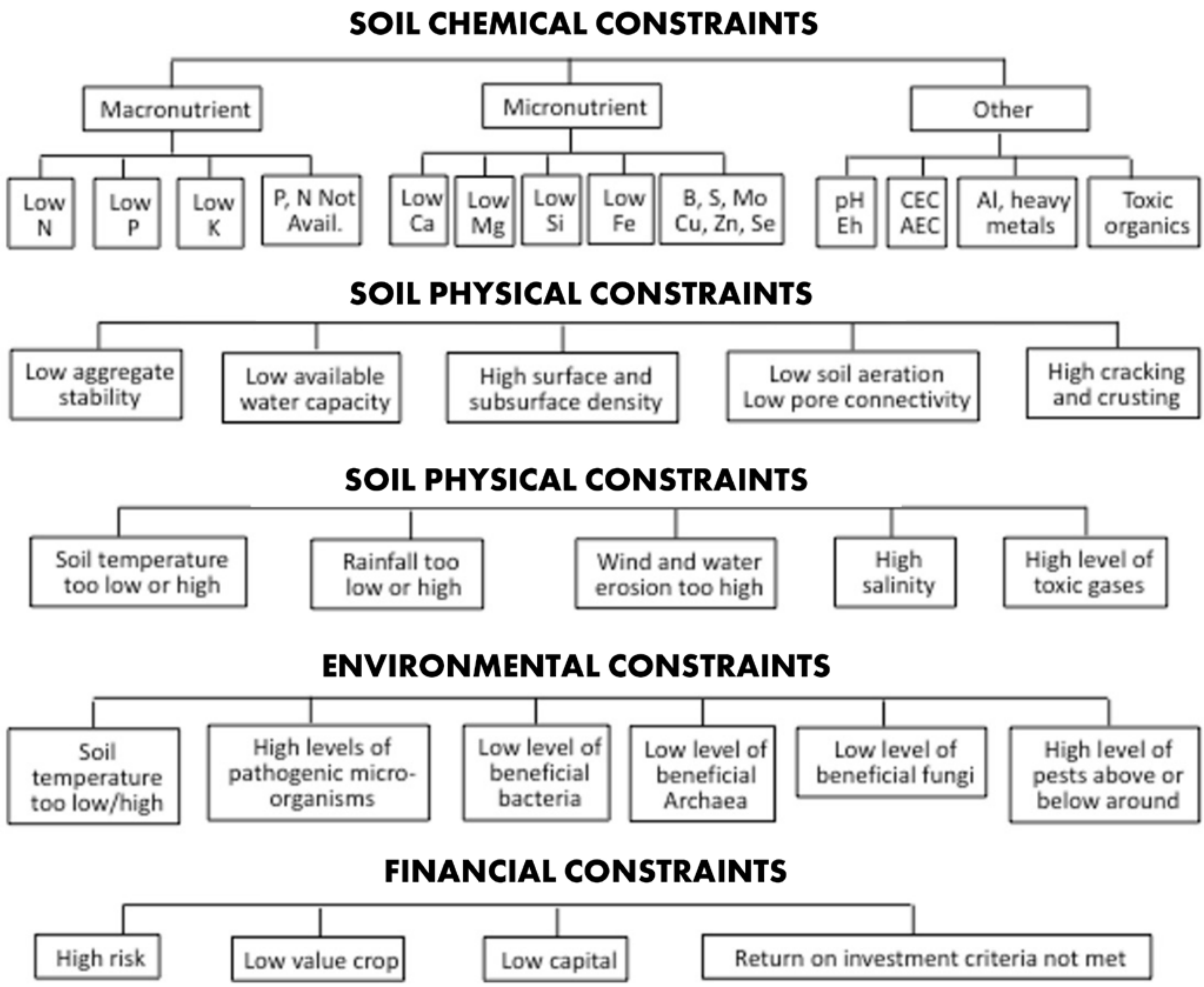

Figure 7.1 Potential constraints to farm productivity. List all that apply to your situation to guide your choice of appropriate biochar(s) and enhancement strategies

Note:

- Different plants require different quantities of macro and micronutrients and, therefore, biochars need to be formulated appropriately to be able to meet these requirements.
- Soils are heterogeneous and their properties vary over a field and between fields. Therefore, application of one amendment alone may not give the greatest agronomic or soil benefits, nor the greatest financial return on investment.
- The application rates for maximising crop yield, resistance to disease, resilience to environmental stress, and net financial return may all be different.
- Maximum benefit is achieved when the biochar is concentrated where the roots will grow (the rhizosphere).
- Repeated applications of biochar to the rhizosphere at low rates per season, producing a seasonal return, could optimise the economic viability of biochar amendment. The fuller spectrum of benefits offered by biochar, including those that require high application rates such as improvements in soil tilth, water retention, and carbon sequestration, will then accrue over time.

CHOOSING UNTREATED BIOCHARS FOR GROWING PLANTS

Biochars can be used without pre-treatment of biomass or post-treatment of the biochar; however, they should be chosen strategically to meet constraints. Often, biochars from various feedstocks can be combined to assist in maximising yield and minimising fertiliser use. In this section we review key findings from previous chapters, then provide general guidelines related to choosing untreated biochars.

Key findings on untreated biochars

In Chapters 4 and 6 we learned some relevant characteristics of untreated biochars:

- Biochars often give greater beneficial plant response when applied to sandy soils than when applied to other soils.
- Low-temperature biochar made from manures and crop residues produce the greatest increase in crop yield and beneficial microorganisms for most plants and soils.
- Physical properties of many soils, especially water-holding capacity, are usually improved by higher temperature biochars applied at high application rates (>10 tonne/ha).
- Grinding or crushing the biochar to small biochar particles (less than 50 microns) that can migrate through the soil, and attach on the roots, can have a greater impact on soil water-holding capacity, plant nutrient uptake efficiency, and disease resistance than larger pieces (>1 mm).
- Adsorption and binding of toxic organic and inorganic compounds and metals tends to be highest using biochars produced below 400°C or above 600°C and especially in sandy soils.
- Biochars, especially biochars derived from woody biomass, often have a low cation exchange capacity (CEC) compared to some minerals (Figure 7.2). To increase the soil CEC, choose biochars produced at low temperature from manures or other feedstocks that have a high mineral content (Chapter 4).

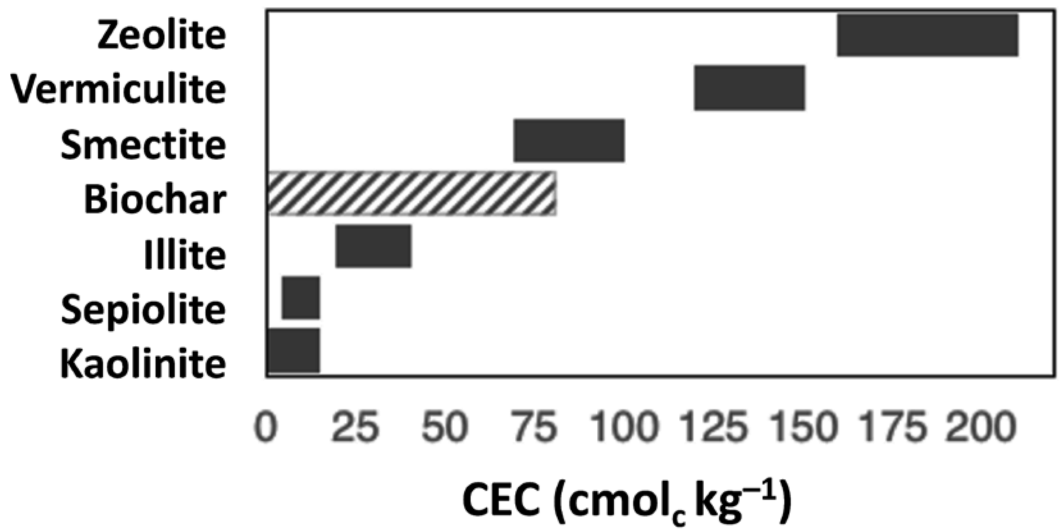

Figure 7.2 Range of cation exchange capacity (cmol$_c$/kg) of various minerals and biochar.[1,2] (Modified from Zwart)[3]

General guidelines for choosing untreated biochars

Choose a biochar made from residues of the same or a similar plant to that which you intend to grow. For instance, if you are growing corn, use corn stalk and corncob biochar. This will return to the soil most of the macro and micronutrients that have been used in the growth of the plant. If this is not possible to obtain, use biochar produced from straw, grass, nutshells, manure, or bamboo in preference to biochar produced from woody biomass.

Mixing different feedstocks with complementary mineral and nutrient compositions can enhance effectiveness. For example, Bian et al.[4] found that blending biochar produced from a combination of rice husks, rich in silica, and food waste with high nitrogen and phosphorous content, boosted yields when incorporated into granulated chemical NPK fertiliser. Yields showed improvement both at high and very low application rates (1% w/w of the soil and approximately 100 kg/ha, respectively). The inclusion of rice husks furnished additional silica, aiding plants in withstanding environmental stresses and pest pressures.

If crop-residue biochar is unavailable, opt for biochar derived from mixed feedstocks, like a combination of wood and manure, pyrolysed at a low temperature. When manure is blended with woody biomass and pyrolysed, fine minerals from the manure, including potassium chloride, magnesium and calcium carbonates and sulphates, calcium phosphate, iron oxide clay, and silicon dioxide, are deposited onto the biochar's surface (see Figure 7.3). Conducting pyrolysis at a low temperature ensures that most of these minerals are easily accessible to microorganisms and plants. The cation exchange capacity (CEC) of such mixed-feedstock biochars surpasses that of biochar produced solely from wood.[5]

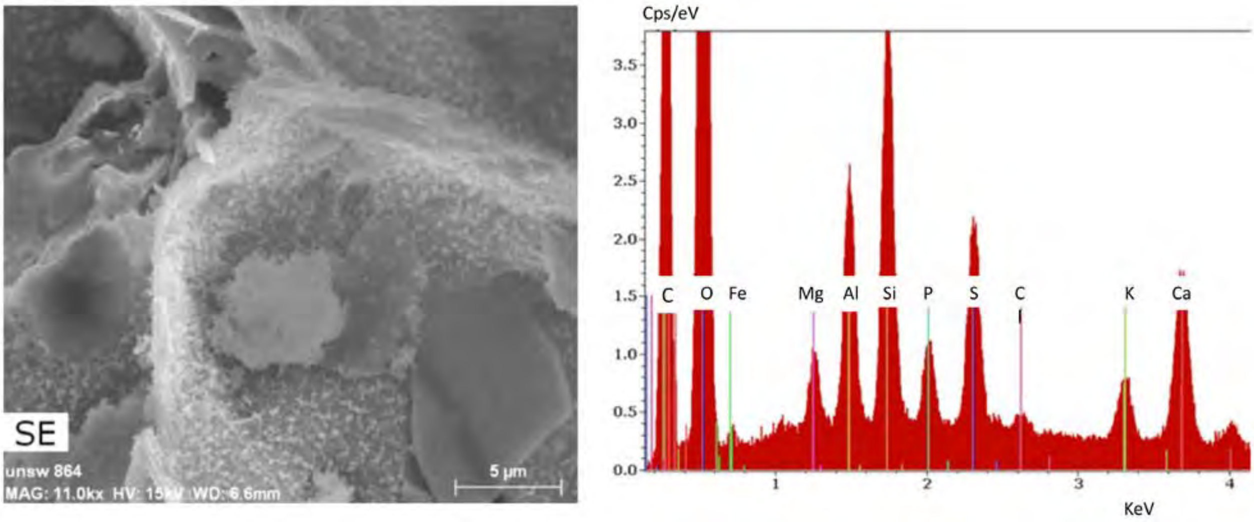

Figure 7.3 An electron microscope image of a mixed-feedstock biochar pyrolysed from wood and manure at 450°C–600°C in a simple kiln (TLUD). The woody biochar is coated in very fine particles of minerals and nutrients. The spectrum shows high contents of Mg, Ca, P, and S. Very high levels of Al and Si in the spectrum are from the clay that was on the straw collected from the fields. There was no nitrogen, possibly due to the high temperature of production

If the only available biochar is one produced from wood, which has a low nutrient content, mix it with specific nutrients and minerals. As a general guide, the minimum ratio of biochar to nutrients and minerals is 1:4. See Chapter 8 for a case study on yield and return with different NPK to poultry litter biochar ratios and various application rates.

Choosing untreated biochars for specific constraints

Some guidelines to assist in choosing untreated biochars to target particular constraints or goals are given in the table below.

To maximise the amount of carbon and macro and micronutrients that are returned to the soil	Pyrolyse the crop residue at a low temperature (i.e. 400°C–450°C).
To maximise income from carbon credits	Use biochars produced at temperatures greater than 500°C. These have a higher content of carbon and significantly longer lifetime than biochars produced at lower temperatures.
To improve water-holding capacity or enhance water use efficiency	Add finely-ground biochar produced at a higher temperature (500°C–600°C).
To reduce levels of toxic metals or bioavailability of organics	Add finely-ground biochar produced at 500°C–700°C, or biochar produced at a low temperature (around 400°C) that has high contents of oxygen functional groups and iron (see Chapter 4 and 6).
To address physical and chemical soil constraints at the same time, or to meet a greater range of constraints from a single feedstock	Combine low- and high-temperature biochars. The specific ratio may depend on the relative severity of individual constraints, including financial.
To raise the pH of acidic soil	Use a biochar with a pH greater than 7.
For basic soil	Use a biochar with a pH between 6 and 6.5, which can be produced from lower-temperature pyrolysis (350°C–400°C), or by treating biochar with an acid (preferably phosphoric, acetic, or citric), or wood vinegar.

Meeting soil nutrient requirements with untreated biochars

Biochars made from high nutrient feedstocks, especially if made in low or mid temperature ranges, may have enough of N, P, K, or S to have fertiliser value in their untreated form. Biochars made from manures and other animal wastes (e.g. paunch and carcasses), food waste, and biosolid have high contents of N, with chicken feather having the highest content of N, at up to 20%[6]. Most straw and grass biochars have a high content of K if produced at between 400°C and 500°C, but have relatively low concentrations of N and P. Nutrient content ranges of these biochars are listed in the table below.

Feedstock	Temp. °C	N %	K %	P %	S %
Manures, animal wastes (paunches, carcasses) food waste, biosolids	400-500	3.5–4.5	0.5–2	2–5	0.3–1
Chicken feather	300-600	Up to 20	na		.6%
Straw and grass	400–500	1–2	3–5	<1	.1

High-nutrient biochars may also provide calcium and have a range of other beneficial properties. Some high nutrient biochars (e.g. biochar produced from food waste) may have high amounts of salt (NaCl). Others (e.g. biochar produced from biosolids) may have a high concentration of heavy metals. It is important to have a detailed chemical analysis before using these biochars by themselves at high application rates (especially for rates >1 tonne/ha).

Much of the N and P in these biochars can be released slowly over 30–90 days, although this depends on the pH of the soil and the biochar, the frequency of rain events, and the particle size of the biochar. Dissolution, and therefore bioavailability, is greater in acidic soils and for small biochar particles, especially those less than 1 mm in diameter.

Typically, to produce the same yield as chemical fertiliser applied at 100–500 kg/ha, these high-macro-nutrient content biochars need to be applied at rates of 0.5 to 5 tonnes per hectare and concentrated in the rhizosphere of the plant.

METHODS FOR ENHANCING BIOCHARS

Most high-nutrient biochars sold in Australia in bulk cost over $1000/tonne and most woody biochars cost between $200–$1000/tonne. Consequently, methods have been developed to enhance biochars, or integrate biochar with chemical or organic fertilisers, sea and land minerals, or compost, so they can be applied at much lower rates (as low as 100 kg/ha) in the root zone. This approach is especially relevant for crops that have low value, where it may only be profitable to apply an economically sourced biochar.

The three main methods for enhancing biochars are:

- Pre-treating the biomass before pyrolysis with chemicals, minerals, or nutrients
- Ageing the biochars by passing them through an interim process before applying to soils
- Post-treating the biochars by combining with additives (chemicals, minerals, and nutrients)

A combination of all three methods can be used. Figure 7.4 illustrates the flow of materials and processes that could occur at a pyrolysis facility or on a farm to produce enhanced biochar. The ageing process can be considered an activation of the biochar. Commercial manufacturers of biochar should consider incorporating these principals to make enhanced biochars.

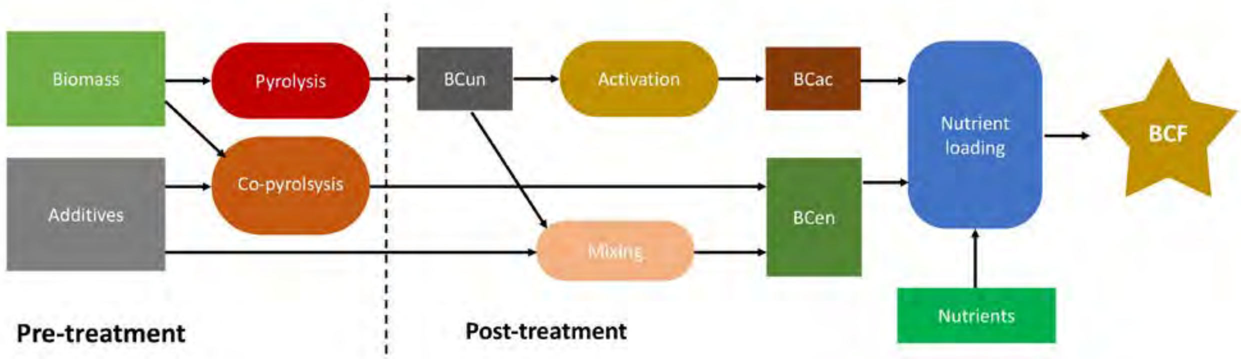

Figure 7.4 Simplified representation of biochar compound fertiliser (BCF) production processes, where BCun, BCac, and BCen are biochars that are untreated, activated, and enhanced, respectively. Material types are in rectangles and processes in ellipses. (Modified from Rasse et al.[7])

The following methods have been developed and tested to ensure that applications of less than 1–2 tonne/ha can give a return on investment through (a) increasing the macronutrients (N, P, K, Ca, S, and Mg) and micronutrients in the rhizosphere, and (b) enhancing the efficiency of uptake of the nutrients. The methods need to be adapted and refined for each particular farming system.

Pre-treating biomass

Commercial biochar makers and farmers who have their own biochar kiln can pre-treat biomass before pyrolysis. Mixing biomass with minerals before pyrolysing can increase the carbon content and yield of biochar, help retain more of the nutrients in the biomass, and result in the added minerals being beneficially bound and complexed with the carbon. The minerals are coated with the carbon compounds during pyrolysis and form a source of energy and nutrients for microorganisms. Some microorganisms like to live in environments that have oxygen-rich minerals and carbon-rich char particles. These microbes can help make organic and inorganic nutrients available.

Pre-treating the biomass can involve various combinations of:

- Adding clay (kaolinite and bentonite or montmorillonite), diatomite, greensands, magnetite, lime, gypsum, dolomite, zeolites, hematite, magnetite, or manganese oxide .
- Adding nutrients such as rock phosphate, ash from wood-fired boilers and fires, bones, potassium chloride, or superphosphate.
- Adding chemicals, including phosphoric acid, potassium hydroxide, chlorides of Mg, Fe, or Zn, and oxides of Cu, Ti, or Zn.

Pre-treating biomass with clays and minerals

- Wang et al.[8] and Dieguez-Alonso et al.[9] researched mineral and chemical pre-treatments of biomass and reported that:
- Pre-treating biomass with minerals (especially clay) increased the yield and stable carbon percentage (Figure 7.5). Typically, the mixture of minerals and biomass should be 20–30% minerals on a dry-mass basis.
- Clay (especially kaolin) is an acid catalyst. Incorporating it with biomass increased the content of C and O functional groups in the resultant biochar, which increased its CEC, AEC, and water-soluble organic compounds.[10] Some of these compounds assist in seed germination, help plants resist disease, and aid in the uptake of nutrients.
- Mixing 50% smectite clay with 50% (dry w/w) dung and then pyrolysing at 450°C–500°C was found to be an optimal mixture for improving pasture in Tibet.[11]
- Soaking bamboo in a slurry of kaolinitic clay and iron sulphate ($FeSO_4$), then pyrolysing at less than 500°C, resulted in bamboo biochars with increased pore volume and stable carbon content. This clay and iron pre-treatment increased the abundance of specific microorganisms on the surface of the biochar. Those microorganisms fix carbon, and make sulphur and iron more plant-available.[12]
- Spraying 1% of a potassium salt (e.g. potassium acetate) onto dry biomass and pyrolysing at 450°C increased yield of biochar and its content of stable carbon.[13] Adding bentonite with the potassium salt and pelleting favoured the transformation of water-soluble potassium to exchangeable potassium and potassium silicates. This greatly promoted the slow-release-potassium characteristic of biochar, potentially making it a cost-effective potassium supplement.

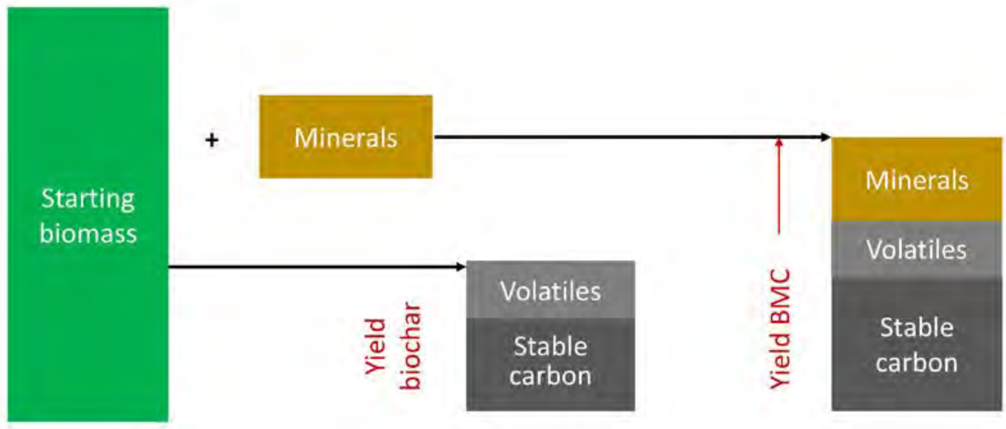

Figure 7.5 Effect of mixing minerals with biomass on yield of stable carbon after pyrolysis. Minerals increase the yield of both biochar and the stable carbon fraction of the biochar. The minerals "complex" with the biochar to form a greater yield of biochar-mineral-complex (BMC)[14]

A biochar composite made by pyrolysing a 1:1 mixture of bamboo and montmorillonite clay at 400°C adsorbed ammonium and phosphate ions and slowly released them, making the composite ideal to mix with either a chemical fertiliser or an organic, liquid fertiliser.[15] The retention of ammonium ions was ascribed to the high CEC of montmorillonite, while phosphate retention resulted from ionic bonding with cations in the biochar (e.g. Ca^{2+} or Mg^{2+}). The addition of montmorillonite facilitated the pyrolysis of bamboo powder to biochar at temperatures around 400°C, since montmorillonite acted as a solid acidic catalyst.

Pre-treating biomass with chemicals

Soaking biomass in solutions of iron sulphate and iron chloride (with or without the addition of K) before pyrolysis results in sites that bind phosphates and nitrates onto the biochar.

Soaking rice straw in concentrated magnesium carbonate solution and pyrolysing between 400°C and 500°C produced a biochar composite that enhanced phosphate retention (because of chemisorption) and water-holding capacity as well.[16]

Biomass pre-treated with superphosphate, ground bones, or phosphoric acid increased the yield of biochar.[17] The retention of more carbon in the biochar reduced the rate of P release and stabilised heavy metals (Figure 7.6).[17] Typically, the proportion of phosphate-mineral to biomass was 20–30%, with a pyrolysis temperature at 450°C–500°C.

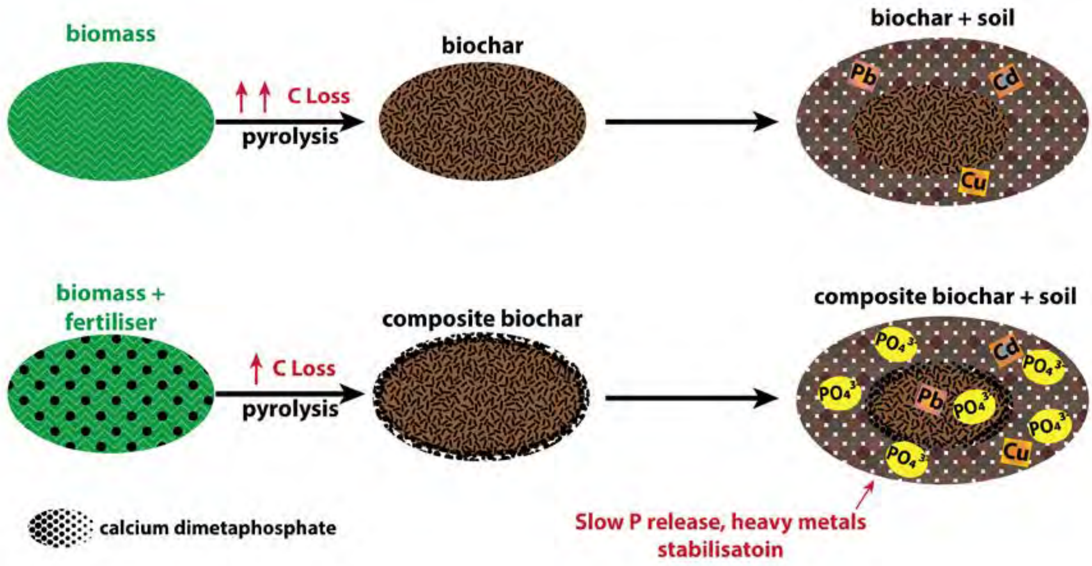

Figure 7.6 Schematic of adding a high-P mineral or chemical to biomass and co-pyrolysing to improve biochar carbon retention, slow nutrient release, and stabilise heavy metals in soils.[17]

The NSW Department of Primary Industries conducted pot trials of a biochar produced by adding 30% gypsum to wheat straw and pyrolysing at 450°C, with and without the addition of a wetting agent (Aquasil produced by CHT Australia Pty Ltd). The gypsum-modified biochar increased grain yield and leaf chlorophyll (Figure 7.7). It also improved soil structure and reduced soil alkalinity, dispersion, and slaking.

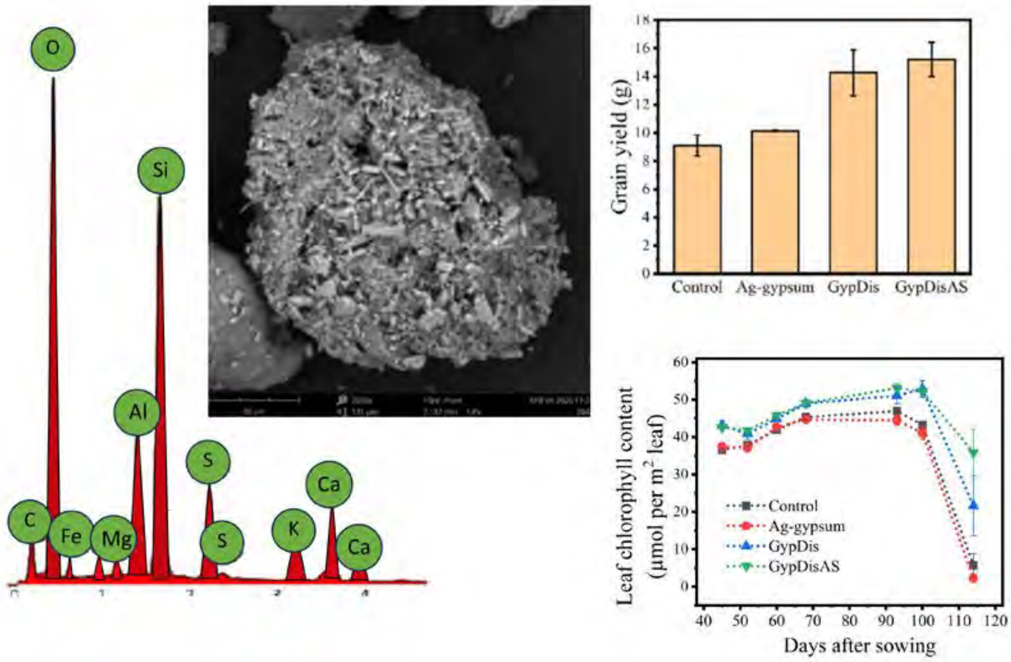

Figure 7.7 Left: Scanning electron microscope image and elemental analysis of a biochar–gypsum particle. **Top right:** the yield of wheat per pot for Control = no amendment, Ag-gypsum = Agricultural gypsum at 500 kg/ha, GypDis = liquid-gypsum-coated biochar, and GypDisAS = liquid-gypsum biochar with Aquasil dispersant. Bottom **right:** leaf chlorophyll content resulting from the four treatments. (Information provided by Dr E Tavakkoli)

Ageing biochars

Applying aged biochars often leads to higher yields, greater plant resistance to disease and stress, and increased soil health. Biochars can be aged by:

- Allowing time for the biochar to interact with soil minerals, organic matter, and microorganisms, preferably at a warmer temperature
- Co-composting the biochar with biomass and minerals
- Feeding the biochar to animals

Ageing in soil or drums

A simple method for ageing biochar is to mix it with high-iron-bearing acidic clayey soil that has a high organic-carbon content and allowing it to sit for at least a month at a temperature of at least 25°C (60°C is ideal). The ageing of the biochar and soil results in the formation of organo-mineral complexes, which increase CEC and help build soil carbon.[18]

Another simple method for ageing biochar and increasing its ability to retain nitrogen is to place it in an unpainted steel drum and add water whose pH is around 5.5. Battery acid can be used to lower the pH, though phosphoric acid is preferred (if not available, use a Cola, which has a low pH and often has phosphoric acid as an ingredient). Again, the ageing process accelerates at higher temperatures.

Biochar can be aged, and nutrients added to it, by cycling it through other beneficial applications, such as water filtration or catching nutrient runoff before adding the aged biochar to soils.

Feeding biochar to animals

One of the most cost-effective methods to age biochar and enhance its properties is to feed biochar to animals, with a little added molasses. The animals can self-feed from a container of biochar-only (or with 1% molasses) or a biochar feed blend, placed in sheds or in the fields. See Chapter 9 for a detailed case study using biochar as an additive for cattle feed.

When biochar is ingested with feed, some of the nutrients from the masticated feed enter the pores of the biochar. The nutrient-enhanced biochar reacts with stomach acid and enzymes, which increases the CEC and AEC of the biochar, enhancing its ability to adsorb and retain nutrients. The animal excretes drier, more nutrient-rich dung pats containing the enhanced biochar. Dung beetles and worms prefer this drier dung and will move it quickly down the soil profile.

Knowledge about the best formulation of biochar for animals is limited. Currently, the majority of animal-feed biochars are produced from wood. However, biochar made from grass, straw, seeds, or other plant-based residues have a mineral and nutrient profile closer to what land-based animals consume and can be used for animal feed.

Mixing clay, zeolites, and diatomite (which are minerals that are fed to animals to deal with plant toxicity) with a softwood or hardwood biochar in a minerals:wood ratio ranging from 30:70 to 50:50, before pyrolysing, can enhance the efficacy of a wood-based biochar for health, weight, or milk gain in animals.

Here are some examples from farmers around the world who have used biochar with animals:

- Dairy and beef farmers observed good weight gains from feeding biochar to weaners and calves.
- Horse owners noted better health in older horses, and in some cases improved racing performance of younger horses, after they had been fed biochar.
- A farmer who trialled feeding 36 weaner cows with regular rations and 36 cows with wood-biochar-clay composite found that the weight of animals fed the biochar composite improved by 36% in a dry period and 16% in a wet period, relative to the weight of those on regular rations.
- A supplier found that ruminants preferred woody biochar that was acidified with hydrochloric acid (6 parts acid:94 parts biochar). When biochar is acidified it has a greater concentration of salts on its surface, which may enhance its palatability for the animal. As well, the AEC and CEC of the biochar increase, which may increase nutrient retention in the animal's digestive system. As a result of the ageing process in the animal's gut, the biochar in the dung has a higher capacity to retain nutrients.
- Rapid improvement in pastures was achieved by supplying biochar-enhanced feed to animals in the field, and dung beetles to take the biochar into the soil (see Chapter 9 for a case study: Profitability in feeding biochar to animals). If biochar is fed to animals in sheds or barns, then the resultant manure–biochar mixture can be applied to the fields, or further processed for storage or sale.

Biochar used for fish farming and for water treatment

Fish and shrimp grown in ponds or tanks can be fed biochar produced from bamboo, hardwood, seaweed, or algae and the residues can be dried and applied as an organic fertiliser or pyrolysed to make a high-nutrient-content fertiliser. Typically, biochar is fed at 1–2% of total feed intake. Biochar can also be used in filters or hung in bags in the ponds or tanks to adsorb nutrients (Figure 7.8). The nutrient-rich biochar can then be applied as a fertiliser.

Figure 7.8 Left: Biochar-filled bags in a nutrient-loaded pond. **Right:** Biochar-filled bags have adsorbed nutrients from the pond water, resulting in a clean-water pond.[19]

Biochar used in animal bedding and sheds

When biochar is used as animal bedding, odours may be reduced. The nutrients in dung and urine diffuse into the pores of the biochar. Other minerals (especially zeolite) can be added to reduce moisture content and odours. The nutrient-rich biochar and dung can be sold or further processed, for example, by torrefying or pyrolysing to make a biochar-organo-mineral complex (BOMC).

Biochar in purpose-built filters placed in animal sheds can be used to remove odours. The efficacy of a pilot-scale odour removal system that used commercial biochar to remove hydrogen sulphide and 15 odorous volatile organic compounds (VOCs), was evaluated by placing the system in a swine gestation stall and continuously treating the inside air for 21 days. All the compounds in the effluent from the biochar filter, except for acetic acid (whose contribution to odour would be minimal due to its very high odour threshold), were below detection limits. The authors suggested that, after being used to reduce hydrogen sulphide and odorous VOCs, the used commercial biochar could be recycled for soil health improvement.[20]

Usually, the water used to remove or wash dung from shed floors is stored in pits or ponds. By introducing biochar into these ponds, soluble nutrients can be adsorbed and subsequently recycled as a soil amendment. A convenient method is to suspend the biochar in the pond in open-weave filtration bags (nylon stockings have proven to be durable and cost-effective). Alternatively, nutrients can be extracted by passing the water through biochar filters (Figure 7.9) and then cascading the nutrient-laden filter char to other uses.

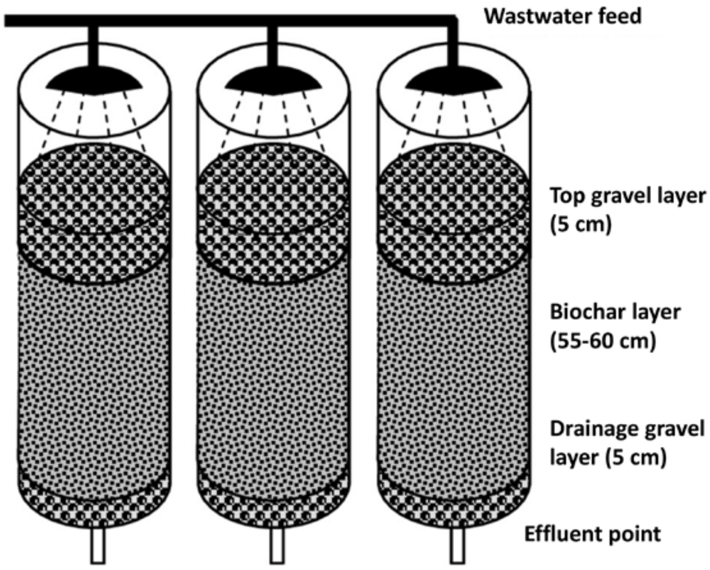

Figure 7.9 Biochar-based water filter[21]

Post-treating biochar after pyrolysis

Biochar compound fertiliser

Biochar can be mixed with minerals and organic or inorganic high-NPK fertilisers to produce a solid biochar compound fertiliser (BCF).

- To adsorb ammonia gas and ammonium cations, use a low-temperature biochar that is mixed 50:50 with a high-CEC mineral such as zeolite.[22]
- To enhance biochar's ability to capture ammonia gas, activate it by soaking the biochar in 30% phosphoric acid for 12 hours, then heat in a furnace at 450°C for 60 minutes.
- To adsorb nitrates, use a high-temperature biochar that has been acidified.
- To reduce emissions, increase the quality of the compost, and produce a biochar–compost fertiliser, add wood vinegar and zeolite with $FeSO_4$-enhanced biochar to the biomass–biochar mixture before composting.[23,24]

Making biochar compound fertilisers at a pyrolysis facility

The greatest plant response is usually seen if nutrients are added either during quenching of the biochar or to aged biochar. Typical nutrients can include:

- Chemical fertilisers such as urea superphosphate, muriate (KCl), mono- and diammonium phosphate, ammonium sulphate or nitrate, or urea.
- Organic fertilisers including those made from feather meal or chicken feathers, kelp or other seaweed, hydrolysed invasive fish species (e.g. Charlie Carp fish-based fertilisers), dry and sterilised or composted manure or biosolids, crushed blood and bone, urine, weeds, fruit and vegetable waste, and nutrient- and mineral-rich soil.
- A combination of the above is important in very depleted soils. Adding a small amount of a chemical fertiliser with organic fertilisers plus minerals and biochar can increase the abundance of growth-promoting microbes. Over time, as the microbes that fix N and make P available proliferate, the use of chemical fertilisers may not be necessary.

Mixing chemical fertilisers with biochar and minerals to produce a biochar compound fertiliser (BCF) and applying the mix in the rhizosphere is unlikely to harm soil health or young plants. The chemicals diffuse into the pores of the biochar where they react and bind with minerals and the biochar, so when they are applied to soil they do not cause large, damaging changes in soil pH or Eh, or reduce the abundance of growth-promoting microorganisms. As biochar ages, organo-mineral layers that form on the surface of the biochar coat the chemicals, resulting in a slow release of N, P, and K. Research indicates that these BCF can, over the years, build soil carbon and increase the abundance of beneficial microorganisms.[27]

The best way to combine organic fertilisers with biochar for the greatest plant response may be to quench biochar at the end of pyrolysis (whether on the farm or at a commercial facility) with manure or biosludge and minerals. Add clay (or soil with a large content of clay), rock phosphate, basalt, and diatomaceous earth for enhancing growth of plants and beneficial microbes (Chapter 4). Any volatile organics released in biochar production can be condensed to give a wood vinegar that can be added into the mix. This sterilises the manure (or sludge) and reduces the rate at which it decomposes in soil.[25] Figures 7.10 and 7.11 illustrate the range of nutrients that are on the surface of the resultant biochar.

A useful video to watch is produced by the Warm Heart Foundation, who mix effective microbes, which they produce themselves, into their fertiliser mix.[26]

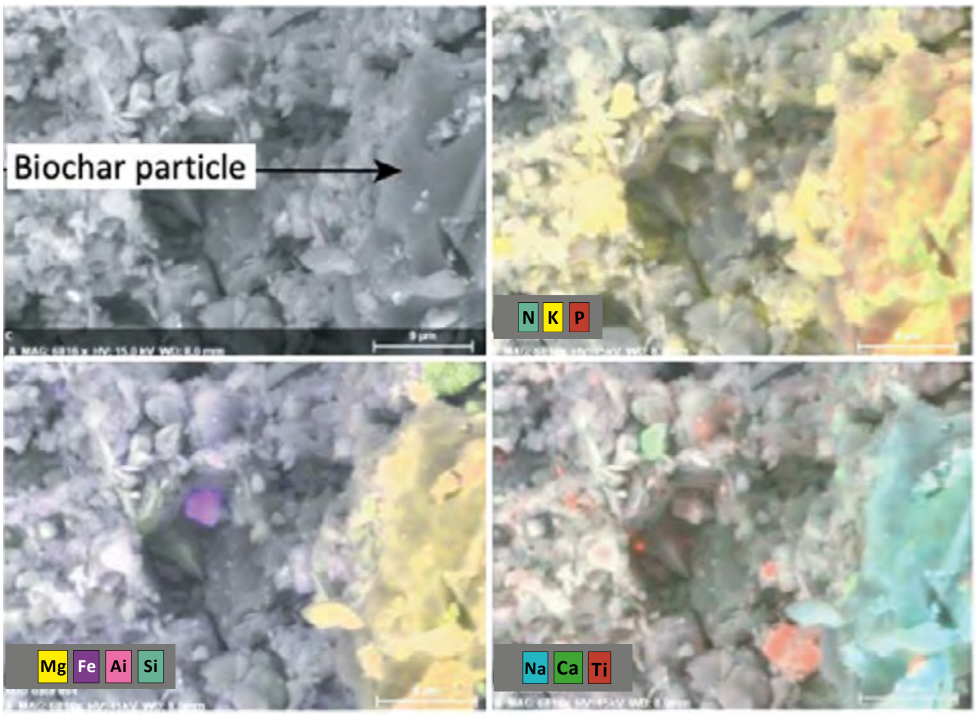

Figure 7.10 Scanning electron microscope image and nutrient map of the surface of a wood biochar that was quenched with a mixture of minerals and manure. **Top left:** a biochar particle near the right margin with mineral particles to its left and over it in the image. **Top right:** potassium (yellow) and phosphorus minerals (red) formed around, on, and in the high-carbon biochar particle; nitrogen compounds (teal) from the manure bonded to the carbon and the potassium mineral. The bottom images show distributions of other minerals. **Left:** Mg (yellow), Fe (purple), Al (pink), and Si (teal). **Right:** Na (teal), Ca (green), and Ti (red)

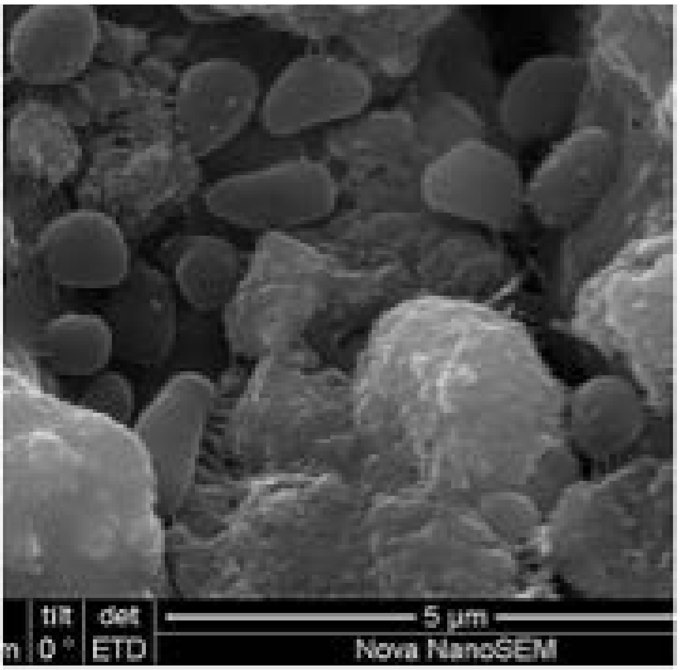

Figure 7.11 Scanning electron microscope image of microbes growing on the post-treated biochar that is depicted in Figure 7.10

Making biochar compound fertilisers on the farm

It may not be possible to obtain a commercial product that meets your soil nutrient constraints, so here are some general rules for customising a suitable BCF, by mixing solid fertilisers with biochar, on your farm:

- The optimal choice and amount of minerals to incorporate into the biochar vary according to the soil type. For most applications, consider adding kaolinite and bentonite clays, basalt dust, iron sulphate, diatomaceous earth, and rock phosphate. Some recipes for addressing specific soil constraints are given in the table.

A general-purpose fertiliser using a woody biochar	Use a mixture of biochar and minerals in the proportions of: 10 biochar, 1.5 kaolinite, 1.5 bentonite, 2 basalt dust, 1.5 diatomaceous earth, 1.0% rock phosphate.
Clayey soils	Reduce the amount of clay to 10 biochar:0.5 clay, using both bentonite and kaolinite, and add gypsum to help break up the clay.
Sandy soil	Add more clay (10 biochar:2–5 clay).
Soils that are very low in most micronutrients	Soak the biochar in a solution of sea minerals or equivalent.
Only a few micronutrients are lacking from the soil	Add the specific micronutrients to the other minerals, preferably as a liquid. Determine the amount to add from a soil analysis and the biochar application rate.

- Other minerals such as green sand (glauconite), ilmenite, waste calcium silicate board ($CaSiO_2$), magnetite or hematite, zeolites, agricultural lime, and gypsum can also be added to provide specific micro- and macronutrients and to enhance the abundance of growth-promoting microorganisms.
- When adding fertilisers that have high ammonium content, zeolite helps to reduce volatilisation and dissolution.
- Bring the pH of the biochar-plus-minerals to around 6–6.5 using an inorganic acid (such as phosphoric acid) or an organic acid (such as vinegar, citric acid, or wood vinegar). Doing this reduces the chance of volatilisation of ammonia.
- Add concentrated organic liquids that have high CEC and AEC (e.g. humates; https://ecogrowth.com.au/products/eco-humate) to the biochar, especially if the biochar has been produced at high temperatures (which depletes its nutrient levels) or will be applied to soils that have little readily available organic matter. Organic matter forms a film around the biochar and can increase AEC, CEC, and the abundance of microorganisms.
- Mix the fertiliser and ground minerals with biochar, with or without infused, concentrated, organic liquid. The best mixing ratio depends on soil constraints and plant requirements. As a rule, for both organic and inorganic BCF, use 15–25% biochar, 5–8% minerals, and the remainder (67–80%) the fertiliser.
- Apply low heat to the biochar-mineral-fertiliser mix to enhance the binding of the three components in the final amendment and enhance the availability of nutrients to the plant.
  - For an organic fertiliser, the best method is to heat the mix to at least 60°C. One way of doing this is to place drums or bags containing the BC plus minerals plus fertiliser into the middle of a compost pile.
  - For a chemical fertiliser, a simple method is to leave the mix in an open-mesh container at 25°C–35°C for a month. Figure 7.12 is a scanning electron microscope image of a wheat-straw biochar mixed with clay and urea diammonium phosphate and allowed to stand in a bag for a month.
- Once all ingredients are mixed, spray them with a solution of iron sulphate. The amount of $FeSO_4$ required depends on the type of soil and the plant requirements for Fe and S. For sandy soils with low Fe content, use the ratio 20:1 BC:$FeSO_4$. Some soils may require amendment in the range 40:80 BC:$FeSO_4$. For soils with a high Fe content there is no need to add more.

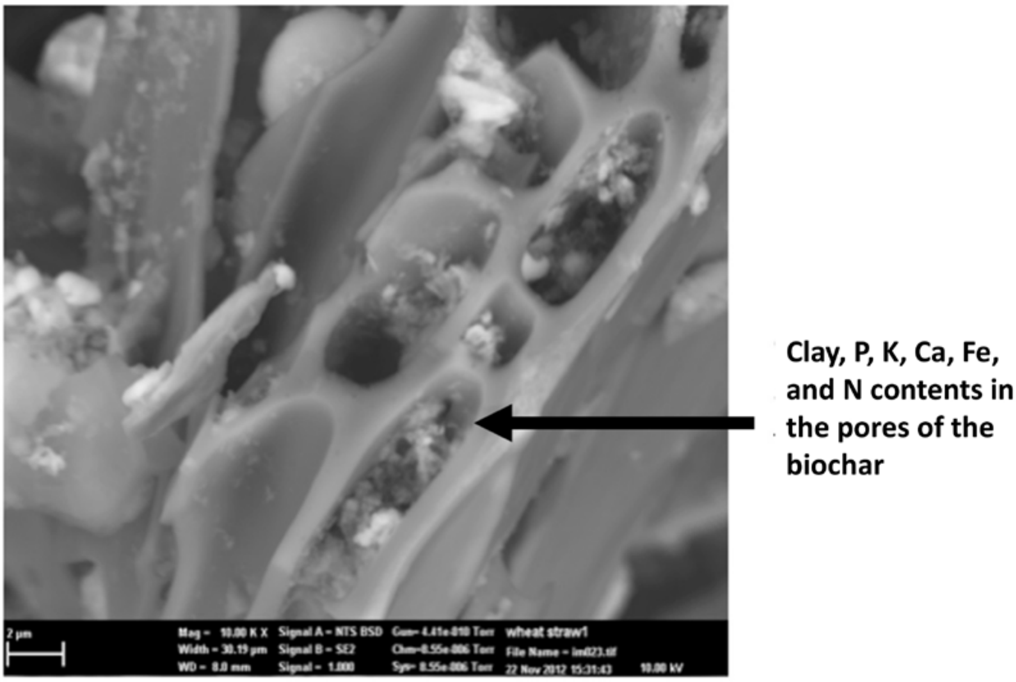

Figure 7.12 Electron microscope image of a biochar with pores filled with chemical NPK fertiliser

Important Points

- Most manure, biosolids, and straw biochars produced at low temperatures (<450°C) usually do not need added organic compounds.
- After mixng, it is important to dry any organic liquids and minerals that you apply to the biochar, so that they have a stronger bond to the biochar.
- You need to input your experience to produce these formulations. This starts with understanding the soil constraints, using ingredients that have worked on your farm, and doing some small trials with different formulations.

Producing biochar–urea composite

To produce a biochar–urea composite, begin by heating the urea until it becomes a liquid. Absorb the liquid by mixing in a biochar produced at high temperature and treated with acid to achieve a pH of 6.5. Then mix heated bentonite clay (80°C) into the moistened biochar. The clay coats the biochar, and the interstitial space between alumina (Al_2O_3) and silica (SiO_2) layers in the clay, which are expanded by the heat, can fill with residual nitrogen (Figure 7.13).

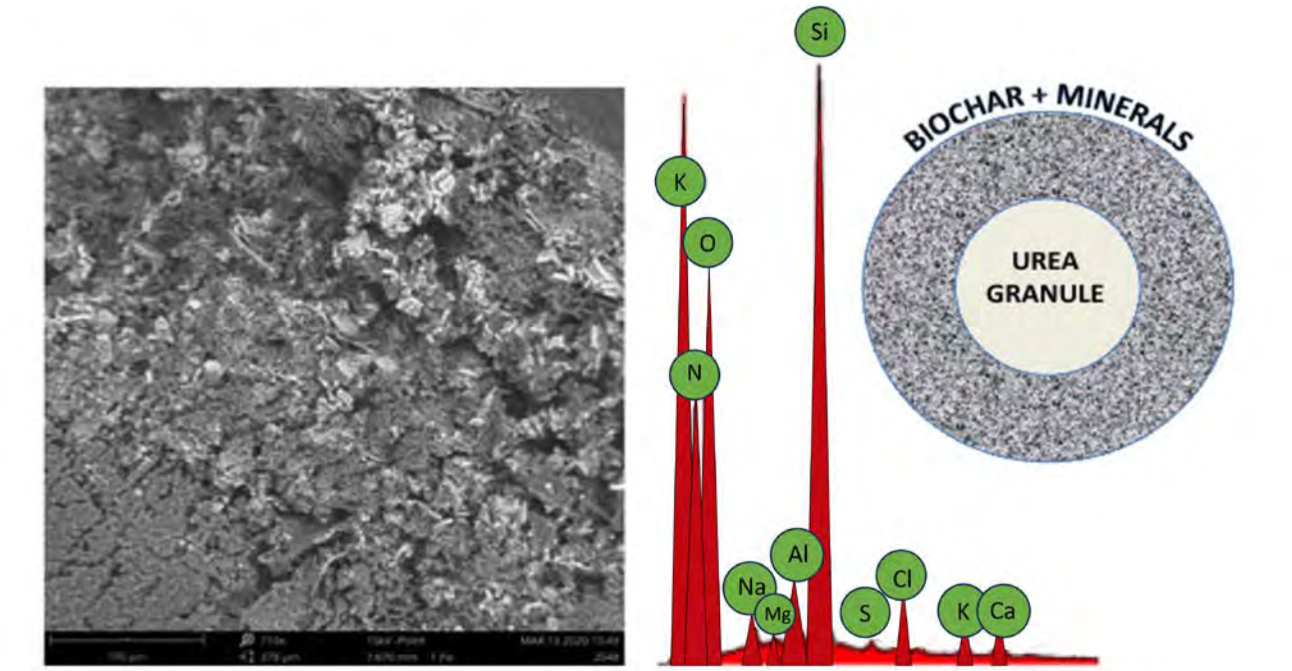

Figure 7.13 Biochar-plus-mineral encapsulated urea. **Left:** Scanning electron microscope image of the biochar–mineral surface. Centre: Elemental analysis shows the high nitrogen content that has infused into the surface. **Right:** Schematic depiction

An alternative method is to acquire an affordable, low-pressure pellet machine and pelletise all components together, generating heat within the pelleting die. Another option is to use an inexpensive granulator to combine the ingredients into granules, and then dry the granules (Figure 7.14). Existing chemical fertilisers, having a pH around 7, and a binding agent (such as lignin, clay, or starch) can be combined with biochar within a granulator.

Figure 7.14 Coating urea granules. **Left:** Adding a mixture of damp clay and biochar powder to urea granules in a plate agglomerator. Middle: The clay and biochar are coating the urea granules. **Right:** Drying the granules with a hair dryer

Making biochar-organo-mineral complexes (BOMC)

A third method is to make a slow-release organic fertiliser known as a biochar-organo-mineral complex. These fertilisers are used to enhance growth of arbuscular mycorrhizal fungi (AMF). BOMCs were originally designed following a detailed analysis of the magnetic high-phosphorus small, black, carbon particles extracted from the Terra Preta.

To make this product, treat the biochar with 6% concentrated phosphoric acid. Make a mixture containing 33% biochar, 33% manure or poultry litter, and 33% minerals comprising a mixture of clay, rock phosphate, basalt dust, lime gypsum, diatomite, and an iron mineral (preferably magnetite or ilmenite). The exact ratio depends on the soil constraints in your farm. Heat this to a temperature of 220°C (e.g. using the waste heat from your kiln). Add 0.5% to 1% (w/w) wood vinegar to the mixture. The product is sterile with a high concentration of available NPK and a high concentration of organic compounds that increase the abundance of microbes and can help plants to resist disease and other environmental stresses.

Making liquid biochar fertilisers and foliar sprays

There are many ways of making liquid biochar-organo-mineral fertilisers and foliar sprays. One method is illustrated in Figure 7.15. In this case, biomass is mixed with minerals and pyrolysed at 450°C. The resultant biochar is mixed with water and heated in a drum or an emulsifier. The mixture is passed through a pump that breaks down the biochar and produces a liquid that has a high content of organic molecules and carbon-coated minerals and biochar with a particle size of less than 100 microns. The pH is adjusted to 6.5 with either an acid or a base. Other nutrients that are not volatile can also be added to the tank to ensure that the pores of the biochar are loaded with specific nutrients.

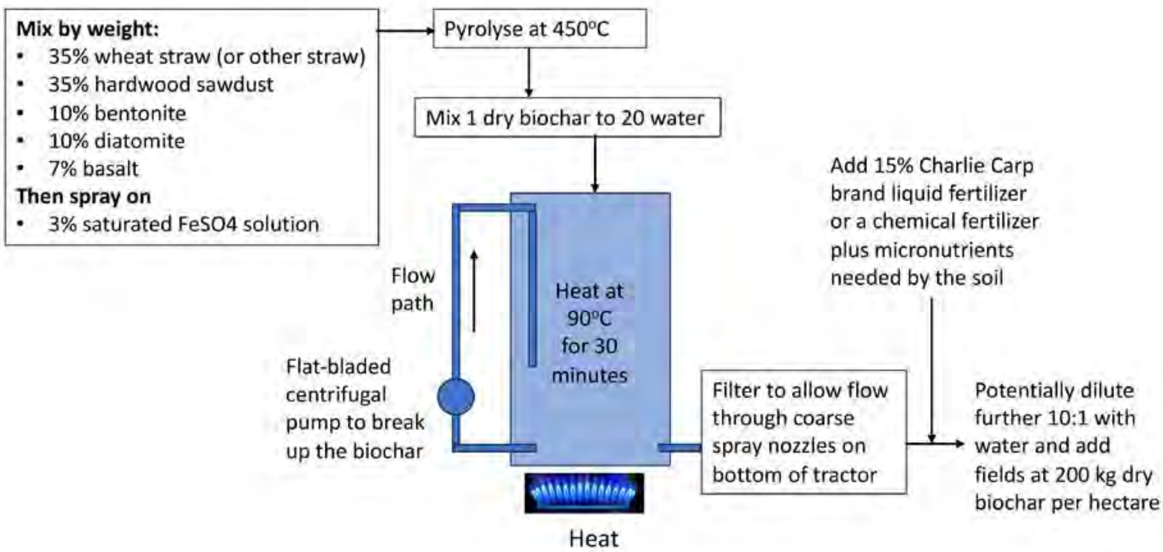

Figure 7.15 A method to make a liquid biochar fertiliser

CONCLUSION

In this chapter, we have outlined a number of techniques that can be used to enhance the properties of biochar to meet specific soil constraints. A subsequent manual publication will give more details of how to manufacture and apply specific enhanced biochars.

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Chapter 8

Methods for applying biochar

Key Points

- **Follow guidelines for applying biochar:**
  - Mix biochar and fertiliser together
  - Follow standard practices for nutrient content rates
  - Apply biochar in the future root zone of seedlings
  - Apply the biochar amendment every crop cycle
  - Avoid dust pollution and loss of biochar by erosion
- **For each biochar–plant–soil combination there are specific application rates that result in the greatest increase in yield, plant resistance to disease, soil health, and profitability. The application rates to optimise these different outcomes may not coincide.**
- **Carry out trials of different application rates on your own farm to determine the application rate that is most effective in addressing plant and soil constraints within cost constraints.**
- **When post-treating and applying fine biochar, use safety protection equipment as recommended by local authorities.**
- **Combining targeted moderate rates of biochar with diammonium phosphate (DAP) fertiliser can reduce fertiliser costs and improve profitability.**
- **Biochar-based fertiliser, applied as a root-zone layer, enhances agricultural practices, boosts plant growth, and improves soil fertility in acidic and phosphorus-deficient soils.**
- **Some practical ways to apply biochar include:**
  - Apply as root-zone layers and bands under or next to the future seedlings
  - Inject compost-biochar and manure-biochar mixtures as solids, slurries, or liquids to the subsoil
  - Apply biochar in deeply ripped bands or wells next to vine and tree crops
  - Apply liquid biochar or wood vinegar directly to the plant leaves as a foliar spray
  - Coat seeds with biochar
  - Use biochar as a substrate in green roofs and walls on buildings

INTRODUCTION

Biochars can be applied in many ways to different crops and soils. For each combination of soil type, plant, and climate there is an optimum application rate, type of biochar, type of fertiliser, and biochar-to-fertiliser ratio to maximise both yield and profitability. This chapter provides some guidelines that will help you to get the optimum benefits from plant, soil, and financial perspectives when applying biochar-based amendments for agricultural or horticultural improvements. Basic methods are outlined, and are illustrated in seven case studies: cocoa production, no-till wheat, vineyards, liquid application to pasture, biochar-coated seeds, green roofs, and small urban garden spaces.

The information is based on the authors' experiences, published literature, and conversations with farmers who have used biochar over many years.

GUIDELINES FOR APPLYING BIOCHAR FOR AGRICULTURAL PRODUCTION

Drawing on material presented in previous chapters, we have learned that biochar can be greatly improved in effectiveness by combining it with fertiliser as a source of nutrients—we refer to this mixture as biochar compound fertiliser or BCF. Biochar can also be quenched with a mixture of minerals and organic matter such as manure to form enhanced biochar-organo-mineral complexes (BOMC). The previous material allows us to outline some important guidelines for applying these biochar-based amendments.

Mix biochar and fertiliser together

It is best to mix the fertiliser (whether minerals, NPK or organic) and biochar together and let the mixture stand for at least a week, before application. This facilitates the process of nutrient adsorption onto the biochar surface and into the pores, resulting in enhanced bonding. When adding organic matter to biochar, allow the mixture to react for three to four weeks. This allows time for growth-promoting microorganisms to increase in abundance and coat the biochar with organic compounds, which have a high cation-exchange capacity and anion-exchange capacity. This in turn reduces competition between the biochar and plants for nutrients, reduces the leaching of nutrients away from the root zone of the plants, and increases the supply and duration of time-released nutrients and water to the plants, ensuring that the plants have nutrients and water available throughout their development

Follow standards for nutrient contents

A biochar compound fertiliser made with biochar + minerals + chemical fertiliser should be applied to the soil at similar application rates as is usual farmer practice when using a straight chemical fertiliser. It is important to follow guidelines given by the manufacturer of the BCF for the optimal application rate and placement of their product. If there are no guidelines, trials should be undertaken to determine the application rate and the ratio of biochar to nutrients that give the greatest return on investment (see Chapter 11). Take account of nutrients in the biochar; a general rule is to not apply more than two tonnes/ha (200 g/m^2) of a woody biochar or 500 kg/ha (50 g/m^2) of a high nutrient-content biochar (e.g. manure biochar).

Avoid dust pollution and loss of biochar by erosion

Applying dry fine biochar or biochar mixtures on the surface of the soil causes dust pollution and risks loss of amendment by wind and water erosion. If applying dry biochar, always apply it under soil. Dust can be controlled by wetting the fine biochar or biochar-fertiliser mixtures and applying them moist or as a slurry to the surface, followed by tilling into the soil. Another method is to granulate or pelletise a BMOC or a BCF and apply it in that form. When post-treating and applying biochar, always use safety protection equipment as recommended by local authorities.

Apply biochar in the future root zone of the plant

When formulated properly, biochars can be applied together with most seed types without adverse effects on germination and early growth. Experience and research indicate that applying small amounts of biochar (<500 kg/ha) with nutrients when a crop is being sown will maximise both yield and profitability. To be most effective, biochar and fertiliser need to be placed around the seed, in the future root zone, so that after germination the young roots encounter the biochar and nutrients, as illustrated in Figure 8.1. The distance to place the biochar from the seed depends on what rate the nutrients (especially nitrogen) are released, soil properties, and how the roots proliferate from the germinating seed. A nominal distance is 10–50 cm. If BCF granules or pellets are being used, then place them as per the recommendation of the manufacturer of the chemical or organic fertiliser. If using a straight biochar, then spread this out in a furrow 2–5 cm wide and, for plants with shallow roots, place the seed 2–5 cm above the biochar layer. As the plant grows, roots, bacteria, and fungi will access nutrients that have been adsorbed by the pure biochar or the BCF (Figure 8.2).

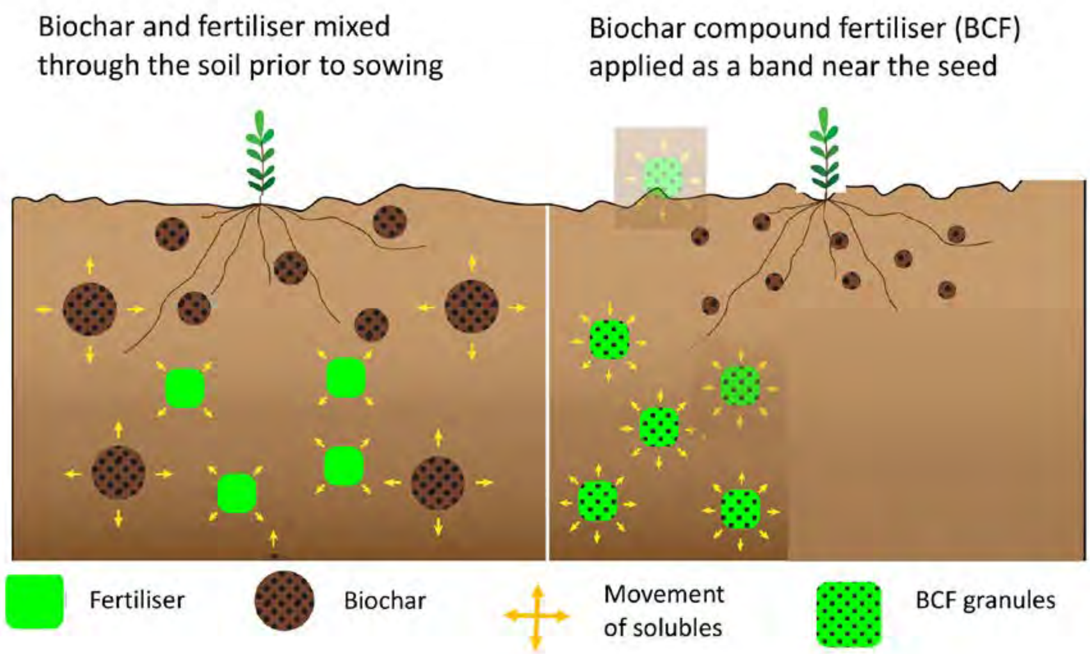


Figure 8.1 Initial dissolution of biochar and interactions with seedlings, for two modes of biochar application. **Left:** Biochar and fertiliser applied together and mixed through the soil prior to sowing, and **Right:** Biochar compound fertiliser (BCF) comprising biochar mixed with fertiliser, minerals, and a binder, granulated and applied to the soil as a band near the seed. (Adapted from Joseph[1])

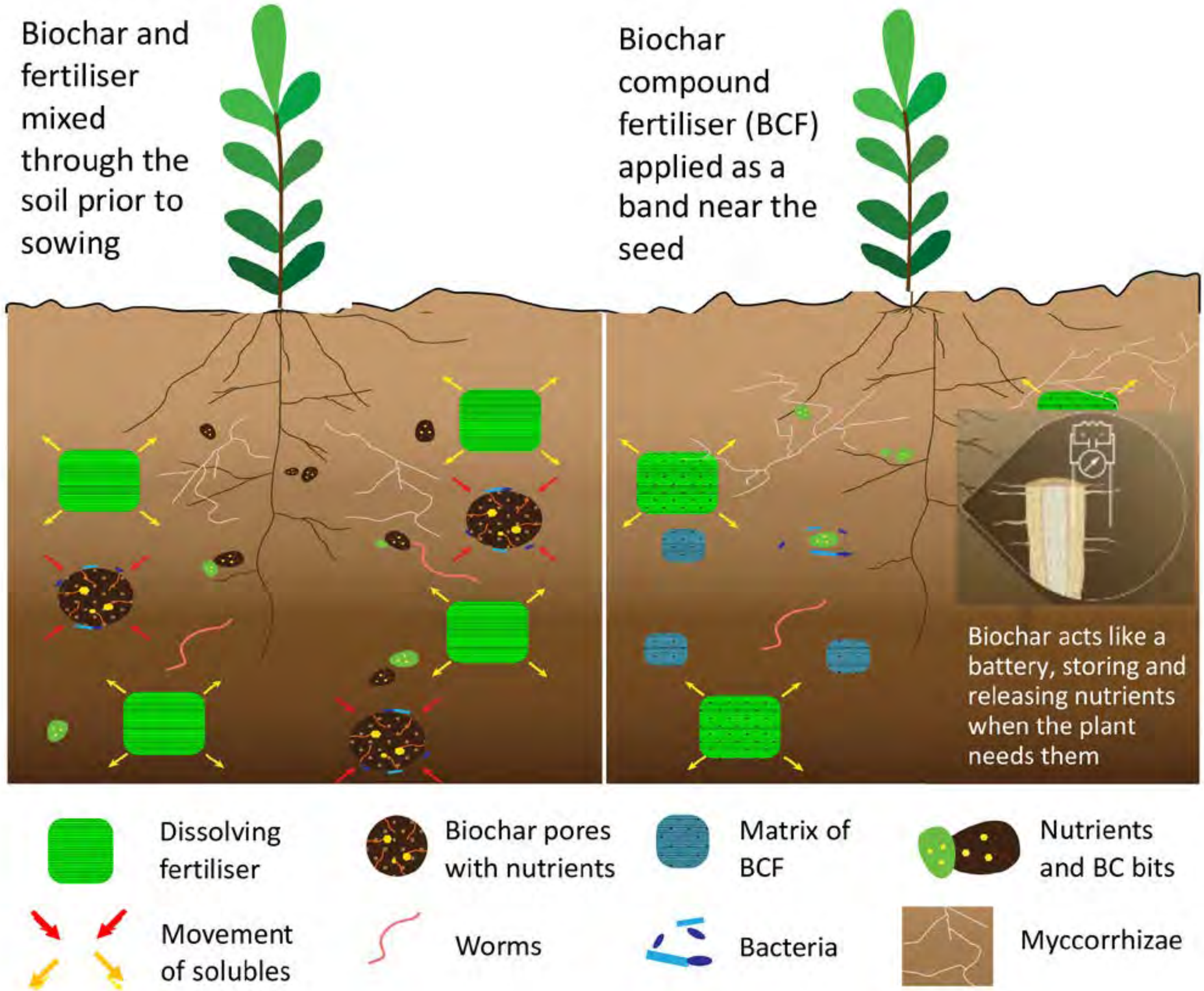


Figure 8.2 A later stage of interaction of the biochar with the soil, soil biota, and growing plants, for two modes of biochar application. **Left:** Reactive surfaces develop on biochar. **Right:** Fertiliser leaches out of the biochar compound fertiliser (BCF) leaving a durable carbon matrix with activated surfaces. BC = biochar (Adapted from Joseph[1])

Apply the biochar amendment every crop cycle

While specific soil, plant, and environmental benefits can be supported by large single applications of biochar, it has been found most cost effective to apply smaller biochar amendments at every crop cycle. This can provide the optimum combination of yield increase, disease resistance, soil health, and carbon drawdown benefits. Biochar and fertiliser application rates can usually be reduced after the 2nd, 3rd, or 4th crop cycle as the biochar accumulates and ages, making nutrients more available and increasing the abundance of promoting microbes. In this way, the long-term benefits that come from high application rates, such as improvement of soil physical and chemical properties and carbon sequestration levels, accrue over time as biochar accumulates in the soil, while the farmer is receiving an annual return on the annual investment in biochar. Both the short-term and the accumulating long-term benefits are amplified by the ageing process that ensues as the biochar interacts with soil.

Optimise application rates for plant benefits and profitability

Plant response, changes in soil properties, and profitability associated with particular biochars depend on the quantity of biochar applied. Figure 8.3 illustrates how, in many cases, the response increases with increasing biochar dose only to a certain point and then limits or reverses (leading to inverted U-shaped curves). Large enough application rates may even result in negative responses, as shown. The response to the disease-mitigating and growth-promoting effects of biochar may be optimised at different biochar application rates. Figure 8.3 shows a disease-response curve with its maximum at a lower application rate than the growth-response maximum, following the interaction of biochar A with the plant, soil, and other factors. Case B shows maximum growth occurring first and the maximum disease-response shifted to a higher application rate.

The maximum profitability may occur at a different application rate than either of these, due to a variety of factors. It may be less than the optimum for yield and disease resistance, due to the cost of the biochar (Biochar A), or it may be in between (Biochar B). It could even occur at a higher application rate (Biochar C). This possibility was found in the potato trials described in Chapter 9, where biochar made from wheat straw and poultry litter was substituted for some of the NPK in the standard regime for growing seed potatoes. The maximum yield and maximum number of tubers were both produced at 20% biochar substitution, but maximum profit occurred at 40% biochar substitution. The latter produced more small potatoes, which as seed potatoes were more valuable per Kilogram.

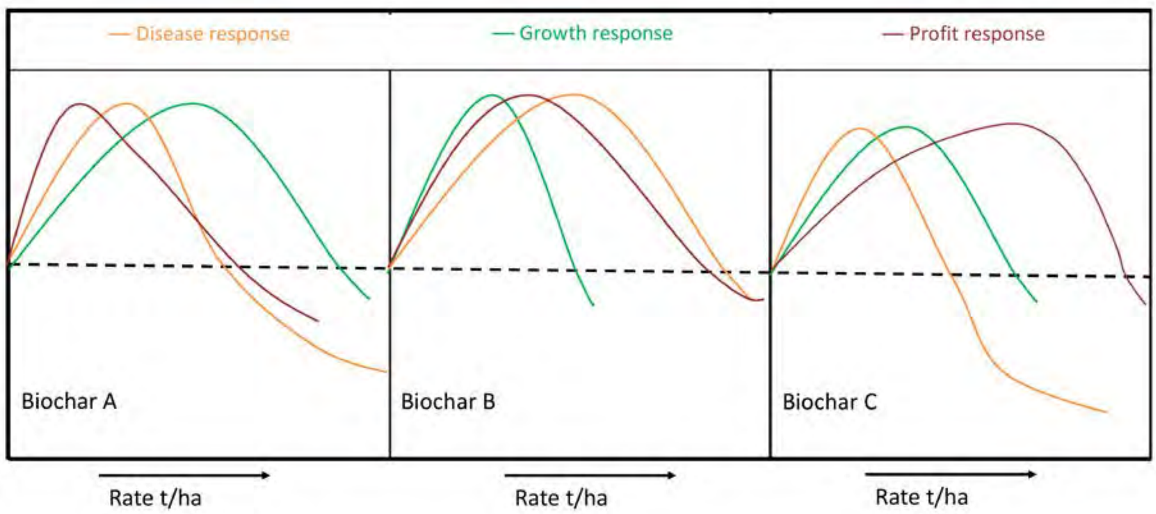


Figure 8.3 Conceptual illustration of changes in yield, disease resistance, and profitability following addition of different biochars. The maxima of the growth, disease response, and profitability may come at different application rates. (Modified from Jaiswal et al.[2])

Key Point

- Maximal yield, disease resistance, and profitability may occur at different application rates of biochar. Since budgetary constraints typically apply, trials should be conducted to determine the optimal rates to achieve the targeted purpose.

METHODS OF APPLICATION

Applying biochar to soil, either alone or in conjunction with amendments such as compost, manures, or crop residues, offers long-term benefits without necessarily requiring frequent re-application. However, it is likely that the most effective and sustainable way of using biochar is by integrating its use into seasonal agricultural amendment practices. It is therefore essential to ensure that the application of biochar is cost-effective and does not contribute to soil toxicity or negative environmental impacts. The following is drawn from the book *The Biochar Revolution*[3] and from the IBI publication *Guidelines on Practical Aspects of Biochar Application to Field Soil in Various Soil Management Systems*.[4]

Conventional field crop systems

In conventional field cropping systems, biochar can be managed and incorporated into routine field operations using standard farm machinery. This approach helps minimise the costs. For example, since lime is often applied as a fine solid, which must be well incorporated into soil, biochar can be applied and incorporated together with lime. Similarly, biochar can be applied with organic amendments such as manure.

Top-dressing

Top-dressing refers to the application of biochar directly onto the soil surface, and is an application method typically employed for established crops. This method poses a greater risk of wind and water erosion losses. To address these issues, several measures can be taken: ensure the biochar is adequately moistened and not overly fine; consider mixing it with other organic or mineral amendments; granulate or pelletise the biochar; apply it to flat land covered with dense vegetation; or utilise mulching techniques in combination with the biochar application.

Uniform topsoil mixing

This process typically occurs after primary soil preparation and before crop planting. Solid biochar, moistened to avoid dust, is initially evenly spread across the application area using a spreader (a manure spreader may be more suitable than a lime spreader for moistened biochar). Biochar can also be applied as a slurry, for example, mixed with liquid manure. Subsequently, the biochar is incorporated into the soil through hand hoeing, rotary hoeing, disking, or chisel tillage. The selection of the most appropriate method depends on soil conditions and available farm resources. Uniform application is particularly suitable for establishing turf, golf greens, athletic fields, and general landscaping post-construction.

Application to planting holes

Applying biochar to individual planting holes uses the biochar efficiently and minimises erosion losses. This technique is useful when establishing orchards, or tree or palm plantations.

Banding

In mechanised agriculture, banding seeds and fertilisers is a common practice. It involves applying an amendment in a narrow band using equipment that cuts the soil open with limited disturbance to the soil surface. Biochar can be banded at various depths, either manually or with machinery. Deep banding ensures thorough coverage of biochar with soil, minimising potential losses post-application. Banding allows biochar to be placed inside the soil next to established crops or trees.

Moreover, banding is effective for new plantings, where seeds or seedlings are planted next to or above a band of biochar, ensuring that growing roots will encounter the biochar.

Mixing biochar with other solid or liquid amendments

Mixing biochar with other soil amendments such as manure, compost, gypsum, or lime before application to soil can improve efficiency by reducing the number of field operations required. Since biochar has been shown to sorb nutrients and protect them against leaching, mixing with biochar may improve the efficiency of manure or other amendment application. Biochar can be mixed with liquid manures and applied as a slurry, alleviating dust problems, and getting effective application of well-combined mixtures. Fine biochars will be well suited to this type of application using existing application equipment. Biochar mixed with manures in holding ponds may reduce gaseous nitrogen losses.

Innovative systems of application

The development of no-till agriculture and other sustainable and regenerative methods are pushing innovation in amendment methods and equipment to reduce runoff, nutrient loss, odour (from using organic amendments like poultry manure), and cost.

Subsoil injection and banding

Subsoil banding can involve making a furrow, adding the biochar and compost, then covering it with soil. Injecting a liquid biochar or biochar-compost-manure slurry into the subsoil results in less disturbance, and has been investigated by Latrobe University (Peter Sale, personal communication). Equipment for disk seeding or no-till farming can be used to open the soil to create seed beds and cavities in which to inject a biochar slurry (Figure 8.4). Possible negative side effects of soil opening, such as soil vapour loss, seedbed and seedling desiccation, and burning of seedling shoots and roots from concentrated fertilisers can be greatly ameliorated by injecting a liquid biochar into the cavity. The combined winged tine and disk opening is closed after the cut and injection, thus minimising the side effects.[5] Several companies have developed systems to apply compost-biochar and manure-biochar mixtures in the subsoil as solids, slurries, or liquid (Figure 8.4).

Figure 8.4 Top left: Subsoil injection equipment.[6] **Bottom Left:** different shaped seed and slurry cavities in soil made by (from left) double-disk seed drill, hoe seed drill, Baker Boot seed drill, and combined winged tine and disk. **Right:** Views from above and in soil profile showing biochar slurry occupying both the horizontal seed bed shelves, and the vertical disk cut. (Graves[5])

Liquid applications of biochar and wood vinegar

Liquid biochar-based fertilisers can be applied to fields before or after sowing, or injected into the soil near plantings, with minimal disturbance of pasture or planting. After a crop or pasture is established, biochar liquid fertiliser or aqueous extracts of low-temperature biochar can be top-dressed or applied as foliar sprays, or both. Wood vinegar can also be applied to soil or by foliar spray, with the choice depending on the pest or constraint being targeted. Companies sell liquid applications and foliar sprays that contain biochar as one of the ingredients. Liquid fertilisers are applied at 200–500 kg/ha, and aqueous extract of biochar and wood vinegar foliar sprays at 10–20 kg/ha at dilution rates of 50–200 times. Applications of these are illustrated in Figure 8.5.

Figure 8.5 Left: Applying liquid biochar using a purpose-built applicator.[7] **Right:** Applying filtered liquid biochar and wood vinegar products as a liquid biochar soil drench and foliar spray at low application rates (<50 kg/ha). **Insert Left:** A biochar-alginate product from CARENCE. **Insert Right:** Wood vinegar by Green Man Char

Targeted biochar applications in precision agriculture

As already discussed, biochar is best targeted to the root zone of plants, for example, by banding or adding to planting holes. Where high-resolution data on soil characteristics and farm machinery equipped with geographical positioning systems are available, it becomes possible to target biochar preferentially to field areas where fertility is low. This can increase the cost–benefit effectiveness of the biochar application in a regenerative initiative; biochar often gives greatest benefits in poor soil.

Employing animals to apply the biochar

Animals can assist in moving biochar into the soil profile of existing pasture without disturbing the surface. With care regarding wind and soil erosion issues, biochar has been successfully applied on perennial pastures and vegetated spaces between fruit trees in orchards without significant losses of biochar. Subsequently, earthworms have been observed incorporating biochar into the soil. One of the most innovative methods has been to feed biochar to cattle, along with sowing dung beetles on the pasture. The animals activate the biochar, and the dung beetles incorporate it deeply into the soil profile. This is discussed in some detail in Chapters 9 and 10. Biochar can also be fed to chickens and other animals that are free-ranged to spread the biochar and manure.

Tree planting and remediation of established trees

Biochar should be applied to the areas of soil from which tree roots will take up nutrients as the tree grows. Ultimately, this area is the dripline of the mature tree. Initially, the biochar may be applied in the planting hole or banded around or beneath the tree roots. This, though, may discourage the roots from progressing further into inhospitable soil. To rectify this, and make a more secure tree planting, biochar can be installed in trenches radiating out from the tree, in circular trenches, or in several holes around the tree, and then covered with soil. Air or water excavation tools have been used to do the same in the remediation of urban trees.

Landscaping, gardening, turfgrass and urban applications
During landscaping, construction, and turf establishment, biochar can be applied in functional layers under the root zone, or the construction zone, for moisture retention, drainage, resistance to compaction, soil tilth, nutrient and toxin capture, and fertiliser reduction. Biochar has been applied in turf aeration holes, achieving application rates up to 5.4 t/ha. These qualities of biochar along with its low density make it an ideal substrate in green roofs and walls.

Watershed management and reclamation of degraded areas
Biochar can help to establish vegetation on degraded soils, while adsorbing a variety of heavy metals and other toxicity. In these cases, biochar can be applied in trenches and char-wells, or in strips near waterways to combine remediation, nutrient and toxin capture, microbial promotion, and sequestration.

CASE STUDIES

this section contains six case studies illustrating some of the guidelines and methods described in previous sections. Chapter 10 presents further case studies describing applications of biochar in regenerative agriculture, such as using biochar in the just mentioned char-wells and trenches to remediate salt-affected land, and using cattle and dung beetles to apply biochar to pasture.

Case Study 1: Root-zone application of biochar-based fertilisers

Meyer et al.[8] investigated the effects of different methods for applying biochar-based fertilisers (BBFs) to the root-zones of young cocoa plants grown in Oxisol soils. Oxisol soils are highly weathered, acidic, and deficient in phosphorus.

The researchers compared four amendments: biochar alone (BC), mineral fertiliser (NPK), biochar-based fertilisers, and fermented biochar-based fertiliser. The biochar-based fertilisers were produced by combining biochar with a foliar fertiliser and deionised water. The fermented biochar-based fertiliser was created by lowering the pH of biochar through lactic fermentation. Three root-zone application methods were tested: topsoil application, layered root-zone application, and hotspot root-zone application (Figure 8.6).

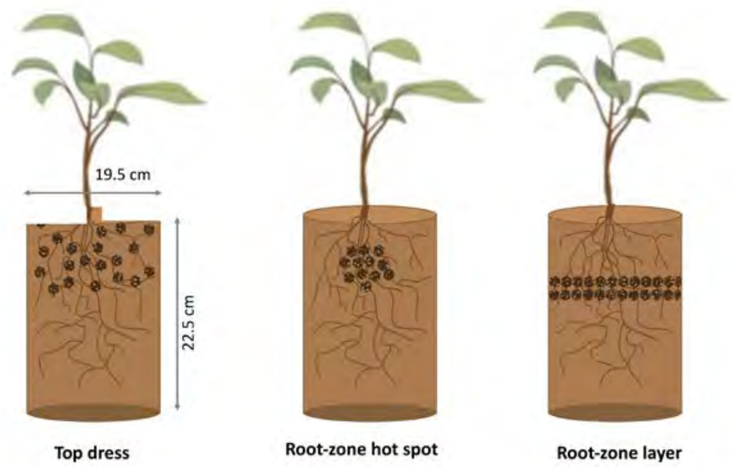


Figure 8.6 Three methods of application of biochar. In each case, the amendment was placed before the seedling was planted, and the plant-roots have grown into and through the amendment (Modified from Meyer et al.[8])

Application of biochar-based fertiliser in the root-zone layer was the most effective method for improving cocoa plant growth. The results for above-ground biomass (Figure 8.7), total leaf area, and chlorophyll content all showed the same trends, with respective increases of 56%, 222%, and 140% compared to the common farmer practice of topsoil application. Additionally, phosphorus levels in the plants increased by 53% and the N:P ratio in the foliar tissue improved, indicating better phosphorus availability.

In contrast, biochar alone (without fertiliser) did not produce significant improvements in plant growth. However, when used as part of a biochar-based fertiliser, even in small doses (16 g/plant or 0.3% w/w soil concentration in the root zone), biochar proved beneficial in ameliorating phosphorus limitations and improving plant nutrition.

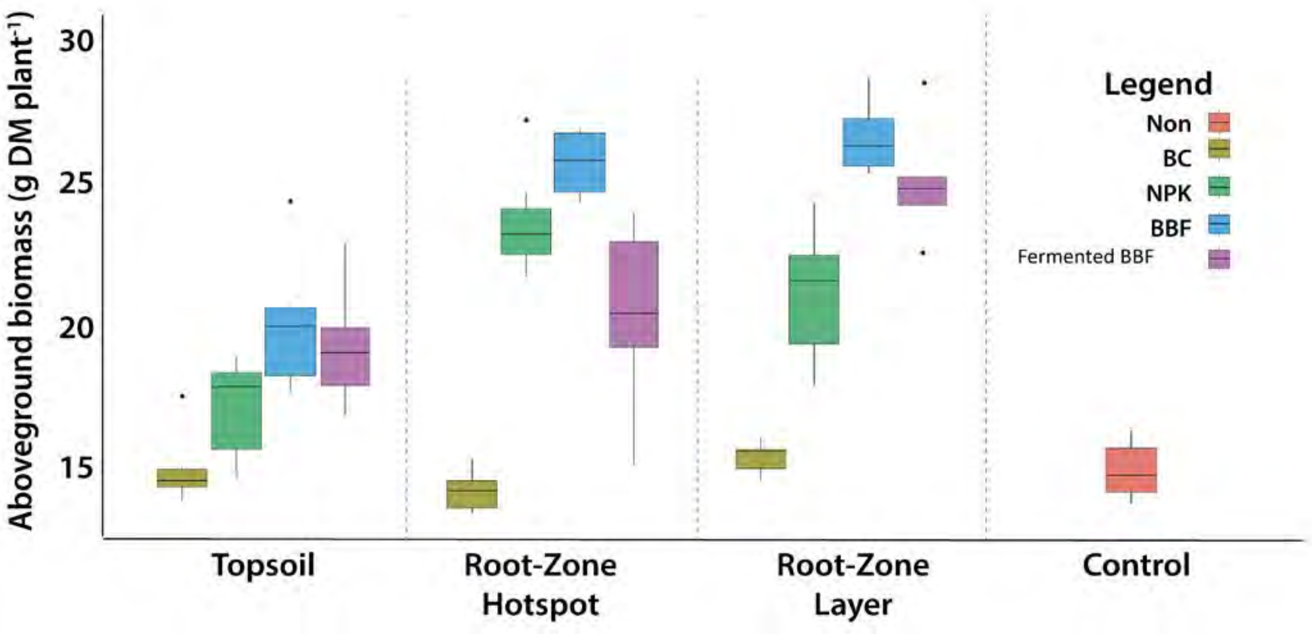


Figure 8.7 Above-ground biomass from pot trials of four amendments applied by three application methods to cocoa seedlings in poor Oxisol soil. BBF = biochar-based fertilisers; BC = biochar; DM = dry matter (Modified from Meyer et al.[8])

Case Study 2: Biochar with NPK for no-till wheat farming

The rates of application of biochar and other amendments can affect crop yield and returns to the farmer. The South Australia No-Till Farmers Association (SANTFA) undertook trials where they injected different ratios of poultry litter biochar and diammonium phosphate (DAP) underneath the wheat seed (Figure 8.8, Figure 8.9)[9]. The application of 100 kg/ha of diammonium phosphate (DAP) with 35 kg/ha or 100 kg/ha of poultry litter biochar (T6, T7) gave the biggest wheat yields; however, the greatest increase in profits to the farmer occurred when an application rate of only 50 kg/ha of DAP was combined with 35 kg/ha of biochar (T3), priced at $500/tonne. Notably, wheat that received 50 kg/h of DAP alone (T2), or 35 or 100 kg/ha of biochar alone (T8, T9) did not give significant increases over no treatment (T1).

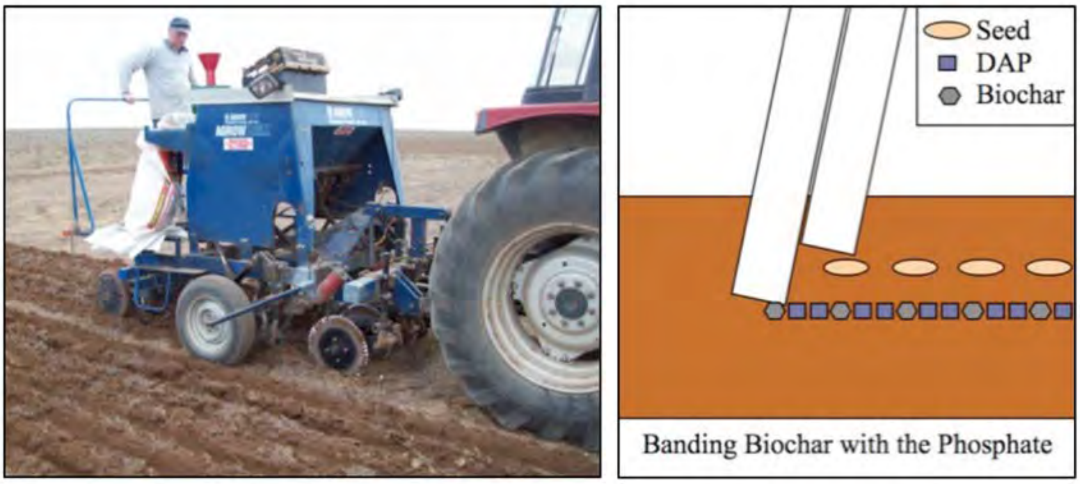
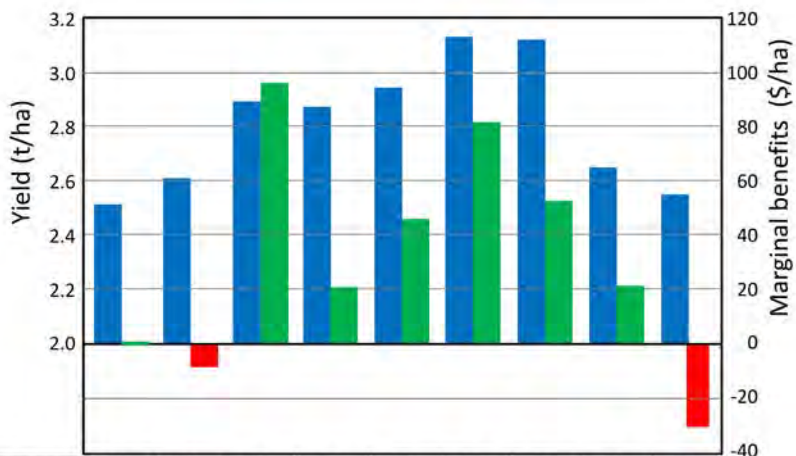


Figure 8.8 Method of sowing of biochar and diammonium phosphate under seeds in no-till wheat farming. DAP = diammonium phosphate (Courtesy Greg Butler, SANTFA[9])



Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9
DAP kg/ha	–	50	50	50	100	100	100	–	–
PL BC kh/ha	–		35	100	–	35	100	35	100
	2.517	2.612	2.899	2.876	2.943	3.132	3.124	2.654	2.555

Figure 8.9 Yields and marginal benefits from sowing biochar and diammonium phosphate under seeds in no-till wheat farming, for combinations of DAP/BC. BC = biochar; DAP = diammonium phosphate; PL BC = poultry litter biochar. (Adapted from data courtesy Greg Butler, SANTFA[9])

Similar results have been reported for banding biochar with DAP using existing seed drilling equipment (Figure 8.10) and higher rates of application of biochar.[10] Interestingly, the combination of 1.5 t/ha of wheat straw biochar with the low DAP usage of 25 kg/ha was a most favourable combination, giving better yield than wheat straw biochar at higher DAP levels, better yield than chicken litter biochar at low DAP, and almost equal yields to those from chicken litter biochar at higher DAP levels.

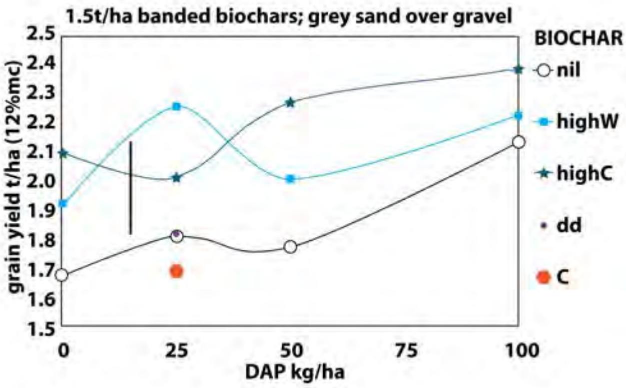


Figure 8.10 Grain yield after application of wheat straw biochar (W) or chicken manure biochar (C) at 1.5 tonnes per ha with different rates of application of diammonium phosphate (DAP)[10]

Case Study 3: Biochar with compost in vineyards

In response to the California droughts, a multi-year trial was run between 2016 and 2021 in California to determine how different treatments of wood-biochar, compost, and a combination of the two could improve water efficiency and crop production and quality in a newly planted vineyard.[10,11] The trial was conducted at Oasis Vineyard[11,12], King City, California on a sandy soil with 0.7% organic matter.

The biochar (provided by Pacific Biochar at US$240/t delivered) was produced from softwood forestry residues, fired at 750°C. On a dry basis, it had organic matter of 74.5% and ash content 25.5%. The compost was described as a blend of spent mushroom compost, green material, and grape pomace with organic matter 42.5% and ash 57.5% (contents on dry basis). The biochar compost blend was mixed in a compost windrow and left to further compost for a month to allow the nutrient and biology to develop in the biochar.

The replicated trial included the four different treatments shown in Table 8.1. For the control, no compost or biochar was added but the soil was still mixed.

Treatment	Compost, t/acre		Biochar, t/acre		% SOM
	Wet	Dry	Wet	Dry	
Control					0
Compost	15	7.7			0.3%
Biochar			10	6.2	0.42%
Compost+biochar	15	7.7	10	6.2	0.7%

Table 8.1 Four combinations of biochar and compost applied in vineyards in California. % SOM is the calculated direct soil organic matter addition to the soil

The application of each treatment involved deep ripping a GPS-guided delve down the vine row into which the amendments were applied. A second pass with a winged plough mixed the amendments into the soil, forming a band approximately 60 cm wide and 75 cm depth (Figure 8.11). Vines were placed 1.5 m apart, resulting in about 0.7 m^3 of cultivated and amendment soil per vine. Plots of 0.5 acre each were replicated four times in a complete randomised block design. All treatments received the same regimen of irrigation and NPK fertiliser. Fruit from each treatment was harvested annually and the yields compared to those of the control and of previous years to highlight the best treatment for crop production. Cluster counts, pruning weight, fruit quality, vine vigour, soil health, and moisture content were also monitored in some years.

Figure 8.11 Applying soil amendments to a vineyard in California by deep ripping down the vine rows, leaving a delve in the soil into which the amendments were applied. The amendments were then mixed with the soil to three-feet depth via a second ripper pass, and covered to make planting mounds. (Photos[12])

The mixture of biochar+compost produced the highest yield, compared with other treatments and the control, in all but the first harvest (Figure 8.12). In the first production year, 2019, the biochar alone produced the biggest yield; however, vine vigour was observed to be highest in the biochar+compost treatment plot, which appears to have set the stage for it excelling in later harvests. In 2021, yields suffered owing to poor weather conditions during flowering and fruitset. In this circumstance the biochar+compost treatment especially showcased its value, producing more and larger clusters, resulting in 24% higher yield than either the compost or the biochar alone, and 74% more yield than standard NPK practice (the control).

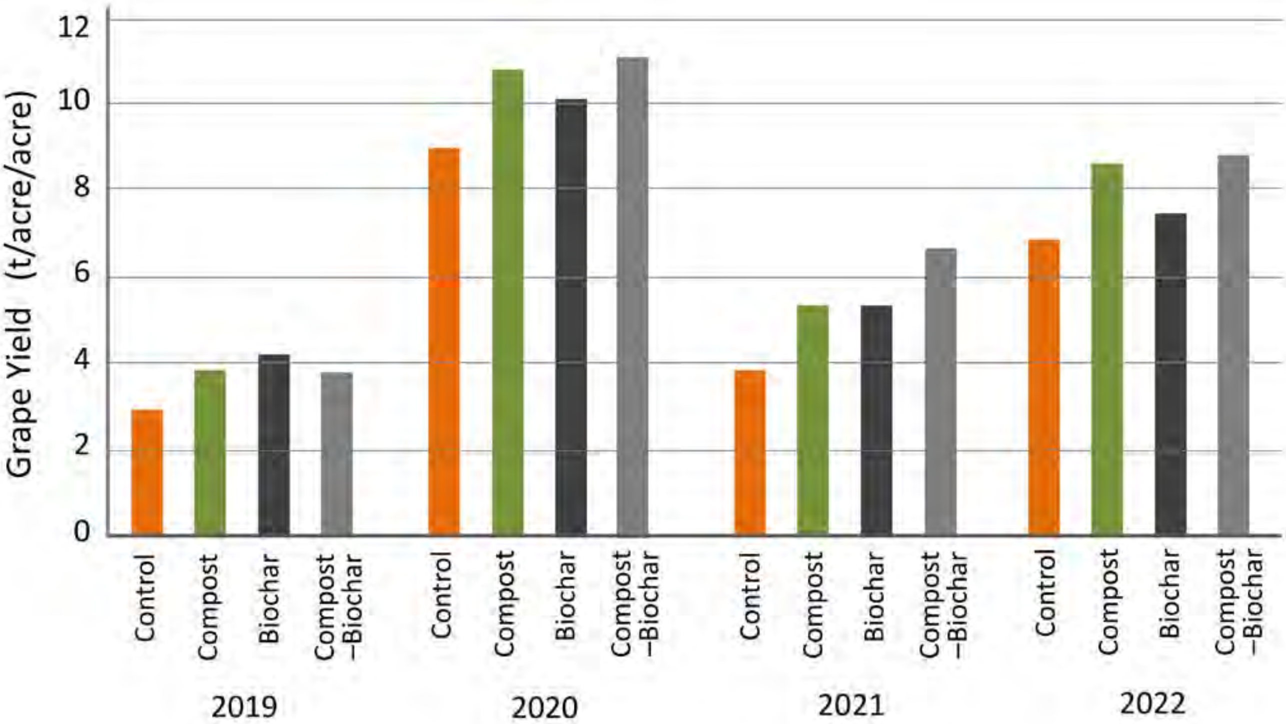


Figure 8.12 Gain in grape yields values per acre following application of biochar, compost, and both to vineyards on sandy soil, King City, California, 2019–2022[12]

In terms of quality parameters, the biochar-alone treatment produced the biggest increase in berry volume, weight, sugar, brix, anthocyanins, and tannins. These results indicated the absence of any negative impacts from biochar application, and potential positive impacts on grape quality from applying suitable biochar formulations.

Soil parameters measured in 2021, four years after amendments began, showed substantial improvements. Notably, the biochar treatments excelled over compost alone in all soil indicators. As shown in Figure 8.13a, increases in measured soil organic matter over the control were highest for the biochar+compost amendment (0.4% increase), followed by those for biochar (0.3%), and then compost (0.1%). This is the same order as that of the amount of organic matter added to the soil (Table 8.1). Soil respiration (indicating total microbial biomass) and organic nitrogen release followed this same pattern. The treatments with biochar alone, followed by biochar+compost, excelled for increasing extractable P (Figure 8.13b), microbially active carbon, and nutrient value. Compost additions were important for the overall soil score, with the best increase in soil health coming from adding the biochar+compost mix, followed by that from adding compost alone.

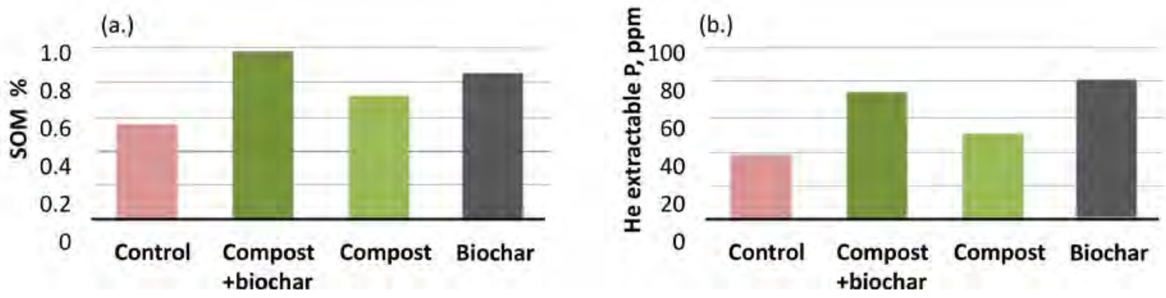


Figure 8.13 Increase in soil organic matter (SOM) and extractable P following application of biochar, compost, and both to vineyards on sandy soil, King City, California, 2019-2022[12]

A main objective of the study was to evaluate the effect of biochar and compost on water saving. All plots received the same irrigation, so higher crop yields from the amended soils indicated higher water use efficiency.

Financial calculations showed that while compost alone was the most cost effective in the short term, the higher cost of combining compost+biochar was rewarded in later years with higher income, due to the biochar's ability to retain and regulate the nutrient release from the compost and help retain water within the soils (Figure 8.14).

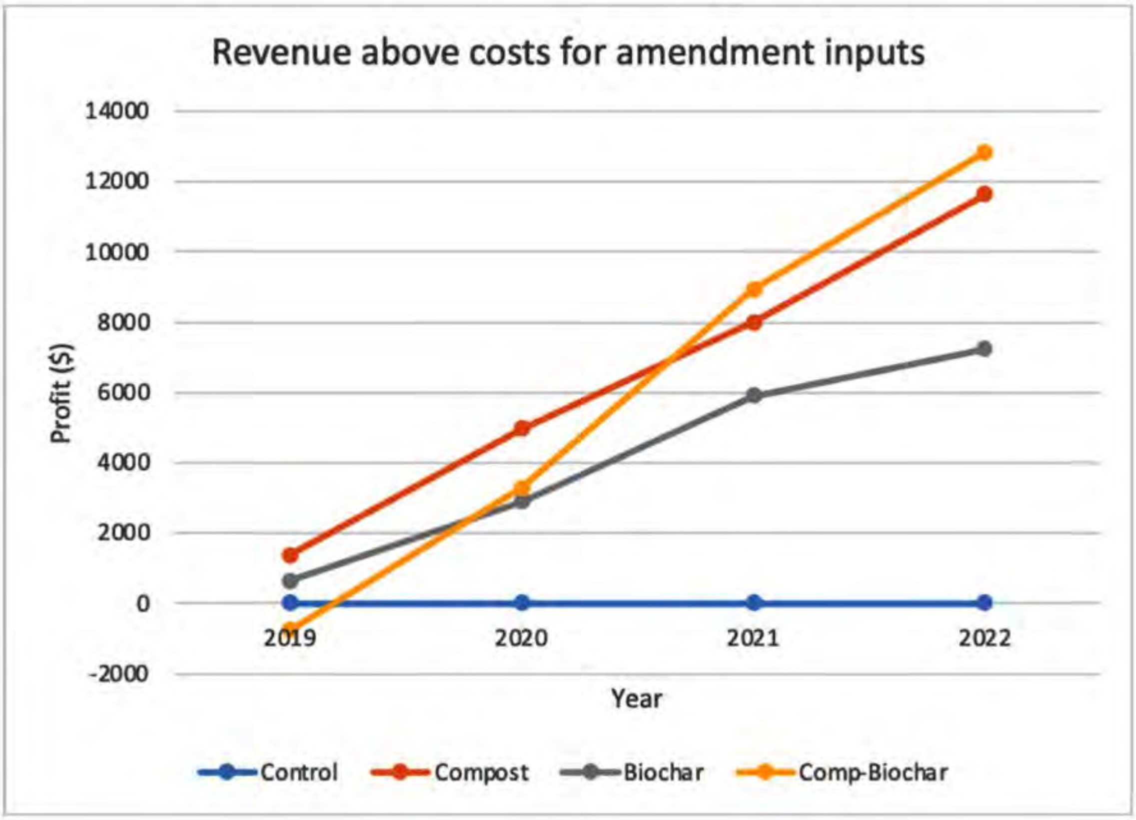


Figure 8.14 Additional revenue above costs ($/acre) for grape harvests following application of biochar, compost, and both to vineyards grown on sandy soil, King City, California, 2019-2022[12]

Case study 4: Biochar-coated seeds

Biochar can be coated onto some types of seeds (especially grass) with a binder such as lignin or bentonite (Figure 8.15). Nutrients can also be infused into the pores of the biochar to help the seeds to germinate and grow These seeds can be broadcast by hand, from a plane or tractor, subsoil-injected using seed drillers carried by a tractor, or injected from a drone (Figure 8.16).

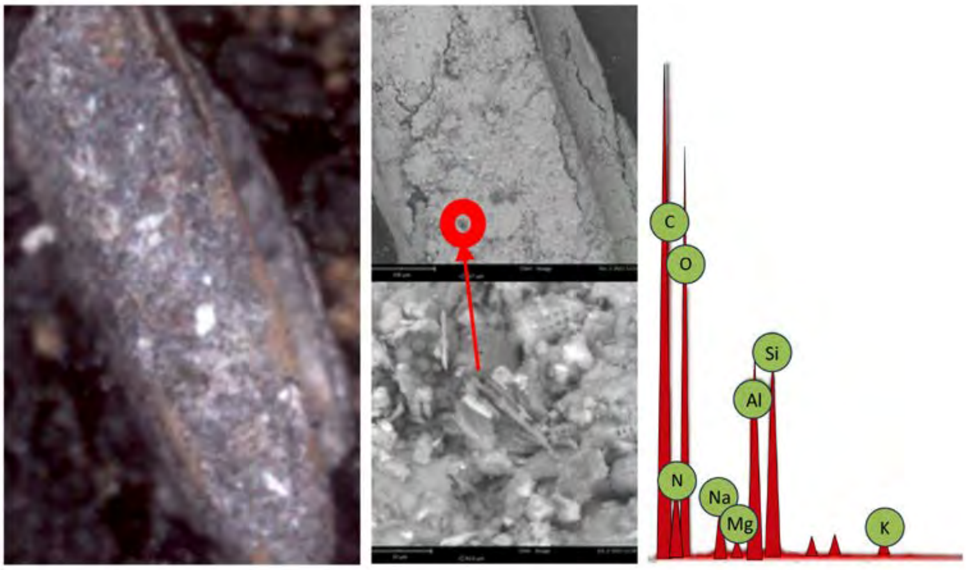


Figure 8.15 Left: Rhodes grass seed coated with a mixture of bentonite, diatomite, and biochar. **Middle:** Scanning Electron Microscope image of the coating on the seed showing tiny pieces of biochar bonded with bentonite and diatomite. **Right:** X-ray analysis of biochar indicating that it has high content of N and small amounts of Mg, Na, Cl, S, and K. Modified from Maraseeds[13]

Figure 8.16 Applying biochar-coated seeds **(left)** by hand or from a plane[14] or **(right)** from a drone[15]

Case Study 5: Biochar on green roofs

The low density and high water- and nutrient-holding capacities of biochar make it ideal as a growth substrate for green roofs and walls. A Portland State University study concluded that green roofs containing 7% biochar by weight in the soil showed significant water retention and decreases in discharge of nitrogen, phosphorus, and organic carbon.[16] Water retention of up to 100% has been reported. Biochar can also prevent discharge of copper, zinc, and aluminium that are often associated with runoff from green roofs and green walls. Overall, biochar in green roofs can improve water catchment and resilience of the green roof, while reducing drainage and improving water quality of runoff compared with both conventional roofs and green roofs without biochar. Biochar in soil is not readily combustible, so incorporating biochar may improve the fire resistance provided by a suitably planted and properly maintained green roof. Fire-activated sprinkler irrigation can further reduce risk. If considering green roofs or walls in bushfire-prone areas, confirm whether they are allowed within the bushfire attack level (BAL) applicable to their property under Australian Standards.[17]

A simple system using biochar to enhance production of plants on the top of buildings with flat roofs was developed by Rob Lerner (Figure 8.17):

1. Build beds from available material ensuring the walls of the beds are watertight, such as by using an elastomeric membrane seal. The bed depth can vary from 400 mm to 1000 mm depending on the depth to which the roots penetrate.
2. Place about 5 cm of course pumice stone or some other highly porous media on the bottom of the bed.
3. Install a 25 mm water pipe that has 10 mm long slots cut every 20 mm along the pipe on top of the pumice. The water pipe is connected to a header.
4. Make biochar from woody material at a high temperature (about 600°C). Rob used a TLUD drum oven.
5. Screen the biochar through a 1 cm sieve and then mix with the following ingredients:

biochar	16%	red pumice	6%
mixed compost	9%	white pumice	6%
mushroom compost	16%	leaf mould	9%
earthworm compost	6%	river silt	6%
goat manure	9%	decomposed bark	6%
black earth	9%		

6. Place the mixture in the bed and add crushed biochar to the top.
7. On walkways, Rob installed paving stones over a drain mat to carry away water.

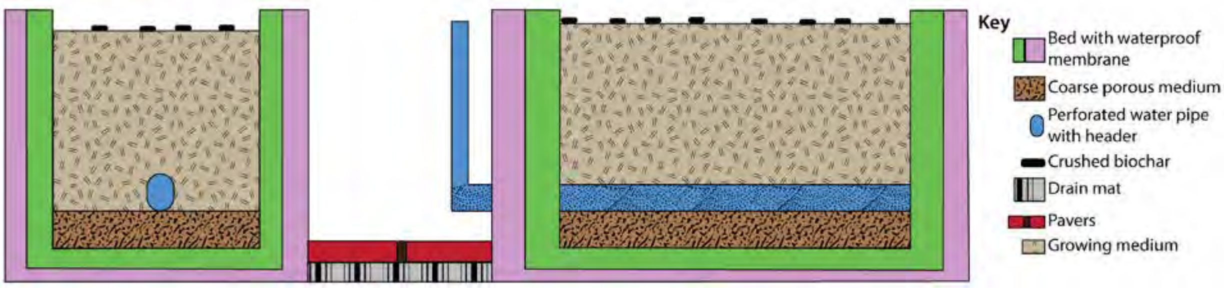


Figure 8.17 Construction of a rooftop crop bed

Case Study 6: Biochar gardens in small spaces

Hermansyah Chen, working in villages in Indonesia, developed productive biochar-based vertical gardens using recycled plastic drums (Figure 8.18). To make this simple biochar garden:

1. Cut the top from a 200-litre plastic drum and in the side use a jig saw to make five rows of straight cuts 12 cm long with five cuts to each row.
2. For shaping grow boxes at each cut, make a suitable wedge that is 9 cm wide, 20 cm long, and 2+ cm thick at one end.
3. Heat the area around a cut with a hot air blower until the area is soft.
4. Insert the thin end of the wedge into the slot and slowly make the oval shape. Use a wet cloth to cool it. Continue until the 25 pockets are shaped.
5. Take two 20-litre buckets and drill 8 mm holes every 5 cm in the vertical and horizontal directions.
6. Join the two buckets together. On the top add a filling tube that is approximately 125 mm in diameter.
7. In the barrel put 10% biochar (preferably made from a mixture of woody biomass, manure, and straw at temperatures between 400°C and 600°C) with 40% worm castings and 40% humus or forest soil. This heterogeneous mixture will allow the cultivation of many different plants.
8. Fill the middle buckets with vegetable waste and 2–5% wood biochar, along with worms.
9. Feed the worms with compatible kitchen scraps.

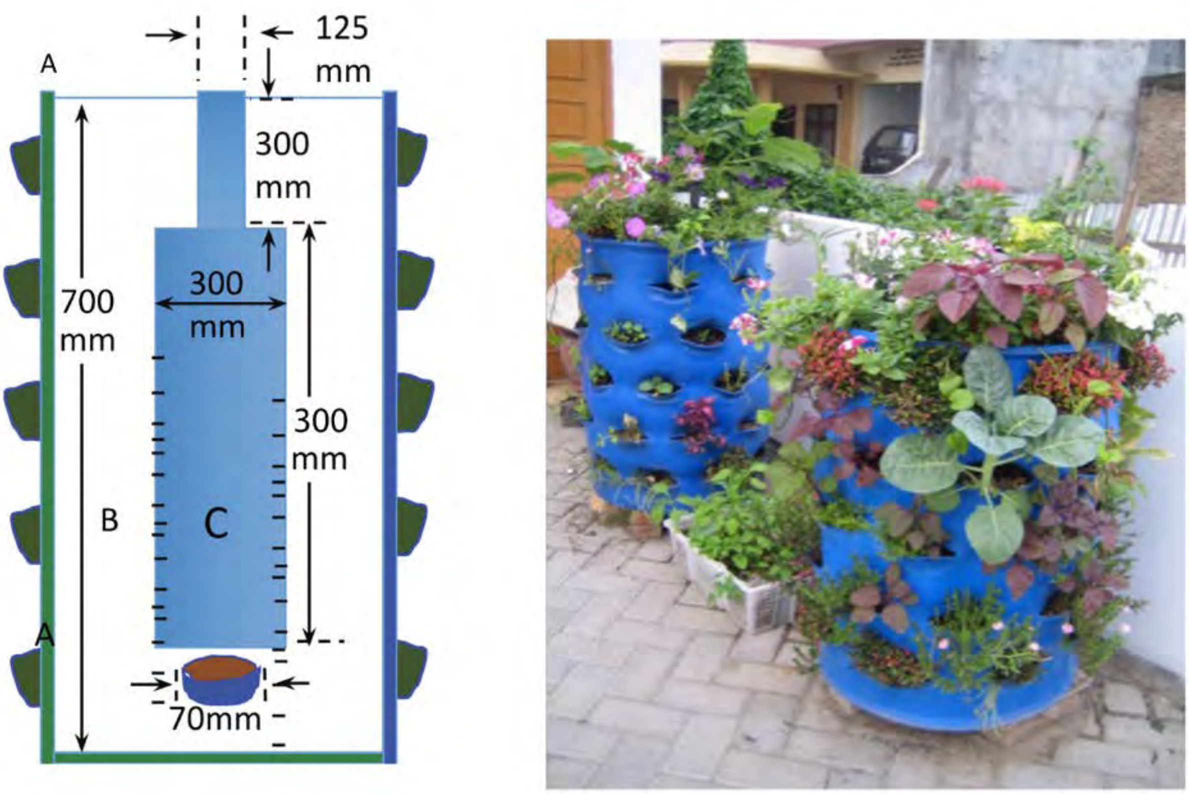


Figure 8.18 Biochar garden for a small space in Indonesia. **A**, plastic barrel with shaped pockets; **B**, soil with biochar; **C**, central buckets with vegetable scraps, worms, and biochar

CONCLUSIONS

This chapter presented practical options for applying biochar (in solid or liquid forms) to soil and as a seed-coating. They illustrate some approaches that have been taken in different settings, and the sorts of outcomes that can be obtained. Some basic rules were outlined, to help you to get the optimum benefits from plant, soil, and financial perspectives. As outlined, biochars can be applied in many ways to different crops and soils. The method, the rate of application, and the type of biochar or biochar-fertiliser combination can affect both yield and profitability. The optimum rate for yield may be different than that for profitability. We recommend that, where practical, you experiment with different methods of application to identify an option that minimises labour input and maximises financial and environmental benefit. Experiment to develop methods that are appropriate for local agricultural and cultural practices, soil constraints, and crop types. Finally, when applying biochar, remember to use safety protection equipment as recommended by local authorities.

Photo credit: Renewable Carbon Resources Australia

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Chapter 9

Case Studies

Key Points

- Different results will be obtained on different farms with different biochars, application rates, and circumstances. Each farmer should do their own trials to determine the best type and application rate of biochar to enhance their yields and profitability.
- "The more costs a production system can eliminate, the more it can afford to spend on biochar and accrue the cumulative benefits." (Doug Pow)
- Harnessing the symbiotic relationship between cattle and dung beetles to transport a nutrient-enriched biochar into the pasture soil enhances the efficacy of biochar and its application into the soil, improving the soil, plant, and animal benefits, and increasing productivity and profitability.
- While the current industrial animal agriculture makes the biggest contribution to degeneration of ecosystem services, properly harnessed it could make an important, and even the biggest, contribution to regeneration.
- High-cost biochar or high application rates of the biochar may limit the return on investment, resulting in less than 100% payback in a season. It is crucial to increase the benefit-to-cost ratio by economically sourcing the biochar, or strategically designing and producing an enhanced biochar that can be more effective at lower application rates.
- The application rate that gives highest return on investment may be lower than the rate that gives highest yield, highlighting the importance of rate-based trials to help farmers minimise the use of biochar and maximise profits.
- Too much biochar relative to fertiliser can result in a biochar that avidly seeks nutrients, depriving the plants of nutrients and growth.
- Biochar's effectiveness may improve in a second season as it ages and saturates with nutrients, underscoring that biochar can be effective for multiple seasons.
- Major cost savings in golf course irrigation in hot, arid environments, along with improvement of the turf grass and reduced fertiliser needs, showcases a powerful application of biochar that can also harness carbon and other environmental credits.
- Innovative financing mechanisms, such as capital leases, enable access to the environmental and productivity benefits of biochar while spreading out the financial cost over time.

INTRODUCTION

This chapter comprises multiple case studies, spanning individual Australian farmers' experiences in profiting from biochar use to larger-scale implementations by a government-supported project in NT and golf courses in California. The results were compiled from interviews with farmers in Australia and the producer of the biochar used in the golf courses in California. The case studies showcase diverse applications and benefits of biochar for cattle, horticulture, fertiliser improvements, soil remediation, and water savings. The six case studies are summarised in Table 9.1. Terminology is provided below it, followed by a discussion to help interpret the table about the significance of return on investment (ROI). The individual case studies are outlined in the subsequent sections.

Case study No.	1	2	3	4	5	6
Case name	**Cattle–biochar**	**Feedlot beef**	**Potatoes**	**Zucchini**	**Cucumber**	**Golf course**
Year	2015	2012–2014	2013	2013	2016–2017	2014–2019
Duration of trial	1 year (third year of trial)	2 months (in feedlot)	Season	Season Jul–Nov	14 months (two seasons)	Benefits from 6y of savings
No. or area for analysis	60 cattle	140 cattle	Hectare	Hectare	Row 25 m^2 row	Golf course (~30 ha turf)
Biochar treatment	0.33 kg/d/head (+ 0.1 kg/d molasses)	0.11 kg/d/head (in feed)	20–40% fertiliser substitution	13.25 t/ha	7 kg/row (25 m^2) single application (in 2016)	Single application
Biochar use	7.1 t	1 t	155 to 311 kg/ha	3.3 t/ha	7 kg per row	<91 t
Biochar cost/t	$120/t	$500/t	$500/t	$1,000/t	$750/t	$2200/t
Total cost of BC treatment	$850	$500				US$200,000
BC cost/unit	$14/cow	$3.60/cow	$80–160/ha	$3300/ha	$9/row (25 m^2)	US$200,000
Net benefit	$12,200 = $203/cow/y	$5,000 = $36/animal/y	$7,800/ha	$2,325/ha	$366/row (25 m^2)	US$2,000,000 (water savings)
Net benefit per tonne biochar	$1,700	$5,000	$25,000–50,000	$700	$52,000	US$22,000
User ROI	12 x	10 x	50 x	0.7 x	40 x	10 x
Payback period	1 month	~ 1 week	~ 1 week	> 1 season	~ 2 weeks	~ 6 months

Terminology

- **Biochar use and cost:** Amount of biochar, and costs to make or purchase and apply it.
- User net benefit: The sum of all benefits minus the sum of all costs of a project.
- User net benefit per tonne of biochar: User net benefit divided by quantity of biochar used.
- ROI: User net benefit divided by user cost.

Sustainability and profitability of biochar applications

The return on investment (ROI) is a crucial indicator for the farmer, who will generally desire a short-term recovery of the investment required to introduce biochar into farm practice. More than that, the farmer would prefer a profit at the end of a season, or within the year, through a consequent increase in revenue. This would enable the ongoing sustainable use of biochar for not only the short-term productivity benefits, but for the longer-term benefits that it can bring to the farm, such as building soil health or drought resilience and accessing carbon credits. If the revenue increase due to improved yield of the product is greater than the cost of introducing the biochar (ROI > 1), then ongoing use of the biochar becomes both sustainable and profitable.

As can be seen in these case studies, the duration of the investment will vary with the application. In practice, recovery of investment requires sale of the surplus product that resulted from the biochar use. For example, increasing weight gain of feedlot-beef (Case 1) required two months in the feedlot before value recovery. For the horticultural crops (Cases 3, 4, and 5), the duration of investment will be seasonal, from biochar application before sowing to sale of the produce after harvest. In Case 5, Cucumber, a single application of biochar produced a bigger increase in yield in the second year, although the payback came at the end of the first season, with a large increase in net profit in the second season. For cattle-assisted pasture enrichment (Case 2) or water and fertiliser savings in a golf-course following biochar application (Case 6), the value enhancement may continue for years and the ROI may be calculated annually, or over a period of years. In the golf course case, the water savings were assumed to continue for 6 years from a single application of the biochar.

In many cases the cost of introducing the biochar was limited to little more than the cost of the biochar itself since it was applied as part the usual fertiliser amendment on the farm. The studies demonstrate that the return on the investment was often a large multiple of the cost of the biochar, resulting in a payback and profit within the duration of the investment, or as soon as the surplus product produced by the biochar amendment was sold. Note that the biochar costs in these case studies pertain to the time of purchase (the year of the study is listed in the tables).

Instances where the increase in product value falls short of the investment call for strategic adjustments to reduce costs and optimize biochar effectiveness if the sustainable integration of biochar into agricultural practices is to be ensured. This is illustrated by Case 4, where the large application rate of biochar limited the ROI.

The Case Studies

For each case study, the background, methodology, and results are outlined. A cost–benefit analysis is presented in a table within each section. The potential impact of the study and key takeaways are summarised. It is important to understand that different results from these case studies may be obtained on other farms with different biochars, application rates, and circumstances. Ideally, each farmer should do their own trials to determine the best type and application rate of biochar to enhance their yields and profitability.

1. FEEDING BIOCHAR TO CATTLE TO ENHANCE SOIL FERTILITY AND FARM PRODUCTIVITY—Western Australia

Background

Doug Pow, a Western Australian grazier and grower, advocates for a paradigm shift in farming practices, emphasising the strategic integration of biochar into agricultural systems rather than viewing it as a mere supplement.

> "The more costs a production system can eliminate the more it can afford to spend on biochar and accrue the cumulative benefits."

Doug Pow procured 150 tonnes of biochar derived from jarrah wood, at a reduced rate of $120 per tonne. The biochar was produced by SIMCOA, Bunbury, from charcoal fines that are a by-product of silica production.

Methodology

For the cattle trial, Pow blended the biochar with molasses to replace a portion of the traditional hay-feeding regimen that he used in conjunction with pasture grazing for his cattle. The biochar was administered to the cattle at a rate of 0.33 kg per cow per day, combined with 0.1 kg of molasses. Through the ingestion by cattle and incorporation into the dung, the biochar absorbed high levels of nutrients, particularly nitrogen and phosphorus. Subsequently, dung beetles (Bubas bison) facilitated rapid processing and burial of cowpats (along with the biochar) deep into the soil profile, up to 600 mm underground (Figure 9.1).

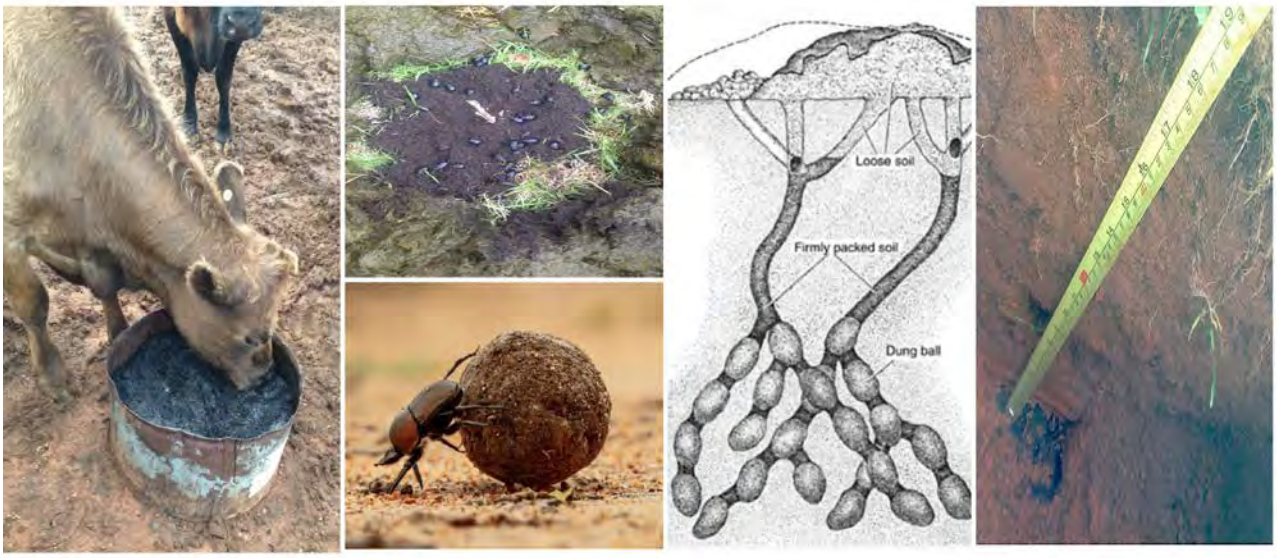

Figure 9.1 Left: Feeding cows biochar (left). **Middle:** Dung beetles attracted to biochar and dung mixture more than underlying dung pat. The beetles roll the biochar-dung into a ball and transport it into the soil, improving nutrient cycling, soil structure, and forage growth. **Right:** Dung balls found at a depth of 50 cm.

Results

The biochar feed and dung beetle ecosystem improved feed efficiency, livestock health, and pasture quality, negating the need for additional fertilisers or supplementary hay purchases. The animal weight outcomes were comparable to those before using biochar. The biochar's recalcitrant carbon structure remained intact while passing through the gut of the animal and being sequestered by the beetles. Preliminary soil analysis indicated there was an increase in non-biochar soil carbon.

Cost–benefit analysis

The overall effect was a significantly boosted profitability. The biochar utilisation amounted to 7.1 tonnes annually, generating a net benefit of at least $12,200 (depending on the practice of hay production) for Pow's herd of 60 cows, or $1,700 per tonne of biochar.[1]

Case study 1	Cattle–biochar
Year	2015
Duration of trial	1 year (third year of trial)
Number of cattle	60 cattle
Biochar treatment per head per day	0.33 kg + 0.1 kg molasses
Biochar use	7.1 t (for 60 head for 1 y)
Biochar cost/tonne	$120/t
Total cost of BC treatment	$850
BC Cost/unit	$14/head
Net benefit	$12,200 = $203/head/y
Benefit per tonne biochar	$1,700
User ROI	12 x
Payback period	1 month

Impact

Dung beetles roll the dung into a ball with clay and take it up to a metre deep into the soil, thus helping to protect the organic matter and stabilising the carbon. The innovative approach of this case study harnessed the symbiotic relationship between cattle and dung beetles to transport a nutrient-enriched biochar to the pasture soil, creating user value at both stages without added labour or expenses, all contributing to increased profitability. Among all the case studies, this one had the biggest impact in terms of overall improvement on the farm. It highlights the potential of biochar utilisation in livestock management, showcasing its ability to enhance farm profitability while promoting regenerative agricultural practices. While the current industrial animal agriculture makes the greatest contribution to degeneration of ecosystem services, properly harnessed it could make an important, and even the biggest, contribution to regeneration.

Key Takeaways

The strategic integration of biochar into the farming system achieved its benefits of reducing costs and increasing profitability, in multiple ways:

- Accessing biochar from affordable sources contributed to the overall profitability
- Adding biochar to the traditional feeding regimens resulted in cost savings and improved animal performance
- Leveraging natural processes, such as dung beetle activity, further enhanced the efficacy of biochar in soil enrichment and nutrient cycling

Consider cascading the use of biochar on your farm beyond its initial use, maximising its utility and benefits.

2. ENHANCING FEEDLOT CATTLE WEIGHT WITH BIOCHAR FEED ADDITIVE—Northern New South Wales

Background

Biochar has shown promise in increasing cattle weight.[2,3] To explore this potential further within an Australian context, a feedlot beef cattle agriculturalist in northern New South Wales conducted a trial to assess the effect of biochar on weight gain. A jarrah wood biochar from SIMCOA was transported from Western Australia to New South Wales, at a total cost of $500 per tonne.

Methodology

The trial utilised two feedlot pens, each capable of accommodating approximately 140 cattle. In one pen, cattle were fed a control diet of wheat straw for fibre along with a standard milled-grain feed mix composed of barley (75%), canola meal (6–10%), soya meal (4–6%), and various salts and additives. In the other pen, cattle received the experimental treatment, being the same wheat-straw and milled-grain feed mix with the addition of 1% biochar, balanced by a 1% reduction in barley grain (by weight). At the trial's onset, eighteen young cattle previously on a grass and hay diet were introduced to each of the pens and monitored for weight. The cattle in the experimental pen were acclimated to the biochar blend feed mix two weeks prior to the trial measurements to ensure that the animals accepted the biochar amended feed and that their digestive system adjusted to the change. Throughout the trial period, all cattle had unrestricted access to both the grain feed mix and wheat-straw hay.

Results

The results (in Figure 9.2) show that over the two-month trial period, cattle treated with biochar gained an average of 11.2 kg more than those on the standard feed ration, representing an improvement of 10.4%. In a full pen it was observed that five or six animals out of 140 who were fed biochar did not consume the biochar-grain mix, approximately double the number of cattle that rejected the control mix. Researchers suggested that the reduced attractiveness of the biochar mix to the cattle could have been due to the biochar diminishing the odour of the grain mix, which otherwise exhibits a stronger grain aroma that may attract the animals.

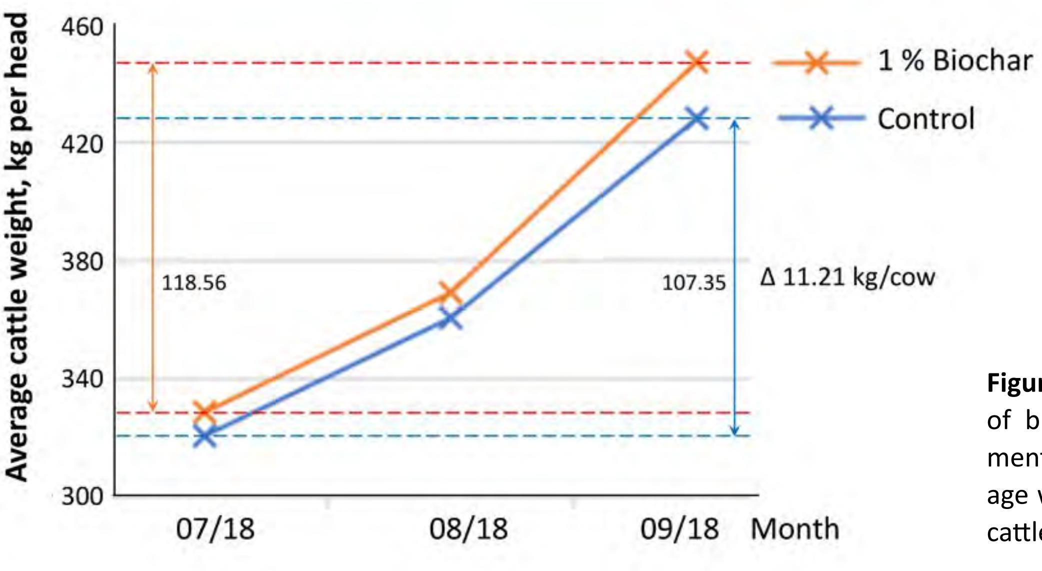

Figure 9.2 Influence of biochar 1% supplement in feed on average weight per head of cattle

Cost–benefit analysis

A cost–benefit analysis was carried out for a full feedlot pen of 140 animals. During a two-month trial period the cattle consumed on average 11 kg of feed per day containing 1% or 0.11 kg of biochar. In aggregate, 140 head of cattle consumed close to one tonne of biochar in the two months at a cost of $500. The 11.2 kg weight increase aggregated to 1568 kg for the feedlot. At a live-weight sale price of $3.50/kg the revenue increase was $5,500, resulting in a net benefit of $5,000. The net return was therefore $5,000 per tonne of biochar, and the return on investment was ten times.

Case study 2	Feedlot beef
Year	2012–2014
Duration of trial	2 months in feedlot
Number of cattle for trial	18 cattle
Number for cost-benefit analysis	140 cattle
Biochar treatment in feed	0.11 kg/head/day
Total biochar use	1 t
Biochar cost/t	$500/t
Total cost of biochar application	$500
Biochar cost/unit	$3.60/cow
Net benefit	$5,000 = $36/head/y
Benefit per tonne biochar	$5,000
User ROI	10 x
Payback period	6 days

Impact

This study focused solely on weight gain, and not on other aspects of animal health which can benefit from biochar use. The data provided did not specify whether the weight difference average was statistically significant. Nonetheless, this result aligns with anecdotal information from other beef cattle agriculturalists who used biochar as a feed supplement.

Key Takeaways

- Including biochar in animal feed in a way acceptable to the animals can lead to a 10% weight gain over two months.
- The net profit created was $5,000 per tonne of biochar, with a ROI of 10 x.

3. BIOCHAR IMPROVED POTATO YIELD AND PROFITABILITY—Ballarat

Background

In late 2013, a field trial was conducted on a Ballarat farm, situated in the red ferrosols renowned for potato cultivation, to assess the efficacy of a mineral-enhanced biochar in improving Nadine seed potato yields while partially replacing the standard NPK fertiliser regime. The seed potato needs to be of a uniform small size (between 50 and 150 grams, smaller in this range being better).

Disease resistance needs to be high and input costs low. The ratio of potassium to magnesium and calcium influences the resistance of potato plants to diseases. Phosphorus and adequate moisture levels, particularly around the time of emergence (7–14 days after planting) and within the following three weeks, are crucial in tuber setting. The biochar was designed to meet these requirements and improve fertiliser efficiency.

Methodology

Biochar was produced using a mixture of wheat straw and poultry litter (hardwood sawdust and manure) as feedstock (approximately 85%) mixed with crushed basalt, wheat-straw ash and lucerne micronutrients (10%), and clay material (5%).

Material	% Dry weight
Wheat straw	60%
Poultry litter	25%
Wheat straw ash	5%
Basalt dust	4%
Lucerne micronutrients	1%
Bentonite/iron-bearing kaolinite	5%

1. Make ash by taking the biochar from the pyrolyser at 350°C, wet and add finely ground basalt and micro-nutrients,
2. Mix and make into a fine slurry. Add clay,
3. Coat straw and chicken litter and allow to dry slowly,
4. Pyrolyse at 425°C–450°C,
5. Adjust pH to 7.5 with 50% solution of phosphoric acid,
6. Mix NPK and biochar and allow to stand in bag for 2 weeks.

Following pyrolysis at approximately 450°C, the biochar was conditioned with phosphoric acid to achieve a pH of 6.8, then dried in open air until moisture levels reached 8% of the dry weight. This acid-activated, mineral-enhanced biochar was then mixed at various ratios with a chemical fertiliser that had 7% N, 14% P, and 14% K, then left in bags for two weeks to allow the NPK to react with the biochar to produce a biochar compound fertiliser. Trials were performed with the mineral-enhanced biochar at 2.5%, 5%, 10%, 20%, 40% substitution for fertiliser by weight (e.g. 40% biochar/60% NPK). All the treatments were applied at 778 kg/ha. The treatments were applied in approximately 50 mm bands below and to each side of the potato seed. Application and the subsequent harvesting were carried out using the cooperating grower's equipment.

Results

At harvest in the fourth month, it was observed that the 20% biochar substitution yielded the highest total crop yield and highest tuber productivity per plant (Figure 9.3). Biochar application at this rate improved the total potato yield per hectare from 38.8 tonnes to 58.1 tonnes, an increase of 19.3 t/ha, or a remarkable 50%. However, seed potatoes meeting the required weight for sale (≤120 g) showed the highest yield at 40% replacement (29.3 tonnes/ha, relative to a control of 17.0 t/ha). In this case the increase was 12.3 t/ha (72%).

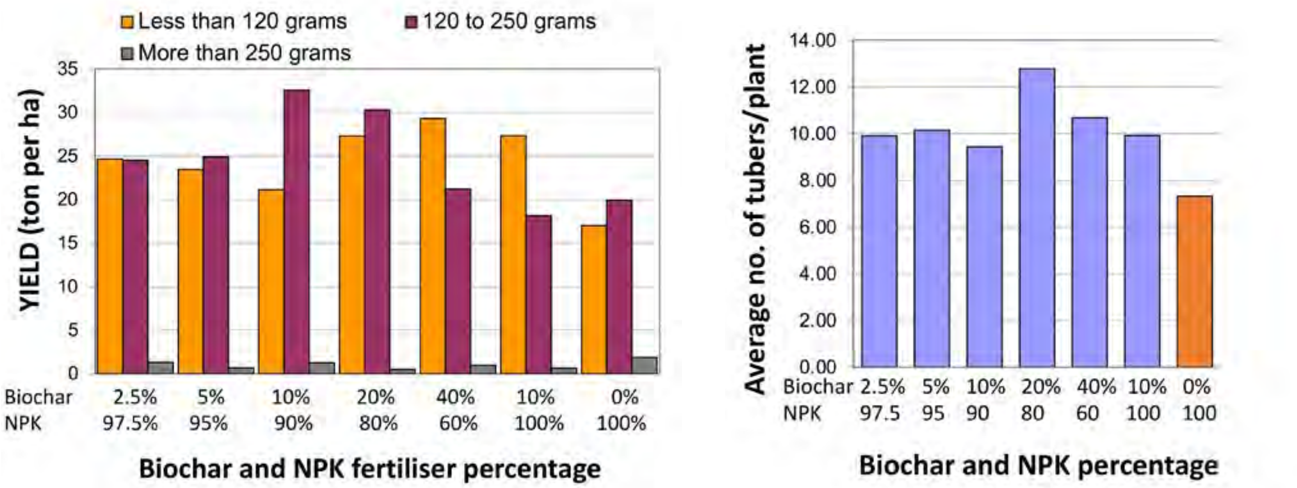

Figure 9.3 Left: Potato yield per hectare with differing biochar and NPK combinations for different potato size ranges. The control was 100% NPK, 0% biochar; a trial was also run with 100% NPK and 10% biochar. **Right**: Average number of tubers per plant for the same biochar–NPK combinations.

Cost–benefit analysis

At 40% biochar substitution the biochar application rate was 311 kg/ha, costing \$160/ha (biochar at \$500/tonne). At a seed potato price of \$650/t, the resulting yield improvement of 12.3 t/ha led to an increase in farmer revenue of \$8,000 and a net benefit of \$7,800 per hectare.

Case study 3	Potatoes
Year	2013
Duration of trial	Season
Area for trial	12.5 m^2 x 12 rows total
Area for analysis	Hectare
Biochar treatment	20–40% fertiliser substitution
Biochar use	155 to 311 kg/ha of biochar
Biochar cost/tonne	\$500/t
Biochar cost/unit	\$80–160/ha
Net benefit	\$7,800/ha
Benefit per tonne biochar	\$25,000–50,000
User ROI	50 x
Payback period	<1 month

Impact

The acid-activated biochar-mineral complex has the ability to bind both cations and anions that exist in the chemical fertiliser. This results in much slower release of nutrients and reduced loss of nutrients due to leaching and volatilisation. The biochar itself has water-soluble organic compounds that are similar to those found in wood vinegar, as well as other compounds that are similar to humic acids. Infusing the biochar pores and surfaces with chemicals and minerals results in products that outperform both commercially-available slow-release fertilisers and non-enhanced biochar products, making the resultant products economic prospects for use in cereal agriculture.

Despite the limitation of a small number of replicates and the absence of soil or plant tissue analysis, the substantial improvements in potato yield and economic gain highlight the potential of biochar-mineral-fertiliser complexes as sustainable and cost-effective fertiliser alternatives.

Key Takeaways

- Overall, the biochar application increased potato yield per hectare by 50%.
- The net profit increased by $8,000 per hectare.
- Trials uncovered a non-intuitive outcome: an application rate double the rate that produced maximum tuber mass yield, produced greater net profit in the farm's main product due to selectively enhancing the yield of more profitable seed potatoes.
- This underscores the importance of preliminary trials to find the optimum biochar and application rate for the particular crop and conditions.

4. BIOCHAR IN HORTICULTURE: ZUCCHINI—Northern Territory

Background

Territory Natural Resource Management (Territory NRM) collaborated with Earth Systems Bioenergy and Hu Organics in 2013 to explore the potential benefits of incorporating biochar into zucchini cultivation in the Northern Territory (NT). The trial took place at an organic farm in Lambells Lagoon, 56 km southeast of Darwin, during the late dry season over a period of four months (July to November 2013). The farm featured kandosols and sandy loam soils, and the trials were designed to examine the effects of biochar on crop yield of zucchini and on soil characteristics.[4]

Methodology

The biochar was produced from pine feedstock from Victoria using the CharMaker MPP20, which is a mobile pyrolysis plant made and supplied by Earth Systems. The mobility of this plant, and its ability to process chunk wood, obviated the cost and time involved in processing feedstock and transporting it to the pyrolyser. The chunk biochar was ground to a size suitable for horticulture, premoistened, and applied with a spreader in 0.5 m wide strips 100 metres in length. The biochar was then harrowed into the soil to 10–15 cm of depth, along with the control fertiliser. The control fertiliser consisted of the components listed in the box.

Control fertiliser components	
Pelletised poultry manure	8000
Crushed rock dust	400 kg/ha
Micronised lime	200 kg/ha
Guano	180 kg/ha
Potassium sulphate	250 kg/ha
Stabilised boron humate granules	20 kg/ha
Plant inoculants of arbuscular mycorrhizal fungi microbial input, post emergence	

The dry-weight biochar application rates were 5.3, 13.25, and 21.2 tonnes per hectare (approximating per plant rates of 0.25 kg, 0.65 kg, and 1 kg respectively) and a control with no biochar was established. All plots received the same fertiliser as the control. The trial plot layout consisted of eight 100 m x 0.5 m rows, with each row divided into two units resulting in 16 units of 25 m^2. The three application rates and the control were replicated four times by assigning them randomly to the 16 plots. After planting in the amended plots, the zucchinis were managed to standard organic farm practices, including regular nutrient fertigation, foliar applications, and irrigation twice daily, through a dripline system.

Results

Figure 9.4 illustrates that the 13.25 tonne per hectare biochar application rate yielded a 25% increase in yield compared to that of the control group. Notably, both lower (5.3 tonnes biochar per hectare) and higher (21.2 tonnes biochar per hectare) applications produced slightly lower yield numbers than the control (although this trial included no statistical analysis to indicate significance).

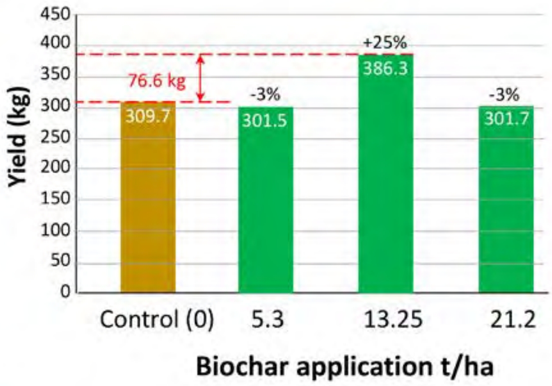

Figure 9.4 Zucchini field trial (left). Zucchini yield as a result of each trial amendment (right). The 13.25 t biochar rate produced a 76.6 kg or 25% increase in yield (2013)

Cost–benefit analysis

The yields reported in Figure 9.4 are from the total of 100 m^2 planted for each amendment in the trial (4 units x 25 m^2). Assuming 50% of a hectare was in zucchini rows, the reported control yield of 309.7 kg in 100 m^2 of rows corresponds to a control zucchini yield of near 15 t/ha. This is consistent with NSW Dept of Primary Industry published yield range of 12–18 t/ha.[5] Assuming this control yield of $15 t/ha, an increase of 25% at a price of $1,500/tonne translates to a revenue increase of $5,625 on 3.75 tonne zucchini. Assuming that the application of biochar to the rootzone equated to application to ½ the cultivated area, or ¼ of the entire hectare, a biochar dose of 3.3 tonnes was required, at a cost of $3,300. The net benefit was therefore $2,325, or $700 per tonne of biochar, and the ROI was 70%.

Case study 4	Zucchini
Year	2013
Duration of trial	Season, Jul–Nov
Area for trial	50 m^2 row x 4 per treatment
Area for analysis	Hectare
Biochar treatment	13.25 t/ha
Biochar use	3.3 t/ha
Biochar cost/t	$1,000/t
Biochar cost/unit	$3300/ha
User net benefit	$2,325/ha
Benefit per tonne biochar	$700
User ROI	0.7 x
Payback period	> 1 season

Impact

The net benefit per tonne of biochar was limited by the high application rate and high price of the biochar, resulting in less than 100% payback for the season. This underscores the importance of economically sourcing the biochar, or strategically designing and producing an enhanced biochar that can be more effective at lower application rates. Either strategy, or the combination, could greatly increase the benefit-to-cost ratio.

Key Takeaways

- It is important to do trials to find a beneficial application rate.
- Biochar application at a rate of 13 tonnes per hectare resulted in a 25% yield surplus compared to the control in zucchini, while higher and lower rates resulted in no effect.
- The farmer observed a significant improvement in health, size, and appearance of the zucchini plants and fruit, highlighting the holistic benefits of biochar utilisation in agriculture

5. ENHANCING CUCUMBER PRODUCTION WITH POULTRY LITTER BIOCHAR—Geraldton, Western Australia

Background

A cucumber farm near Geraldton had subsoil dominated by highly leached sand with poor nutrient retention capacity. In 2016, a collaborative trial with Energy Farmers Australia (EFA) was initiated to investigate the application of poultry litter biochar to improve soil health, nutrient availability, plant health, and yield in a cucumber horticultural system (Figure 9.5).[6]

Figure 9.5 Left: Poultry litter biochar applied in rows in 2016. **Right**: Cucumber harvesting

Methodology

Energy Farmers Australia produced biochar from poultry litter, aiming to reduce nutrient runoff and enhance nutrient uptake in crops. A chemical analysis of the biochar used in 2016 is shown in the box. The trial involved applying biochar at different rates along with varying levels of starter fertiliser to cucumber plants. The trial's aim was to assess the effects of both low and high rates of biochar application combined with both high and low rates of starter fertiliser (T1, T2, T3, T4), along with treatments of biochar only (T5, T6), and fertiliser only (the controls) as shown in Table 9.2.

Characteristic	Value
pH (H_20)	9
pH ($CaCl_2$)	8.5
EC (mS/cm)	7.7
Total C	38.8
C–N Ratio	10.6
Total N	3.7
P %	2.53
K %	2.8

Table 9.2 Treatments and costs in 2106 for cucumber production with poultry litter biochar. PLB – Poultry Litter Biochar, NP – Nitrophoska, CPM – Compound Poultry Manure. Costs based on: $750/t for PLB and CPM, $1000/t NP. Treatments are indicated as low, high, or very high biochar (LB, HB, VHB) + low or high fertiliser (LF, HF)

	Kg per row			$ per row			Total cost
kg/row	**PLB**	**CPM**	**NP**	**PLB**	**CPM**	**NP**	**$/row**
T1 (LB+HF)	7	9	5	5	7	8	**20**
T2 (HB+HF)	13	9	5	10	7	8	**25**
T4 (LB+LF)	7	1	2	5	1	3	**9**
T5 (HB+LF)	13	1	2	10	1	3	**14**
T3 (HB)	13			10			**10**
T6 (VHB)	33			25			**25**
Control	0	9	5		7	8	**15**

After applying the base fertilisers, the biochar was applied with a small fertiliser spreader and incorporated into the soil by rotary hoe. Cucumbers were managed as part of normal farming operations. Recording sheets were installed at the end of each row and a set of scales was supplied. During the harvest period, cucumber weights were recorded for each treatment. In the 2016 season, the biochar was laid down in mid-March with the cucumber seedlings planted in early May. In the 2017 season no additional biochar was applied, and the cucumber seedlings were planted in late April. However, the farmer did apply 5 kg/row of CPM (starter fertiliser) across the whole farm as a base.

Results

The trial results, shown in Figure 9.6, demonstrate higher cucumber yields across the board in 2017 compared with 2016, which may be related to other factors than the treatments. Notable differences in yield were observed among different treatments. Treatments T1, T2, and T4 outperformed the controls in both seasons. In the 2017 season, Treatment T4 with low biochar and low fertiliser gave the highest yield of cucumbers, at 1,205 kg per row. Across the two seasons Treatment T2, with high fertiliser and high biochar, was the best performer. T1, with high fertiliser and low biochar, also performed well. Notably, the high biochar with low fertiliser combination and the biochar-only applications (i.e. T5, T3, and T6) underperformed the control, likely because the biochar was insufficiently loaded with nutrients and competed with the plant for the available nutrients.

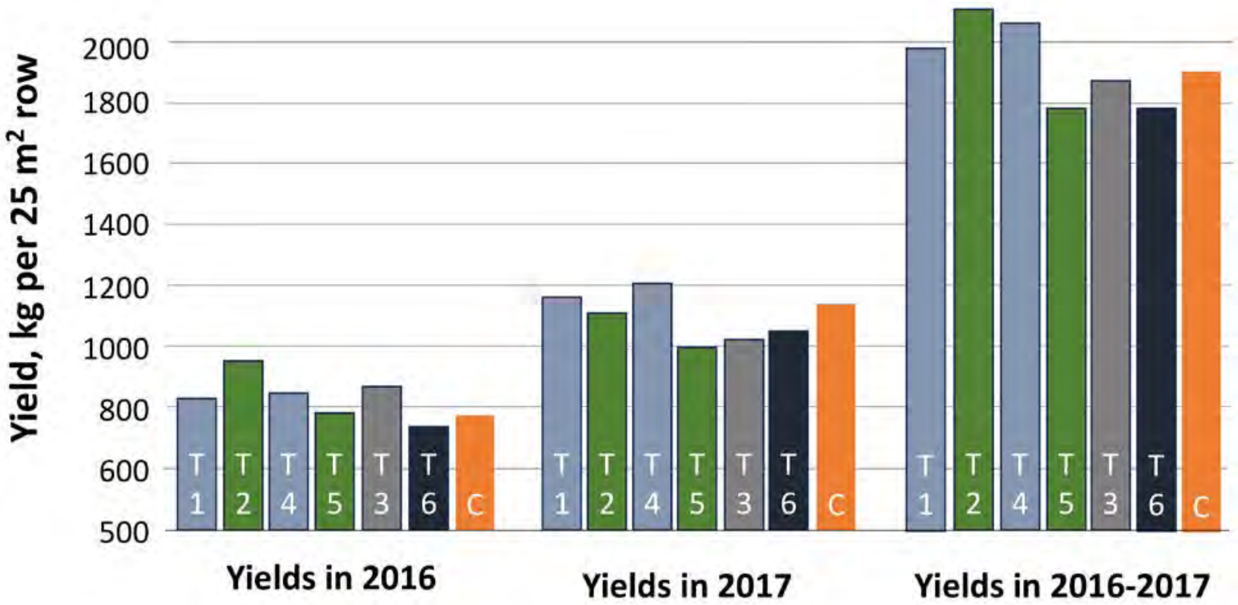

Figure 9.6 Cucumber yields in kg per row for the 2016 and 2017 seasons, and the combined yield. The treatments, T1 to T6, have varying rates of biochar and fertiliser as shown in Table 9.2. The control (C, shown in orange) has no biochar. Note: The base of the vertical axis is 500.

Cost–benefit analysis

T1, T2, and T4 created significant net user benefit over the control, as shown in the Table below. Treatment 2 with the high biochar and high fertiliser produced the greatest net return per row. However, Treatment T4 with a low rate of both biochar and fertiliser was the cheapest treatment and gave the biggest net return per kg of biochar and best return on investment. The costs of biochar and fertiliser for the various treatments are given in Table 9.2, and the ROI for this case study is computed on the investment in biochar plus fertiliser. The ROI would be greater if attributed to just the biochar investment.

Cucumber (2016-2017)	Biochar used/row (fertiliser cost)	Net benefit per row	Net benefit per kg of biochar	ROI on fertiliser cost
Treatment T1	7 kg ($21)	$188	$27	9 x
Treatment T2	13 kg ($25)	$498	$38	20 x
Treatment T4	7 kg ($9)	$366	$52	40 x

Impact

The poultry litter biochar trial demonstrated its potential to improve soil health, nutrient availability, and cucumber yield in sandy, nutrient-deficient soils. By enhancing fertiliser efficiency and reducing nutrient runoff, the biochar contributed to sustainable agricultural practices.

Key Takeaways

- The application rate that gave highest return on investment was lower than the rate that gave highest yield, highlighting the importance of rate-based trials to help farmers minimise the use of biochar and maximise profits.
- Too much biochar relative to fertiliser can result in a biochar that avidly seeks nutrients, depriving the plants of nutrients and growth.

6. GOLF COURSE—California

Background

Colorado-based company Biochar Now has pioneered the production of high-carbon biochar using slow pyrolysis in batch kilns over 8 to 10 hours. In collaboration with golf courses in southern California, Biochar Now's forest-waste biochar product was trialled (during 2014 to 2019) to improve water retention in turf grasses, particularly in the sandy, coarse-textured soils prevalent in the region. The aim was to reduce water consumption costs and minimise environmental impact.

Methodology

To overcome dust challenges, Biochar Now developed a pelletised biochar product. For the trials, this was applied by golf course managers at a rate of 2% of soil weight (dry basis) at the root zone of the turf. Following application, the golf courses were watered as usual for one week, after which watering was reduced.

Results

The trial demonstrated a large reduction in water usage, of 30–65%, enabled by the biochar's capacity to hold six times its weight in water. This was accompanied by improved turf grass growth and reduced fertiliser use. These beneficial effects will persist over time without issues of biochar decomposition or translocation by erosion. The high-carbon biochar produced by Biochar Now showed remarkable longevity, boasting a half-life of 17,000 years, according to laboratory trials.

Cost–benefit analysis

The raw product produced by Biochar Now was sold to golf courses for $2,000–6,000 per metric tonne. The biochar was applied at a rate of around 2% in the root zone. The overall cost of applying the biochar to typical golf courses ranged from $100k to $200k. Golf courses in popular residential and tourist destinations such as Palm Springs can consume 1 million gallons of water per day at a cost of 0.5 to 1 million USD annually. The investment in biochar application, while initially expensive, yielded substantial financial benefits, with savings ranging from $300k to $500k/year in irrigation costs, resulting in a payback of approximately 6 months. The water-saving benefit was assumed to continue for six years. The overall net benefit presented in the summary table below was based on the lowest-performing golf course (where the applied biochar cost $200,000 and the water savings were 30%). Much higher returns on investment were found in the best-performing trial (which had the lowest application cost of $100,000 and produced a 65% savings).

A financing option was arranged for the golf courses to facilitate investment in biochar application for more golf courses. The capital lease provided for the financiers to receive their capital and interest back at an Internal rate of return (IRR) of 30–40%. At the conclusion of the lease, the golf course received the on-going savings. The lease arrangement produced slightly lower user net benefits than a non-financed investment, as shown in the table.

Case study 6	**Golf course**	
Year	2014–2019	
Duration of trial	Benefit from 6 y of water savings	
Area for trial	Golf course (~30 ha turf)	
Area for analysis	Golf course	
Biochar treatment	Single application	
Biochar use	<91 t	
Biochar cost/t	$2200/t	
Finance option	**None**	**With financing**
Total cost of BC treatment	US$200,000	$0
User net benefit	US$2,000,000	US$1,600,000
Benefit per tonne biochar	US$22,000	US$18,500
User ROI	10 x	No investment
Payback period	6 months	0 months

Impact

The successful implementation of biochar in golf courses highlights the potential for biochar to enhance water efficiency and reduce environmental impact in turf grass management. The utilisation of biochar not only resulted in substantial cost savings but also contributed to improved turf grass health and growth. Revenues from carbon credits were elusive at the time of the trials due to compliance costs. However, the methodology framework for obtaining carbon credits from biochar is improving rapidly, unlocking additional economic opportunities in the carbon market. This US golf course case study demonstrates a novel biochar use that has many applications in both Australia and New Zealand and will grow in importance as global warming increases.

Key Takeaways

- Biochar demonstrates effectiveness in improving water retention capacity in turf grasses, leading to significant reductions in water and fertiliser usage.
- Innovative financing mechanisms, such as capital leases, can enable access to the environmental and productivity benefits of biochar while spreading out the financial cost over time.
- Continued research and development efforts are crucial to further enhance the understanding and application of biochar in sustainable agriculture and land management practices, and to achieve them cost effectively.
- Income from carbon credit programs will boost the profitability.

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Chapter 10

Biochar in regenerative agriculture and carbon draw down

Key Points

- Using biochar in regenerative agricultural practices can reduce the time and costs involved in transforming degraded soils into productive ‘land.
- The use of biochar can be integrated into animal husbandry to improve animal health, reduce odours and greenhouse gas emissions, and increase pasture productivity.
- Feeding biochar to ruminants can be combined with the introduction of new species of dung beetles to further process the biochar and move it deep into the soil profile. The biochar balances the manure and makes it more attractive to the dung beetles, which are harmed by toxins, antibiotics and worms.
- Applying biomass, compost, minerals, wood vinegar, and biochar in trenches and around trees in char wells can boost growth of plants and their resistance to disease.
- Producing biochar on the farm from on-farm residues then using the energy from the pyrolysis gas on the farm and integrating photo-voltaic energy systems can boost farm profitability and shrink its greenhouse gas footprint.
- Applying liquid biochar-organic compound fertiliser to existing pasture can greatly increase growth in low season.
- Integrating Indigenous fire-management practices with application of biochar could reduce the damage caused in bush fires.

INTRODUCTION

Biochar can serve a pivotal role in regenerative agriculture, which aims to restore soils and enhance biodiversity, while securing farmer prosperity. Integrating biochar into this approach is relatively new but offers significant benefits. It kickstarts soil regeneration and maintains soil health and productivity over time. Persistent use of biochar also taps into additional soil benefits, such as water-holding capacity, that accrue with higher levels of biochar in the soil. It leads to the accumulation of both stable and available carbon in the soil, thereby expanding the values associated with carbon credits, ecosystem services, biodiversity, and resilience to drought and climate change. In this chapter, we explain how biochar can be integrated into regenerative agriculture and highlight its benefits for both farms and farmers through selected examples and case studies.

BENEFITS OF BIOCHAR IN REGENERATIVE AGRICULTURE

Integrating biochars into regenerative farming initiatives can aid the success and longevity of the transition from conventional agricultural practice by reducing costs, increasing the quantity and quality of the farms output, improving resilience, and ensuring higher profitability.[1,2,3] Not all biochars will be effective in a specific regenerative initiative. Biochars need to be designed, formulated, and tested at various application rates for effectiveness and profitability in the context of the specific soils, crops, constraints, and climate conditions on the farm. As detailed in Chapter 8, biochars can exhibit hormetic dose-response relationships, being effective at an optimal application rate, ineffective at too low a rate, and even deleterious to crops and soil, or unprofitable, at too high a rate. Therefore, application rates can be as important as the design of the biochar. We will call biochar that is strategically targeted and applied at an effective rate, fit-for-purpose (FFP) biochar.

Applying liquid and solid FFP biochar, biochar-organo-mineral complexes (BOMC) and biochar compound fertilisers (BCF) can assist and promote a regenerative transition through their ability to:

- Catalyse the build-up of soil carbon
- Promote the abundances of growth-promoting microbes
- Enhance soil water-holding capacity
- Improve nutrient-use efficiency
- Increase resistance to disease and other environmental stresses such as high temperatures
- Reduce nutrient runoff and loss
- Mitigate greenhouse gas emissions
- Reduce soil toxicities
- Act as a barrier to the ingress of water that has a high content of salt or toxic substances
- Control weeds and pests (using wood vinegar)
- Drawdown atmospheric water and reduce risk of severe fires
- Incorporate and add value to farm and local residues, wastes, and resources

These attributes of FFP biochar combine to support:

Improved soil health—fostering overall soil vitality and farm resilience.

Enhanced crop performance —improved crop yield, quality, disease resistance, and resilience to environmental stressor, ensuring robust agricultural output.

Reduced external inputs—increasing nutrient retention, availability, and efficiency, as well as reducing nutrient losses, significantly diminishes the need for external inputs such as fertilisers and agrochemicals, and promotes a more self-sufficient farming system.

Mitigated environmental impact—reducing greenhouse gas emissions, nutrient runoff and loss, and soil toxicities, contributing to environmental sustainability, which will be increasingly valued and rewarded by society.

Weeds and pest management—the use of wood vinegar, in conjunction with reduced inputs of other herbicides, can reduce losses and expenses and increase pasture and crop yields. In particular, reducing the use of certain chemicals allows growth-promoting microbes to rebuild.

Water management—most biochar produced at temperatures over 450°C–500°C acts as a barrier to water with high-salt or toxic-substance content, facilitates the absorption of atmospheric water, and may reduce the risk of severe fires, thus aiding in effective water-management practices.

Waste management—biochar is best made from agricultural residues (noting that biochar production should be balanced against other beneficial uses of agricultural residues, such as composting and mulching). Combining biochar with mineral wastes and composting or feeding to animals enhances its properties.

Restoration of degraded land—degraded land on farms and elsewhere can be regenerated for ecosystem services and food and fibre production, making a major contribution to farm resilience and indeed to overall planetary resilience.

Improved profitability—incorporating biochar into regenerative agricultural practices can increase farmer profits, particularly when the biochar is produced on-farm from agricultural residues, thereby minimising production costs and maximising returns.

The financial benefits of incorporating take many forms, including those accruing from reduced input costs, increased crop yields and quality, improved disease resistance, increased drought, fire, and climate change tolerance, improved fertility, land remediation, water remediation, pollution control, heat and energy production, and carbon credits. Other environmental credits will be monetisable in the future as their value is recognised by society. Even now, pro-environmental actions are beneficial in terms of good-will they generate within the farm's network of customers and community relations.

All these benefits underscore the transformative potential of FFP biochar in regenerative agriculture. Incorporating FFP biochar in regenerative agriculture offers a sustainable pathway towards soil rejuvenation, biodiversity conservation, and agricultural prosperity.

INCORPORATING BIOCHAR IN REGENERATIVE AGRICULTURE

Biochar can be incorporated into regenerative farming systems by manifold methods, some quite innovative. Here we gather a few of the many ways of using biochar that were introduced in other chapters.

Seed coating: Mixing biochar with many types of seeds before sowing at the optimal rate improves germination rates and seedling establishment. Biochar's moisture-retention capabilities create favourable conditions for seedling growth without necessitating additional equipment or processing steps.

Enhanced nutrient delivery: Supplementing biochar with microorganisms and nutrients, such as those found in compost tea, worm juice, feather meal, algae, seaweed, fish extract, and manures, further amplifies its benefits. This combination not only enriches the soil but also fosters microbial activity, promoting nutrient cycling and soil vitality.

Co-composting: The multifaceted benefits of co-composting biochar and biomass on the farm are discussed in a later section of this chapter.

Manure management: Biochar serves as a valuable addition to manure management practices by controlling odours and enhancing nutrient retention. Biochar added to animal pens is incorporated by animal hoof-action with manure, easily producing an enhanced, nutrient rich, low-odour biochar for field spreading.

Weed and pest management using wood vinegar: The use of wood vinegar in conjunction with other herbicides and pesticides can reduce pasture and crop losses, increases abundance of growth promoting microbes, and increase yields.

Animal feeding: Feeding biochar to animals may increase animal health and productivity, and produce an enhanced biochar-loaded manure for incorporation on the farm. In particular, feeding biochar to ruminants along with introducing new species of dung beetles can enhance pasture productivity and build soil carbon within 2–3 years.

Bale grazing integration: Combining biochar application with bale grazing facilitates animal health and productivity as well as soil enrichment and regeneration. An easy method is to spread a suitable biochar on the soil surface and set bales directly on top. Hoof-action integrates biochar, manure, and hay-seed residues into the soil, effectively rejuvenating unproductive areas. Introducing new species of dung beetles will aid the incorporation of biochar-manure-hay residue into the soil profile.

Heat utilisation: Integrating surplus energy from biochar production into the energy requirements of the farm reduces reliance on fossil fuels and shrinks the farm's greenhouse gas footprint. Surplus heat generated during biomass pyrolysis for biochar production can be harnessed to dry or process crops, heat greenhouses and animal sheds, or even power adsorption chillers or generate electricity.

Waste utilisation: Producing biochar from farm residues (including wood waste, agriculture and aquacutlure residues, and nearby waste-mineral sources) enables efficient utilisation of the waste while also generating valuable soil amendments.

Carbon sequestration: The conversion of waste feedstocks to stable carbon and incorporating it into the farm system for any of the above benefits and practices also has the potential to generate carbon credits. Carbon credits may be generated by sequestering the stable carbon in the biochar and from the additional soil organic carbon stimulated and protected by ageing the biochar. These credits may be worth significantly more than those from other soil-based practices and may also enhance the farm's environmental credits within its community.

EXAMPLES OF INTEGRATION OF BIOCHAR WITH REGENERATIVE PRACTICES

In this section we gather and outline a few innovative examples of utilising biochar in regenerative practices or to provide ecosystem services.

Example 1: Co-composting biochar with biomass

Biochar can be incorporated into composting processes on farms in various ways. The best choice of method depends on location, climate, soil, plant types, plant diseases, and goals. Biochar can be added after the composting process, prior to adding the compost to soils, and the compost and biochar will age and enhance each other in the soil. Alternatively, biochar can be mixed with the biomass at the start of the composting process, which enhances the composting process. When added to soil, the final co-composted product is of more benefit than separately produced compost and biochar.[4,5] Co-composting has become popular due to the multiple benefits it provides to both the compost and the biochar, which flow on to enhanced benefits for microbiota, the soil, and plants.

The process of composting creates heat, which evaporates water from the substrate. This may result in the compost being too dry. When such dry compost is applied to the soil, it may cause harm by absorbing water from the soil. Co-composting with biochar aids the retention of water throughout the composting process, resulting in reduced water loss and a higher water-holding capacity. Furthermore, biochar can be added to substrates that have too much water, reducing moisture content to an appropriate and manageable level.

As well, the porous nature of some biochars allow for increased oxygen flow, which increases microbial growth during the composting phase. This, in turn, often allows the co-compost to be a better sorber of ammonia and hydrogen sulphide released by microbial activities. The presence of additional functional groups on the biochar surface reduces leaching of nutrients from the compost when the co-compost is added to soils. The porosity and active surfaces of co-compost-biochar and organic matter help to reduce the presence of toxicities in soil. Biochars produced at high temperatures have high sorption capacity and are useful for immobilising organic and inorganic contaminants, including heavy metals. High-temperature, high-ash biochars also tend to have high pH and liming ability, which can raise the pH of acidic soils and aid in reducing the availability of contaminants. Co-composting helps to neutralise biochar pH and increase dissolved organic matter in the soil, improving overall soil quality. Applying co-composted biochar to cropping soils increases the degradation of dissolved organic carbon relative to that in regular compost.

The amount of biochar added to biomass has varied between 5 and 20% (on a dry basis). There is no consensus on the optimal rate. From a financial perspective, addition of 5% biochar may give the greatest return to the farmer, but 10–20% may be optimal for carbon sequestration. The other issue that needs to be considered is maintaining an optimal C/N ratio. Adding a high percentage of wood biochar will result in too much carbon in the compost pile. Higher rates (up to 20%) of a high N biochar, such as poultry manure biochar produced at a low temperature, can ensure that the C/N ratio remains optimal (approximately (30:1). It is important that the farmer or land manager experiments with different ratios to ensure that a cost-effective product is produced.

Example 2: Co-composting in trenches and wells to build soil carbon and store water

Composting of biomass with biochar can be effectively carried out on a farm, tree plantations, and remediation sites in wells and trenches in the soil, as well as on the fields. Trenches and wells, where biomass is slowly transformed into compost catalysed by biochar, act as reservoirs that slowly release nutrients and water and build diverse microbial communities. Trenches can be used as reactive barriers to control the movement of salty, nutrient laden, or contaminated water.

Figure 10.1 summarises some potential applications of biochar trenches and other methods of using biochar within regenerative agricultural practices.

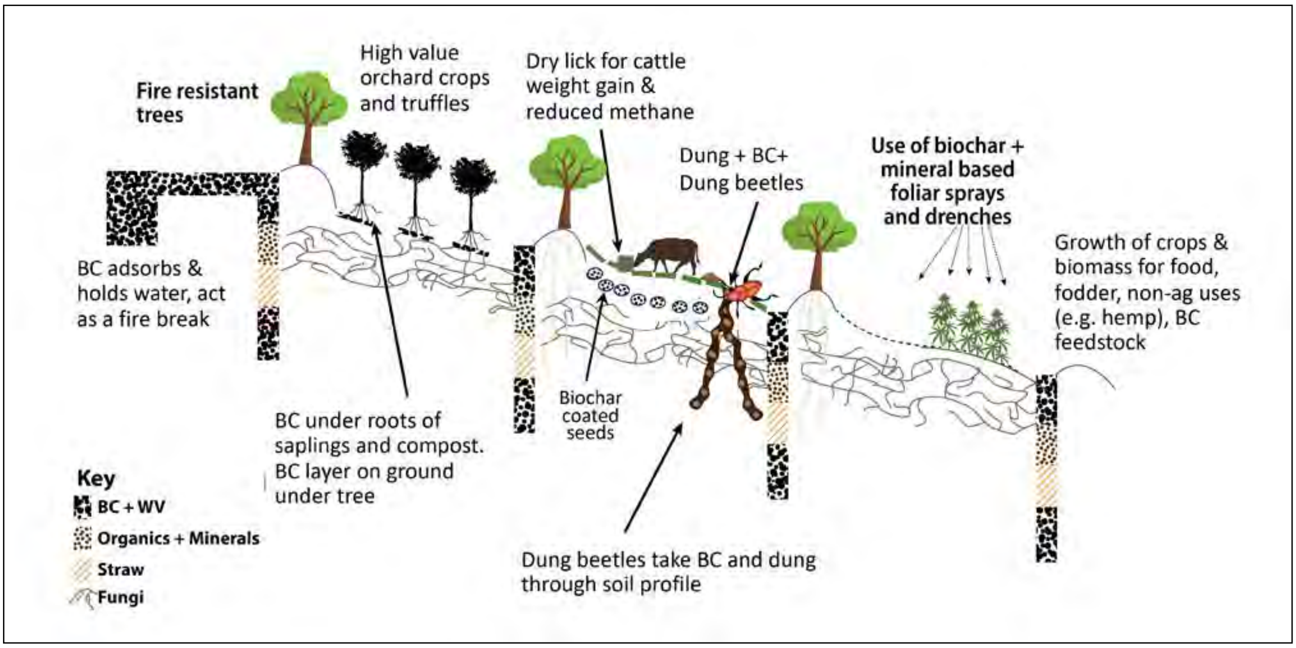

Figure 10.1 Application of biochar trenches along with some other uses of biochar within regenerative agricultural practices (from Joseph). BC = biochar. WV = wood vinegar

Example 3: Biochar in trenches as a reactive barrier to remediate land and water

Case Study: Biochar remediation of salt-affected soils in Western Australia

A trial conducted at a native food and sandalwood farm of 1.8 hectares in Western Australia demonstrated the capacity of biochar to reduce the impacts of salt on plants in saline soils (Figure 10.2). The biochar acted as a permeable reactive buffer, which allowed medium- and long-term remediation of the salt-affected soil.[6]

Figure 10.2 Case Study: Biochar remediation of salt-affected soils in Western Australia. **Left:** Initial poor-quality, salt-encrusted soil. Right: The same site two years after installation of reactive char wells and biochar-mineral-biomass-filled trenches (black area in photo on right).[6]

The soil was loam over clay with some fine gravel sediments. The soil had been affected by salt for some time. Previously, salt-tolerant plants had been introduced and the affected land covered in straw to minimise evaporation. Previous farm managers had also installed a subsurface agricultural ditch to leach saline subsurface waters. However, after four years the pump failed, likely due to fine sediments causing blockages.

To overcome the soil constraints, char wells 15 cm diameter were drilled to a depth of 30 cm adjacent to tree seedlings, about 50 cm from the tube-stock base (see Figure 10.3). The reactive wells were filled with biochar, lucerne fines, and a range of organic amendments (including fish amino acids, water-soluble calcium, lactic acid bacteria, and oriental herbal nutrients). The char wells developed a high abundance of beneficial fungi and bacteria, which in turn promoted new growth and enabled the ponded water to access the soil profile, resulting in more rapid drainage and improved water holding capacity.

A trial was conducted to assess how effectively biochar, combined with various natural amendments, could serve as a permeable reactive barrier against saltwater runoff and stress, while also providing long-term remediation for salt-affected soil. Trenches measuring 800 mm deep and 150 mm wide were excavated each positioned one metre away from a growing tree. These trenches were then filled with layers of straw and biochar, along with different combinations of additional natural ingredients to create five distinct trial treatments labelled as T1 to T5 in the box. Molasses water and wood vinegar were introduced into the experiment to enhance microbiological populations and root development, promote seed germination, increase photosynthesis, repel pests, and prevent plant infection from fungal, bacterial, and virus-like diseases.

Ingredients for char wells or trenches	T1	T2	T3	T4	T5
Straw	Y	Y	Y	Y	Y
Biochar (jarrah wood)	Y	Y	Y	Y	Y
Lactic acid bacteria	Y		Y	Y	Y
Wood vinegar	Y		Y		
EM-1	Y			Y	Y
Molasses	Y		Y	Y	Y
Worm juice	Y				
Fermented urine	Y				Y

Each trench had four layers: 150 mm topsoil cover, 100 mm of a biochar mixture, 200 mm of wheat straw and 100 mm of the biochar mixture. One trench was backfilled with soil to act as a control (T6). Tree species planted in front of the treatments included Eucalyptus erythrocorys, Eucalyptus preissiana, Eucalyptus pleurocarpa, Grevillea olivacea, Hakea petiolaris, Eucalyptus kruseana, Grevillea Robyn Gordon, and Frost Kill Hakea baxteri. These trees were planted next to the char well holes and the trenches.

Figure 10.3 Case Study: Biochar remediation of salt-affected soils in Western Australia. **Top:** Drilling holes near tree planting and filling with organic matter, minerals, biochar, and wood vinegar. **Middle:** Some of over 3000 char wells. **Bottom:** Two years later.[6]

One year after establishing the treatments, soil salinity levels had significantly reduced. Before-and-after soil analyses demonstrated that pH, carbon, nitrogen, phosphorus, and microbial biomass levels increased in the soil around the biochar-treated trenches compared with those in the untreated control soil. The most notable result from the trial after one year was reduced pooling of water in the lower sections of the farm. The wells also increased plant growth and partially reduced soil-borne diseases and insect attack. Trees involved in the trial were all healthy and none showed signs of being salt affected.[6]

Key Takeaways

After one year, permeable biochar wells:

- accelerated plant growth
- appeared to reduce ponding of water
- increased resilience against-soil borne disease and insect attack
- reduced or eliminated soil health problems caused by salinity
- reduced soil salinity levels and increased carbon and nitrogen levels

Example 4: Regenerative grazing

Regenerative and sustainable grazing practices involve dividing a property into smaller paddocks and rotationally grazing them. The short duration of grazing combined with a longer planned plant recovery period reduces overgrazing of desirable pasture species. A higher stock density can lead to a more even pasture over each paddock. Perennial cropping is often integrated into this grazing practice.

Incorporating biochar into sustainable livestock production:

- significantly reduces or eliminates external inputs of fertiliser and other agrochemicals
- reduces greenhouse gas emissions
- helps restore degraded land

Feeding biochar to animals and adding dung beetles to the pasture further enhances these regenerative grazing and pasture practices. Throughout the year, the dung beetles actively move the biochar-loaded dung into the soil profile. Dung that has biochar in it has lower moisture content, does not decompose as quickly, and emits less greenhouse gases.[2]

The addition of biochar into cow and sheep feed mixtures aids animal growth and reduces the emission of methane and N_2O from the dung. Specific types of biochar added to cattle feed improved cattle muscle growth and increased milk production. Biochar fed to chickens increased eggshell solidity and thickness. Furthermore, addition of biochar to cattle feed acted as an antibiotic, reducing the need for synthetic medications for animals, and improving health and resilience against disease and illness.[3] For further detail on a case study using biochar animal feed, see Chapter 9.

Example 5: Applying liquid biochar to pasture

Southern Cross University (SCU) and the Australian New Zealand Biochar Industries Group (ANZBIG) conducted a trial on a farm in Mallanganee, NSW, to investigate the application of liquid biochar on soil and pasture yield. Biochar combined with either an organic liquid fertiliser (Charlie Carp brand; T3) or liquid inorganic NPK fertiliser (T4; Figure 10.4) were compared with unamended, fertiliser only and liquid biochar only controls, as well as with manure only and solid biochar–manure mixture. The total NPK for each treatment was matched to the NPK content in the manure application at 10 t/ha. This equated to N = 92 kg/ha; P = 26.23 kg/ha and K = 41.78 kg/ha.

The treatment and first harvest of pasture occurred in a very low rainfall period. In the first harvest, the liquid biochar with NPK (T4) yielded pasture growth rates 3–4 times higher than those following application of straight liquid biochar (T7) or biochar-manure (T5), and over two x times higher than those following application of NPK alone (T2) or solid biochar with NPK (T6). These observations indicate greatly increased resilience in drought conditions from the nutrient availability and microbial promotion of the liquid biochar+NPK treatment.

Rain was returning for Harvest 2, and the control pasture yields were about double. Again, there was no difference between the unamended control (T1), manure (T5) and straight biochar (T7), and they were all outperformed by over a factor of two by the biochar+nutrients treatments (T3, T4, T6). However, there was no significant difference between those biochar+nutrient treatments and the straight NPK (T2). The returning rain would result in more dissolution of the macro- and micronutrients; however, soil data at the time of these two harvests would be required to hypothesise a mechanism. A webinar with the full results can be found at www.youtube.com/watch?v=rGS9459YTpU

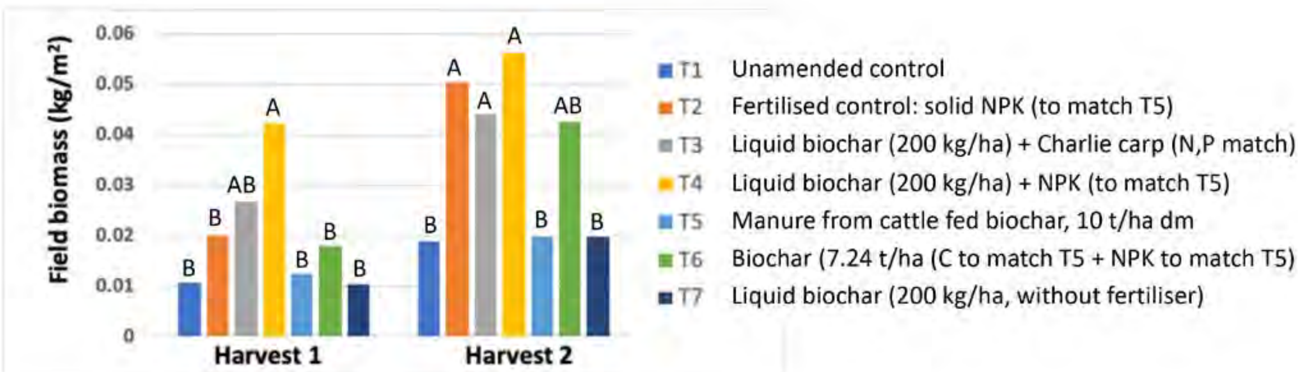

Figure 10.4 Trials of liquid biochar with and without other soil amendments on a farm in Mallanganee, NSW. The two pasture harvests were after a single application of treatments in a low rainfall period. Only results labelled with a distinctly different letter combination are significantly different (e.g. in harvest 1, only treatment T4 is significantly higher than others) (Data adapted from Southern Cross University and Australian New Zealand Biochar Industries Group)

Example 6: Using heat from biochar production

Extra heat produced by pyrolysing biomass can be used to dry or process crops and heat greenhouses and animal sheds. It can also be used to run adsorption chillers and cool animal sheds. With more sophistication, the excess energy can be utilised to produce electricity. Integrating the energy released during biochar production to supply some of the energy needs of the farm reduces reliance on fossil fuels and the overall greenhouse gas footprint, while improving soil and reducing fertiliser inputs.[7] Figure 10.5 illustrates the integration of biochar into energy production and the carbon balance on the farm.

Systems that take advantage of both the biochar and the energy produced are called Combined Heat and Biochar or CHAB. Generally, wherever possible in biochar production, whether on-farm or commercial, CHAB systems should be designed, implemented, and promoted to enhance the resource efficiency, profitability, and regenerative capacity of biochar systems.

This combined use of heat and biochar reduces reliance on fossil fuels and reduces the farm's greenhouse gas footprint.

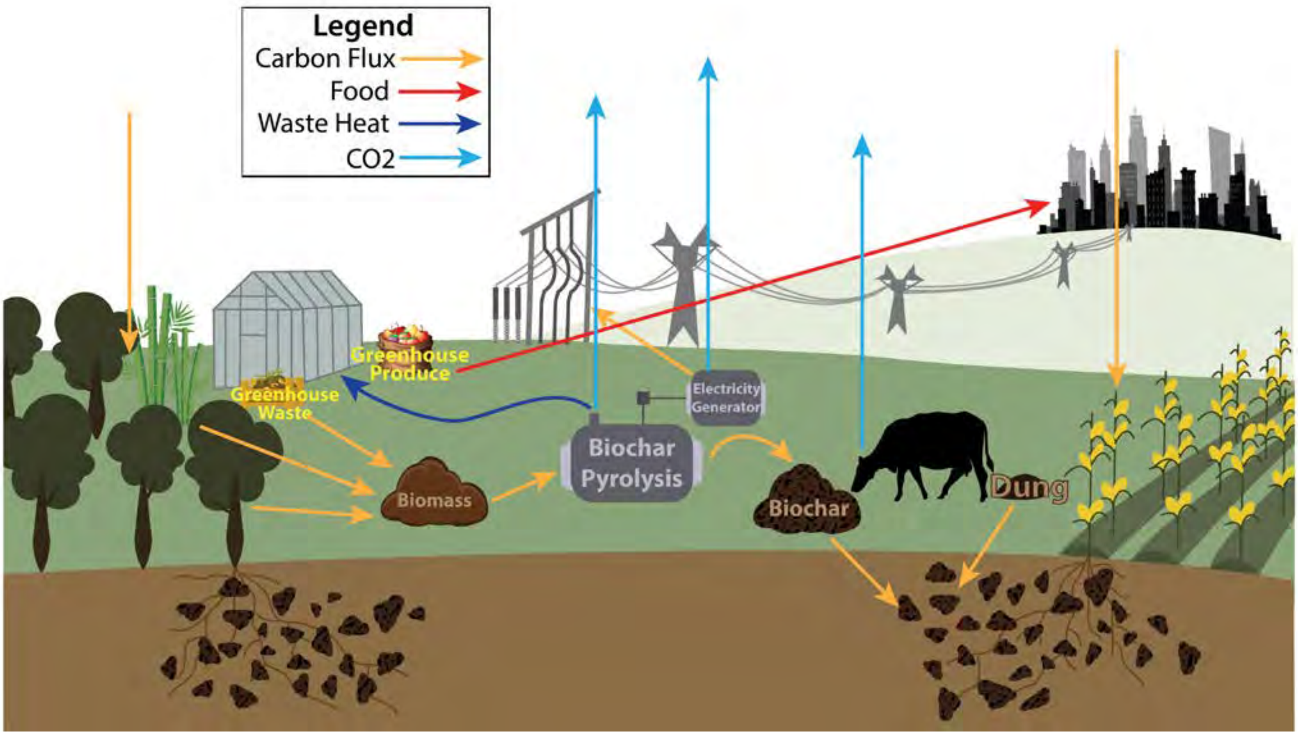

Figure 10.5 Potential energy utilisation pathways and carbon fluxes for heat, electricity, and biochar generated during biomass pyrolysis.[8]

Example 7: Integrating biochar with solar photo-voltaic and wind energy on farms

Biochar integrated with on-farm solar and wind systems reduces the greenhouse footprint of wind and solar systems and ensures that soils under and around the renewable energy remain productive to grow food or pasture.

Biochar can be incorporated into the concrete and bitumen that is used in buildings and roads on renewable energy farms. Biochar trenches placed under the drip edge of solar panels catch and store the water condensed on the panels at night. This enhances food production under the panels and pasture production between the panels (Figure 10.6). The biochar would also adsorb moisture from the atmosphere, and potentially the panels could be kept cooler by extra biomass, moisture, and water vapour around the panels.

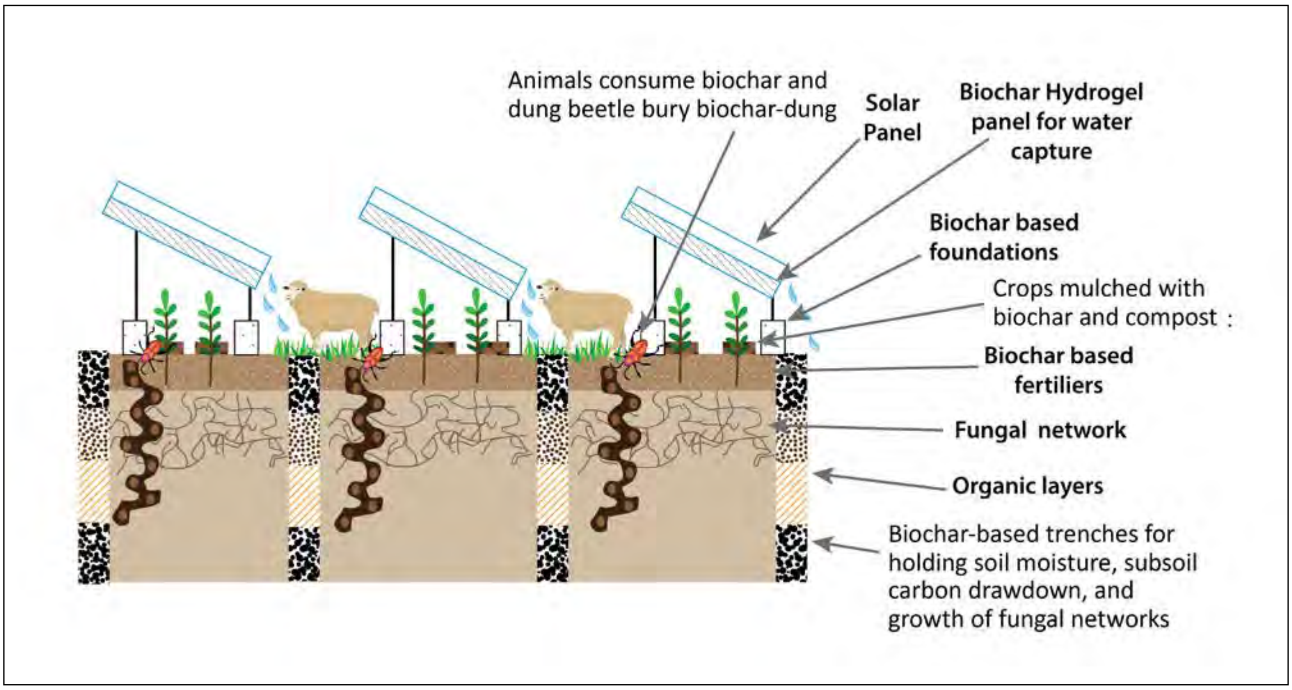

Figure 10.6 Integrating biochar underneath and between solar arrays (S. Joseph)

Example 8: Fire and water management with cool burns

Figure 10.7 Low-intensity cool burns create a biochar cover over the ground, which adsorbs moisture, aids germination (also due to smoke chemicals adsorbed on the biochar and soil), builds soil organic carbon, and improves soil characteristics, creating drought resilience. (Photo credits: Left, James Kidman/blogs.unimelb.edu.au[9]; Right, Michael-Shawn Fletcher/casw.org[10])

Traditional methods of reducing the severity of fires by cool burning, especially between tree coupes, have been practised in Australia for tens of thousands of years by indigenous land users. This long history of cool burning has added pyrolytic carbon (biochar) to soils[11] and contributed to soil and plant health.

Experiments by foresters in Australia indicated that a thin layer of high-temperature, very porous biochar on the ground or in trenches within firebreaks has the potential to reduce the intensity of a fire.[12] Thin layers of biochar are difficult to ignite when on the ground, and more so when their pores are saturated with water. Biochar adsorbs moisture during times of significant differences in day and night temperatures and stores water after very heavy rain events. When fires are imminent, and water (preferably including a green fire suppressant) is sprayed onto the surface of the biochar, most of the moisture is tightly held and is only slowly transpired during the hottest parts of the day. When a fire reaches the periphery of the fire break, the temperature of the biochar will increase and water will be released as steam. This has the potential to suppress and slow the forward movement of the flames. Trials are planned to determine how effective this fire prevention method could be.

CONCLUSION

Using biochar as a tool for regenerative and sustainable agriculture helps to rehabilitate degraded soils, increase farm productivity and profitability, and facilitate a transition to regenerative farming. Integrating on-farm biochar production with the use of waste heat, then applying the biochar on the farm, will reduce a farm's greenhouse gas footprint. Similarly, using biochar in the construction of solar and wind farms and applying it to the soil under and around solar panels will improve the carbon balance in these ventures.

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Chapter 11

Simple biochar testing on the farm

Key Points

- This chapter contains multiple simple and cheap tests that can be carried out on the farm or garden to characterise a new biochar and get a basic understanding of its likely effects on the soil.
- Because biochar materials vary widely, we recommend that you always test a new biochar material before using it in your soils.
- Biochar only needs to be tested once if you are using the same feedstock of the same moisture content, pyrolysed at the same temperature in the same type of kiln.
- Test at different application rates to see what is going to happen in the soil, especially the effect of the biochar on pH. A small shift in pH such as from 5.0 to 5.3 may foster a big effect because the pH scale Is logarithmic.
- The ash content of the biochar, total dissolved solids (TDS), and pH will give a good indication of the pH shift and liming effect induced by the biochar in the soil, and whether adverse effects may occur due to a high salt content. This is especially true if the pH and TDS are measured when the biochar is combined in the intended ratio with the soil.
- If adverse effects can be predicted based on the simple tests, then a lower application rate or a different biochar may be called for.
- Easy-to-carry-out germination and worm avoidance tests help to detect toxicity and in choosing a biochar that best promotes soil biota and plant growth from among several candidate biochars.
- Pot or field testing is required to determine the optimum biochar and application rate to meet soil constraints at maximum profit. It will be valuable to develop skills for effective trial design, soil and plant sampling, and basic analysis.
- Sharing and networking the results will help others as well and move the Biochar Revolution along.

INTRODUCTION

Biochars and soils exhibit wide variability in their characteristics. The properties of biochar differ according to their raw materials and conversion processes, and these varied properties affect their performance in their intended application. For these reasons, it is prudent to test any new biochar material before using it in soil. This chapter is designed to assist farmers and gardeners to conduct simple yet essential tests to ensure the safety and efficacy of biochar in soil. The chapter also provides guidance on testing the effects of biochar on plant growth.

Simple tests are given for:

- the primary constituents of biochar, especially moisture content and ash
- soil-relevant properties: pH and TDS, for the biochar itself and when combined with the soil
- toxicity (germination and worm avoidance tests)

The implications of the tests are discussed, with references provided for further details. The chapter ends with a brief introduction to field testing and soil sampling, with referrals to more detailed guides and Australian testing laboratories.

Armed with the results of these tests, farmers and gardeners can make informed decisions about integrating biochar into larger soil areas and ongoing management practices.

PRIMARY CONSTITUENTS OF BIOCHAR

The four primary constituents of biochar are moisture, ash, available organic matter, and persistent organic matter.

Moisture refers to the water content of the biochar, and as measured may include some volatile organic compounds that evaporate along with the water.

Ash refers to the portion of biochar that is not organic.

Available Organic matter is the organic portion of biochar that can migrate into the soil and become a source of food for soil microbes and plants.

Persistent organic matter (also known as recalcitrant matter) is the organic portion of biochar that is expected to remain stable in the soil for a very long time, providing a habitat for microorganisms and nutrients.

These four primary constituents of biochar parallel the constituents of fuel charcoal and coal, known as moisture, ash, volatile matter, and fixed matter, which are determined by a standard procedure called proximate analysis. Some of the procedures of proximate analysis are adapted to measuring the constituents of biochar, with varied adjustment to accommodate the different requirements and properties of biochar relevant to its application to soils (for example, not all volatile matter is water soluble and plant available).

Ash, available organic matter, and persistent organic matter are measured after the biochar has been dried of moisture. Both the inorganic component (ash) and organic components can be further characterised into components that are soluble or insoluble in water. The soluble components leach into the soil and become available to the microorganisms and plants, functioning as nutrients, or in some cases at too high a level, presenting as toxins.

Analytic sequence

All the basic constituents of biochar can be measured by weighing the biochar sample before and after heating it to defined temperatures under defined conditions. By following the simple procedures described in the following sections, these measurements can be done accurately enough with equipment as basic as a thermometer (or thermocouple for the high temperatures), a scale, a toaster oven, and tin cans.

Because the measurements are interrelated, it is most practical to perform the analytic sequence shown in Figure 11.1. This sequence can be stopped when you have the product or information of interest. For example, if you only want moisture content or a dry sample you can stop at DIY moisture measurement.

Read on for the details to do the tests and calculations yourself and understand their implications on your farm.

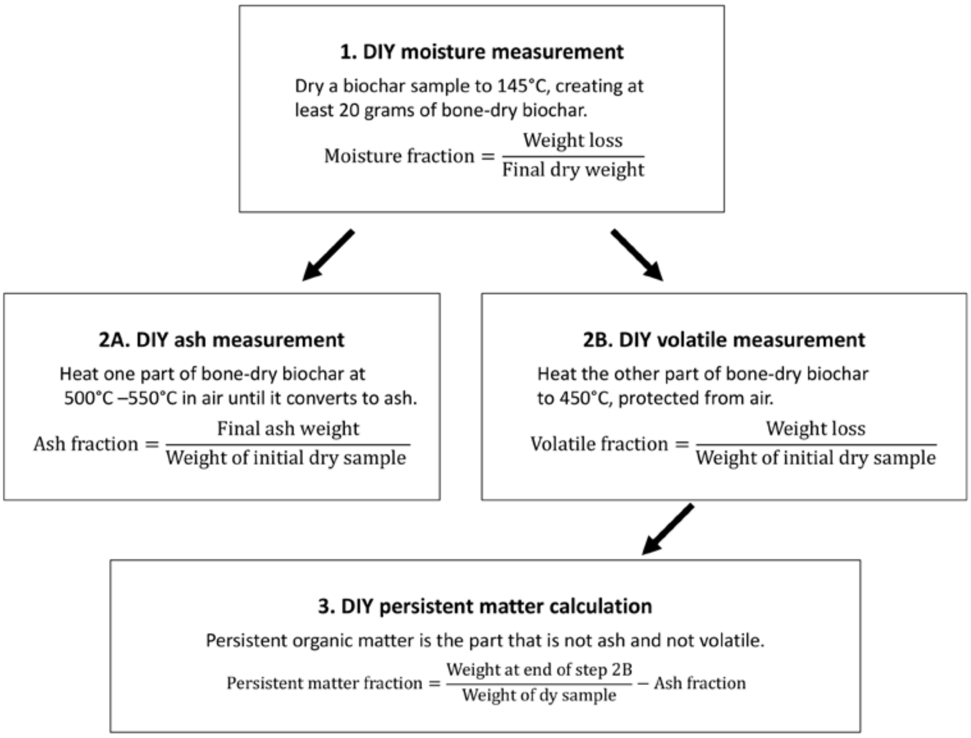


Figure 11.1 Analytic sequence for determining the prime constituents of biochar using simple do-it-yourself (DIY) methods. Note the formulae express the various fractions on a dry basis (db); i.e. relative to the final dry weight. If multiplied by 100 the fractions become percentage contents (db)

Moisture content

Most biochars are hydrophilic—they readily attract and hold large amounts of moisture from the environment. As well, the process of making biochar usually involves quenching with water. Hence the amount of water present in biochar can vary greatly, depending on how the biochar is produced and whether it has accumulated or lost moisture during storage or shipping. There are several reasons to know the moisture content:

- Biochar is an active material, so it is crucial it has enough moisture to avoid spontaneous combustion and mitigate dust hazards in storage and shipping.
- The moisture content in biochar can act as a reservoir of water in the rhizosphere, which can be drawn on by plants and microbes in time of water stress.
- Moisture increases shipping costs and reduces the value of the purchase if paying by weight (for this reason biochar is often sold by volume).
- Assessing and comparing properties of various biochars must be done on a uniform “dry basis,” thus removing the variable of the water content.

The moisture content is measured by weighing the sample before and after drying in an oven at a specified temperature above the boiling point of water. The moisture content is defined as either the ratio of weight loss to the original wet mass (known as wet basis) or to the final dry mass (dry basis). A convenient standard of “moisture-free biochar” is often determined by drying a sample at 105°C until a constant weight is reached (that is, no further weight is lost when drying is continued). This is typically done overnight in a drying oven with internal forced convection. This is the temperature for characterising moisture content of biochar required by the International Biochar initiative (IBI)[5], the European Biochar Certificate (EBC)[6], and other published analytic methods.[8,9] However, this is not the end of the water-content story.

Drying at 105°C removes only part of the actual moisture contained in a biochar sample. Water may also be adsorbed to the large internal surface areas inherent in the small pores of the biochar or held in more tightly bound forms as water of hydration within the ash present in the biochar, or as water molecules chemically involved with the organic portions of the biochar. Figure 11.2 shows the measured weight losses for seven biochars heated from below 100°C to 300°C.

Figure 17: Weight loss curves for a set of seven chars

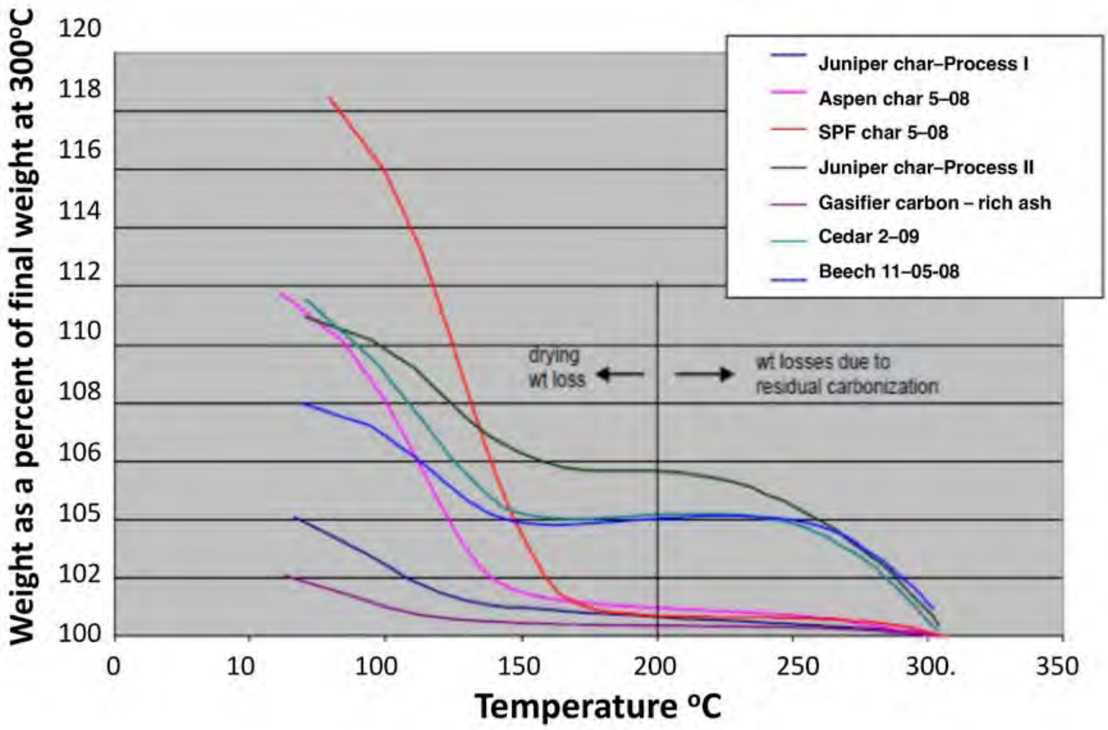


Figure 11.2 Weight loss curves for seven chars. Source: McLaughlin et al. (2009)[2]

A temperature of 145°C–155°C marks the beginning of a stable weight plateau, where most of the water and a small amount of volatile material have been removed but before the char begins to lose mass due to oxidation and carbonisation at higher temperatures. Thus, drying at a temperature of 145°C–155°C conditions the biochar by **desorbing** water and volatile substances that have been adsorbed in the pores of the biochar. If these volatiles were not desorbed, they would interfere with the subsequent measurement of ash and volatile carbon.

Measuring the volatile matter requires heating to 450°C, which would drive off all the tightly bound water still remaining, which would bias the measurements of other fractions. The tightly bound water must also be removed before measuring adsorption capacity. The conditioned or "desorbed" biochar is often referred to as "oven-dry" or "bone-dry" biochar in order to distinguish it from "moisture-free" biochar. Other characteristics of the biochar, such as ash content, may be given either as a percentage of the "moisture-free" biochar, or the "oven-dry biochar" and designated accordingly. However, the ash content and the volatile fraction of biochar are better represented by first driving all the water out, to start with a bone-dry, completely water-free sample.

For most biochars, only water vapour is driven off when drying at temperatures below 110°C and, compared with the water content, insignificant volatiles will be released at 145°C. Some biochars, though, will release significant amounts of organic vapours, typically methanol and acetic acid (which can be detected by their pungent odour) along with the water. The weight loss from drying at the target temperature, will then include not only water but also other low-boiling organic solvents. This fraction will become more prominent at higher temperatures and could bias the measured moisture content to be higher than the actual water content, and bias later measurements of the volatile contents to be too low (since some have been released in the moisture measurement). Thus, if we heat insufficiently, some water may be included in the other fractions, and if we heat too much, some volatiles may be lost into the water fraction.

Notes:

- Drying biochar at 105°C–110°C requires patience or leaving the biochar in the low temperature oven overnight—especially if you're drying wet biochar or you wish to dry a larger quantity—so you have enough to subsequently test for further properties.
- When drying biochar at 145°C the procedure is shorter, but requires monitoring for safety and to detect oxidation of the char. Some biochars when heated to internal temperatures around 150°C, may begin emitting volatiles and even generating smoke. For this reason, drying should be done either under a hood or in a well-ventilated area, such as an open garage or outdoors. Do not leave this process unattended.
- Emissions of volatiles or smoke are indicators that the biochar is not fully carbonised or that it contains torrefied wood. Biochars containing significant portions of torrefied wood are likely to behave differently and possibly less beneficially in soil than fully carbonised biochars.

Recommended simple processes for oven drying at 105°C and 145°C, and to thence derive the lower or higher water content of biochar, are given in Box 11.1. If you do both procedures then the difference in results will be a measure of the more tightly bound water in the biochar, assuming insignificant other volatiles have left the sample at the higher temperature.

Box 11.1: DIY Biochar drying and moisture measurement

What you'll need:

- A simple toaster oven (not a microwave oven).
- A thermocouple or standard oven thermometer suitable for use inside the toaster oven. (Don't rely on the thermostat of an inexpensive toaster oven).
- A scale, accurate to 0.1 or 0.01 grams (available online at prices below Aus$20–$50). You can use a kitchen scale for a larger sample of char.
- A piece of aluminum foil, perforated to let excess moisture escape and allow vapor to circulate.
- For drying at 145°C: A sealed container suitable to store the hot biochar to inhibit adsorption of moisture from the surrounding air.
- A sample of biochar; it can be as little as 1 gram, with a sensitive scale, but 10–100 grams is easier to measure, with the larger quantity producing more samples for further measurements.

Decide your target temperature (see notes and discussion above the box):

- 105°C–110°C for moisture-free biochar and to measure the lower moisture content.
- 145°C–150°C for bone-dry biochar and to measure the higher moisture content.

What to do:

1. Prepare a drying dish or a small tin can with open top and perforations in the bottom for airflow. Record the weight of the container.
2. Place the sample in the container and record the weight. The difference is the initial wet sample weight.
3. Insert the thermocouple (or oven thermometer) into the centre of the biochar sample to measure its internal temperature.
4. Place the perforated aluminum foil over the top of the biochar vessel to shield the sample from direct radiant heat of the toaster-oven heating element. Ensure the vessel is not sealed so moisture can escape the vessel.
5. Follow instructions for your target temperature:

   a. Heat the sample until its interior target tempera ture reaches 105°C–110°C.
   b. Maintain it there for at least two hours or over night.
   c. Weigh the can with dry sample.
   d. Repeat step 7 and step 8 at one- or two- hour intervals until the weight remains constant.
   e. Set the oven for 145°C–150°C.
   f. Turn the oven off when the biochar's internal temperature reaches 145°C.
   g. Keep the biochar in the turned-off drying oven, until you note the maximum internal temperature reached.
   h. Cool the biochar in the drying oven or preferably in a sealed container.

6. Record the weight of the vessel with dry sample. This weight minus the weight of the empty container is the dry sample weight
7. Calculate the difference in weights divided by the initial wet weight or final dry weight. Expressed as a percentage, this is the moisture content on a wet or dry basis; for example:

$$\textbf{Moisture content (dry basis)\%} = \frac{(\text{Initial wet weight} - \text{Final dry weight}) \times 100}{\text{Final dry weight}}$$

Notes:

Because of the cooling effect of evaporating moisture, make sure that the interior of the biochar itself has reached the requisite temperature. This is especially important for larger samples. It takes some care to achieve consistency.

When drying at 145°C, if the biochar's internal temperature exceeds the oven temperature, indicating the biochar is generating internal heat, the biochar has begun oxidising. The drying study should be repeated at a lower oven temperature to get accurate results.

ASH

Ash is the fraction of the moisture-free biochar that is not organic. It is in the interest of the char producer or purchaser to know the ash content because the ash-component of any biochar may be considered a beneficial or detrimental component, depending on the application of the biochar and the nature and amount of ash.

Ash content is measured by grinding a dry biochar sample (either moisture-free or oven-dry) to a coarse powder and heating at a temperature of 500°C–550°C until the sample becomes a pale grey to white powder with no black particles. The ratio of the ash weight to the original dry sample weight provides the ash fraction on a dry basis (either moisture-free or oven-dry, depending on the sample's starting point). A DIY procedure for measuring ash content is described in Box 11.2.

Box 11.2: DIY ash measurement

Like moisture, ash is also fairly easy to measure at home, with due attention to safety.

What you'll need:

- A scale with accuracy to 0.01 grams.
- A propane-fuelled camping stove.
- A clean, dry, open-top tuna fish or cat food tin can (not aluminum).
- A sample of finely crushed or powdered, dried biochar (bone-dry preferred).

What to do:

1. Heat the empty tin can, to burn off any coatings from the manufacturing process.
2. Weigh the container after it cools, and record.
3. Spread a ½-centimeter (or ¼-inch) layer of dried and ground char over the bottom of the can and note the container's new weight.
4. Record the difference; this is the weight of the dry biochar.
5. Heat the open can on the camping stove over an open flame that uniformly heats the entire bottom of the container.
6. Stir the contents periodically and uniformly to facilitate ashing but take care not to knock or blow away any of the ash. Avoid the contents of the tin can catching fire. That would carry ash away as particulates in smoke.
7. Continue until the tin can contains only grey-to-white ash residue.
8. Weigh the cooled can, including the ash therein.
9. Remove all ash and weigh the empty can.
10. Record the difference; this is the weight of the ash.
11. Record the ratio of ash to dry biochar weights, using the values recorded in Steps 4 and 10.

$$\textbf{Ash content (dry basis)\%} = \frac{\text{(Final ash weight)} \times 100}{\text{Initial dry sample weight}}$$

Note:

A completed ashing process will burn off all organic material, leaving behind inorganic ash. Black powder in an ashed sample indicates the presence of uncombusted organic material. Because ashing yields a very stable material, erring on the side of extra time at furnace temperature, under controlled temperature limits, will ensure complete ashing, with no detrimental effect on the measurement of ash content of the biochar sample.

Ash levels and implications

Most chars made from clean wood yield less than 5% ash by weight, while agricultural residues, such as corn stover, may yield significantly higher levels. If the original feedstock material is new, clean wood or agricultural residues, there is generally little worry about ash level or composition.

The ash can be divided into water-soluble and insoluble components. When biochar is added to soils, soluble ash causes its principal effect on pH. The soluble ash can act like lime. The soluble components leach into water and soil and become available to microorganisms and plants. Some of these available compounds will be nutrients for biota and plants, and some, such as heavy metals or high levels of common salt, sodium chloride (NaCl), may be toxic at too high a level.

Whenever the origin of the biomass is unknown, or the ash levels are significantly higher than 10% by weight, it may be worth testing the ash for its impact on soil pH, its total dissolved solids (TDS), and the presence of metals. The pH and TDS can be easily measured by using simple meters, as described below in the section covering Soil-Relevant Attributes. For acidic soils, additional alkalinity is welcome, but for high pH soils, additional liming may lead to poor crop performance. The test for TDS will alert you to high levels of salts. Testing for metals should be conducted by a qualified laboratory, which can also help interpret the analytical results. Not all metals in the ash are bad, but all metals in the ash need to be understood as to their fate and role in the soil. Refer to the sections on heavy metals in Chapters 4 and 6. In Australia, Southern Cross University has an Environmental Analysis Laboratory, which is one of the first specialising in testing biochars (see details at the end of this chapter, or visit https://www.scu.edu.au/environmental-analysis-laboratory---eal/).

Available organic matter

Measuring the volatile fraction of the organic carbon, as in a proximate analysis of coal or charcoal, is done by measuring the weight loss when dried biochar is heated to 950°C in a nitrogen atmosphere. Not all of these volatiles will be water soluble and plant available. Hugh McLaughlin proposes that a better proxy for the available organic fraction is obtained by heating a sample of oven-dried biochar, obtained by the method described above, to a temperature of 450°C and maintaining it there for up to two hours. This lower temperature fraction of volatile matter is the more readily water-soluble, and therefore microbe- and plant-available, fraction. The DIY Volatile Matter Measurement is similar to The DIY Ash Measurement, except the biochar is heated to 450°C in a can with foil lid, or crucible with lid, but the lid must be loose to allow volatiles to vent, while keeping air out.[2,8,9]

$$\textbf{Volatile matter content (dry basis)\% =} \frac{\text{(Inital dry sample weight – Final weight) x 100}}{\text{Initial dry sample weight}}$$

Persistent organic matter

Persistent organic matter is the portion of moisture-free biochar that is neither volatile matter nor ash. At the end of the devolatilisation above, the final weight above consists of the stable carbon and ash.

$$\textbf{Persistent organic matter (dry basis)\% =} \frac{\text{(Final weight) x 100}}{\text{Initial dry sample weight}} \text{ – Ash fraction x100}$$

As mentioned, persistent organic matter is expected to remain stable in the soil for a very long time, providing a valuable substrate for microorganisms and nutrients. Its stable carbon component may be of interest to qualify for carbon credits.

Persistent carbon

The persistent organic matter described above contains a large fraction of carbon and various amounts of other elements, such as nitrogen, hydrogen, oxygen, phosphorus, and sulphur. For typical biochars created from clean wood and grass biomass by slow pyrolysis, the carbon fraction is in the 60–90% range.

This persistent carbon is measured by performing a chemical analysis on a portion of the residue left after measuring the Volatile Matter.

$$\textbf{Persistent carbon (dry basis)\% =} \frac{\text{(Carbon weight) x 100}}{\text{Initial dry sample weight}}$$

This stable carbon fraction of the biochar, and by extension the fraction of the original biomass, can be sequestered for the long term in the soil and potentially qualify for carbon credits.

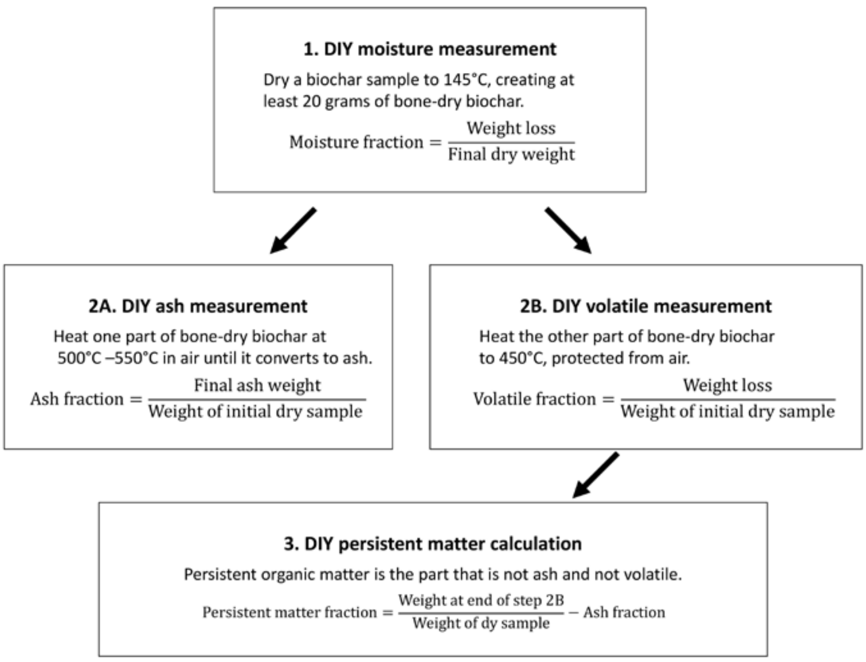
To convert the weight of pure carbon to the weight of CO_2 sequestered, each weight unit of pure carbon is multiplied by the stoichiometric ratio of $CO_2/C = 3.66$.

$$\textbf{Weight of } \mathbf{CO_2} \textbf{ sequestered} = \text{Carbon weight x 3.66}$$

Carbon-credit authorities discount this theoretical CO_2 sequestration, effectively multiplying by a smaller number, closer to 2.5, to allow for methodology errors and leakages of carbon back to the atmosphere as liberated CO_2, including by unforeseen events like fires.

Analytic sequence

The analytic sequence to determine the prime constituents of biochar, using the simple methods referred to and described above, is:



SOIL-RELEVANT ATTRIBUTES

Aside from the fundamental roles played by the four primary constituents of biochar, some other specific biochar properties are pivotal for assessing how a particular biochar will impact the soil. These properties include levels of pH and total dissolved solids (TDS), which are important and easy to measure at the farm or garden.

Biochar total dissolved solids and pH

Tests to assess total dissolved solids (TDS) and pH levels are straightforward to carry out and effectively anticipate the short-term consequences of introducing a specific biochar into a particular soil.

TDS is defined as the combined content of all substances dissolved in water that remain after the water is evaporated. Since mineral salts become ionic when dissolved in water, the electrical conductivity of water is a measure of its level of these salts. In the context of soil analysis, the TDS measures the total dissolved salt content, including fertilisers and neutral salts that are in solution in a soil–water mixture. While TDS in soil may provide important nutrients, too much salt has an adverse effect on most plants. This becomes concerning when amending the soil with biochars containing high ash content, particularly those derived from materials such as chicken litter or paper mill sludge. The soluble salts present in the biochar may leach into the soil, elevating its TDS levels. Some biochars from food, biosolids, and animal residues contain high concentrations of sodium chloride salt, which can be detrimental to plants.

The pH of biochar assumes significance when the introduced biochar influences the pH in an unfavourable direction (either too high or too low) for the crop or microbial communities. Many biochars exhibit a pronounced "liming" effect and can elevate soil pH levels. While this can be beneficial for soils that are too acidic for the crop, it may not be suitable for alkaline soils.

Therefore, monitoring both TDS and pH levels is crucial when incorporating biochar into soil to ensure optimal conditions for plant growth.

Testing biochar for pH and total dissolved solids

Levels of pH and TDS can be easily measured using inexpensive handheld meters on a sample created by mixing a portion of pure biochar with neutral pH water that has low conductivity. Ideally, distilled deionised water is used, but de-ionised water may be inconvenient to obtain outside a research laboratory. Fortunately, many bottled waters are acceptably pure. The measurement process is straightforward and is described in Box 11.3.

Box 11.3: DIY Testing pH and total dissolved solids (TDS)

What you'll need:

- pH paper or a pH meter
- Conductivity or TDS meter
- De-ionised water

Notes:

Generally, bottled water is sufficiently neutral and free of ions. Aquafina® is especially suitable because it's essentially bottled de-ionised water. Inexpensive handheld TDS and pH meters, or combined meters, are available, although consider that the more expensive meters can have a long lifetime).

What to do:

- Calibrate your meter with a standard supplied by the manufacturer.
- Measure the starting pH and TDS of the water.
- Create a slurry by mixing one-part pure biochar to ten-parts water by weight.
- Mix or shake the slurry, then allow it to settle for ten minutes.
- Measure the pH and TDS.

Notes:

- If the mixing and settling cycle is too short, floating biochar may influence the TDS measurement.
- If the biochar takes too long to become wet, see the following section.

Accelerated wetting—a simple test for micropores or hydrophobic oils in biochar

Sometimes, the biochar may take some time to become wet and release entrapped air. This can be overcome by accelerated wetting, as described next, which can also provide insight into other attributes of the biochar.

Biochars may be difficult to wet for a number of reasons. The biochar may have:

a. elevated levels of condensed **hydrophobic** oils and tars,

b. a significant fraction of torrefied wood, or

c. a significant fraction of micropores, requiring water vapour to migrate into and condense in the pores to "wet them out."

The first two conditions do not provide the long-lasting benefits associated with biochar, although they may provide short-term benefits. Hydrophobic oils and tars are dissolved from the biochar by soil water, providing nutrients for microbes and plants. Torrefied wood is not biochar, and likely breaks down in the soil over time. On the other hand, micropores are highly desirable.

One way to ascertain if either significant micropores or hydrophobic oils are present is to heat the biochar slurry to close to the boiling point of water, which promotes the migration of water vapour into the pores. The presence of desirable micropores is indicated if the biochar gives off many tiny bubbles, then sinks. The water developing an oily sheen or turning the colour of tea indicates the presence and release of hydrophobic oils and tars.

Box 11.4: DIY Biochar accelerated wetting

What you'll need:

- A pint canning jar, with lid.
- A saucepan with lid large enough to enclose the entire jar, filled with a shallow depth of water, sufficient to surround the jar in steam.

What to do:

- Make a slurry of 10% (by weight) dry biochar and water (using de-ionised water) and put it in the canning jar.
- Put the jar, with the lid on loosely, into the saucepan.
- Heat the water, bringing it to a boil.
- Cover the pan.
- Boil for 30 minutes.
- Remove from heat and cool.

What to look for:

Upon cooling, the microporous biochars will sink and the less desirable hydrophobic biochars will continue to float, giving you a visual partitioning of the biochar components.

Now you can measure the TDS and pH of the wetted biochar slurry.

Checking the soil–biochar blend

The plant is influenced by the actual pH and TDS in the soil after applying the biochar amendment. If the above-described measurements on a biochar-water slurry indicate that the biochar may have a significant effect on the soil pH or TDS, then the pH or TDS contribution of the biochar should be estimated based on its application rate and dilution ratio in the soil. If this indicates the amended soil would have too high a pH or TDS, then the application rate should be reduced, or another biochar chosen.

Alternatively, and a more accurate way to determine the soil values, the actual proposed soil–biochar blend can be prepared and tested for pH and TDS. To do this, the biochar-water slurry is created and added to a sample of the target soil in the intended ratio. Since soil in the field will not typically have a significant excess of free water (because of runoff, seepage, and evaporation), except during rainfall or flooding events, the pH and TDS of the biochar-soil blend sample should be measured at "saturation." This is where the slurry contains as little water as possible that still fully covers the soil and biochar solids. Measuring soil properties at saturation are standard analytical methods used by soil scientists. The pH and TDS of the soil can be done before and after mixing to see if the biochar is significantly changing or increasing the soil pH and TDS into a range suitable or unsuitable for the plant.

For the soil–biochar ratio being tested, these final pH and TDS tests measure the conditions that will actually be created in the soil. If the pH is unacceptable or the TDS increase is excessive, the biochar should not be added to the soil in the tested proportions. Either a lower biochar load, or a different biochar altogether, should be tested and utilised.

TESTING FOR TOXICITY

Some biochars may contain toxic compounds, including high amounts of organic compounds, salts, or heavy metals, that can harm plants when applied to soils, as discussed in Chapters 4 and 6. However, as discussed in the prior chapters, biochars can lock up heavy metals and organic toxins, and at low application rates are unlikely to cause build-up in crops and animals.

For an initial assessment of the toxicity of biochar incorporated in soil, you can conduct the simple germination test and/or earth worm avoidance test described in the next sections. If in doubt about possible toxic metal, non-metal, and organic compounds in your biochar, send it to a laboratory for testing. Suggested safe levels along with suggestions on how to determine the toxics availability are given ANZBIG's Code of Practice for the Sustainable Production and Use of Biochar in Australia and New Zealand (2021).[7]

Germination tests

Effective seed germination is crucial for the subsequent growth and development of plants. Therefore, the quality of seed germination can serve as a test of how biochar quality may impact overall plant performance. If the biochar negatively affects seed germination, it can be presumed ill-suited for plant application.

Simple germination test

The simple seed germination test in Box 11.5 is elaborated further in The Biochar Revolution[1], and in A Guide to Conducting Biochar Trials published by the International Biochar Initiative.[3]

Box 11.5: DIY Germination test

What you'll need:

- Lettuce seeds (*Lactuca sativa* L.) are commonly used, but radish and clover are also suitable
- Two deep tray-like containers
- Enough soil to nearly fill both containers from the location of the field trial
- The biochar to be tested
- Two clear plastic bags (optional)

What to do:

1. Set half of the soil aside for the control.
2. Mix a specific amount of biochar with the remaining soil, aiming to replicate the intended application rate in the field trial (or use a 50:50 ratio as a first test).
3. Place the soil without biochar in the one container, and an equal volume of the soil-biochar mixture in the other container. Label the containers.
4. Spread the same number of seeds onto the surface of each container using at least 20 seeds, or more if low germination rates occur in normal conditions.
5. Set both containers in the same environment to maintain room temperature, and gently water, ensuring soil is kept moist. Placing a clear plastic bag around each container will help prevent maintain soil moisture.
6. Check the containers daily to monitor germination.
7. Count the germinated seeds in each container once a significant number have sprouted. Do not wait too long, as counting becomes difficult as plants grow and become tangled.
8. Repeat the test to improve the significance of the results.
9. Repeat the tests two to three times for to determine an average and variability.

Commercial germination kits for testing of biochars

Commercial test kits for more precise and rapid assessment of the suitability of biochars for soil application to a range of crops are desirable due to the complex variability of biochar's chemistry and its potential effects on plant performance. The challenge lies in the scarcity of tests tailored specifically for biochar, considering its diverse feedstocks and production methods. Simple methods, such as using Petri dishes, have been employed by researchers to gauge biochar's impact on seed germination and early plant growth. Modifications of standard germination paper methods have also been utilised, incorporating soil or leached aqueous extracts from biochar.

Specialised systems, like germination trays with individual wells or setups to assess the effects of volatile organic compounds, have been devised for more detailed investigations. Moreover, standardised seed germination tests for toxic chemicals and pesticides exist, such as the US EPA and OECD tests, although they typically require larger soil amounts and fewer seeds per container. Commercially available kits like PHYTOTOXKIT (www.microbiotests.be/slideshows/04.%20 Phytotoxkit.pdf) offer more comprehensive assessments, although they have been underutilised for biochar screening.[10]

Rapid testing for the impact of biochar on seed germination and soil health

A rapid-testing method to evaluate the impact of biochar on seed germination and soil health uses a Conviron Model ATC26 growth chamber, which enables the assessment of a large number of seedlings over an extended period of growth.[10] The researchers utilised this method to evaluate 18 different biochars derived from six primary feedstocks at three pyrolysis temperatures of 350°C, 500°C, and 750°C. They examined the effects of these biochars on the germination and growth of specific crop-seeds placed in 15 grams of soil with 1% of a biochar by weight. This test made it possible to quickly assess many biochars and determine which ones gave the best support for specific crops and soils. According to the researchers, this rapid-testing method could be employed to assess a variety of soil-based nutrients or stressors using a limited amount of soil and nutrients or contaminants. It could be adapted for various research purposes, such as studying the effects of liming on growth, and the effects of increases in extractable phosphorus that occur in conjunction with biochar application.

Earthworm avoidance test

Another way to evaluate biochar is by conducting earthworm reactions and survival tests.

These tests are designed to reveal the effect of soil toxicity on earthworms as an indicator of the habitat function of soils. Different earthworm tests are available for various soil types, quality of assessments, and soil use:

- Aquatic test systems
- Ecotoxicity assessment of contaminated soils
- Habitat function of soils for plant growth
- Toxic endpoint
- Reproduction test
- Avoidance test

The avoidance test is used as an alternative to a reproduction test, due to the long timeframe required (56 days) for the latter.

The test requires live worms to complete; however, it may be more sensitive than a germination test. A common type of worm used for this test is the white worm (*Enchytraeus albidus*). It is widely used as a live aquarium fish food and can be bought where aquarium supplies are sold or on the internet. Alternatively, the worm species *Eisenia fetida* (commonly known as redworms, brandling worms, tiger worms, or red wigglers) or the closely related species *Eisenia andrei* can be used. Both species are used for vermicomposting and can be obtained from various suppliers.

In Box 11.6 we describe a simple DIY worm avoidance test and note some limitations in interpreting the results of avoidance testing.

Box 11.6: DIY Earthworm avoidance test

What you'll need:

- One tray-like container (it could be the bottom of a plastic yogurt bucket or milk jug)
- Approximately 1 litre of soil from the location where the field trial will take place or similar soil
- Approximately 1 litre of biochar
- Twenty red or white worms
- One piece of cardboard or plastic sheeting
- Scissors
- A pen or marker
- A glass or other container to measure
- A watering can or container with holes to gently water the soil

What to do:

1. Fill half the tray with a 50:50 biochar–soil mixture (or a mixture at the intended application rate) and fill the other half with an equal amount of control soil. Use the divider to separate them, and mark its location.
2. Wrap the glass vessel with aluminium foil to prevent light penetration into the soil sub layers.
3. With divider in place, gently water both sides to ensure moisture, without saturation.
4. Remove the divider and add 20 worms along the divider location.
5. Place a gauze or perforated plastic over the top to prevent earthworms from escaping while allowing for air and light. Plastic will help maintain moisture
6. Leave the setup for 48 hours, maintaining an artificial 16/8 day/night cycle.
7. After 48 hours reinsert the divider at its marked location.
8. Count the number of earthworms on each side. If a worm was cut, add 0.5 to each side regardless of the amount. Don't count dead worms.
9. Repeat the test at least five times to verify the significance of the results.

If biochar-amended soils show significant avoidance behaviour compared with control soil across multiple trials, it could suggest potential soil toxicity. The biochar should not be applied to soil without further investigation. Conversely, if worms did not avoid the biochar, it is safe for application to soil.

A standardised methodology for this test is available from the International Organization for Standardization (ISO 17512-1:2008); it can be downloaded from the internet for a fee.

Limitations of worm avoidance test:

A study on the avoidance test revealed the effectiveness of the test varied depending on the pollutant and contamination level. The study concluded that biochar might be considered toxic if fewer than 20% of earthworms remained in biochar-amended soil. Limitations of the test included that it did not identify all contaminated soils, it may only detect sensitivity and avoidance reactions to certain contaminants and concentrations, and it could not link a specific property to avoidance behaviour. For more information on the avoidance test, refer to the reference.[11]

CHARACTERISING SOILS AND FIELD TESTING

Optimising the benefits and profitability of biochar on the farm, with its specific soils, constraints, and crops, requires field trials to assess effects of biochars on yields, disease resistance, or quality of crops. Farmers interested in the effects of biochar on their soils, or the relationship of the soil changes to crop effects, will need to sample their soils and have them analysed for various characteristics, including nutrient levels and bulk density.

This section outlines the essential elements of field testing and soil sampling and includes references to resources.

Field trials

The process of conducting field trials to test the effectiveness of biochar involves several key considerations.

Control treatment

Establishing a control treatment is essential as a baseline for comparison of the effects of applying biochar. The control is a portion of the trial soil that has identical management with respect to all amendments and other conditions (such as tillage, shading, plant spacing, pest and disease practices) except for the additional biochar treatment itself. It is often a “business-as-usual” agricultural practice.

Replication

Field trials should be conducted in multiple locations to account for variations in soil quality, drainage, shading, etc. Some factors, such as agricultural residues from previous management practices, weed seed banks, or pest or disease pressure from adjacent areas, may be entirely unknown. If the biochar treatment zone is unequally assigned across these multiple “confounding factors” then results positive or negative may be attributed to the biochar when they are really due to one or more confounding factors. To reduce the possibility of confounding factors it is best to apply each treatment in several plots or strips called replicates. Replication to at least three to five plots is required to determine the statistical significance or reliability of the results.

Experimental design

Design considerations include:

- Replicate layout (many plots randomly distributed is best).
- Plot size (plots containing 5–10 plants at least to measure yields, disease resistance etc.).
- Edge effect (plants at edges of zones may experience different environments).
- Equal treatment (tillage, weed, pest and disease control should be uniform on all units, unless these factors are being investigated).
- Blinded trials (such as without labels to avoid unconscious bias of field operator).
- Crop choice (corn, beans, and carrots are easy to count; squash may intermingle, and tomatoes produce over extended time, making data collection difficult).

Sample collection of biochar and soil (to compare characteristics if one biochar stands out, or to establish a baseline to monitor changes over time). See section on soil sampling.

Application rates and methods

Biochar can be applied alone or with other amendments, using techniques like uniform topsoil mixing, application to planting holes, banding, or top-dressing. Application rates typically range from 5 to 50 tonnes per hectare, but the biochar needs to be amended only to the expected root zone of the plants. Also, enhanced biochar, biochar compound fertilisers, and biochar–mineral complexes can be designed which are effective at much lower application rates, similar to those for common fertiliser.

Handling biochar

Biochar is light, brittle, and dusty, and can spontaneously ignite if very dry, so it requires careful handling. Techniques like moistening or pelleting and incorporating it with sub-surface soil can help control dust and minimize wind and erosion losses.

Yield measurements

Crops should be collected from multiple plants within each experimental plot, avoiding edge effects. Data required to scale your results to a full production field (e.g. plants per area or lineal meters) should be collected consistently and recorded for analysis.

Analysing results

Statistical analysis helps assess the significance of differences between treatments. Graphical representation of data aids in interpreting and disseminating results.

Disseminating results

Sharing results through platforms like the International Biochar Initiative (IBI) Trial Registry facilitates collaboration and contributes to the collective knowledge on biochar's efficacy.

If you would like more detail on running larger-scale tests or trials to test the effects of biochar on plant growth, check out Julie Major's chapter in *The Biochar Revolution*[1] or her IBI Guide to Conducting Field Trials[3] that walks through the needed processes for accurate, scientific trials.

Measuring bulk density

Biochar can help to lower bulk density, which improves soil structure, water-holding capacity, nutrient availability, and aeration, while reducing erosion risk. Hence, measuring bulk density helps to evaluate the effectiveness of biochar in enhancing soil quality, crop productivity, and environmental sustainability. Bulk density is usually measured by taking soil in undisturbed cores (aluminium cores are made for this) and then drying the soil completely. The mass of the dry soil (minus the core), divided by the volume of the core, gives the bulk density. Biochar often has a lower density than soil. You can measure changes in carbon stocks after biochar application by measuring the changes in the soil's bulk density.

Soil sampling

Soil sampling before and after biochar application captures a snapshot of the soil's composition and characteristics before and after the intervention. Samples should be taken from multiple locations within each plot and sent for analysis of key soil properties such as pH, nutrient levels, organic matter content, and microbial activity, which are all essential for plant growth and soil health.

The results provide valuable insights into the changes in soil and plants induced by biochar amendments. Additionally, soil sampling enables the monitoring of long-term trends, helping farmers and researchers understand how biochar interacts with different soil types and climates over time. This information is crucial for optimising biochar application rates and other strategies to maximise its benefits of enhancing soil fertility, improving crop yields, mitigating environmental impacts such as greenhouse gas emissions and nutrient runoff and, importantly, its profitability.

Considerations for representative soil sampling

- If your trial lasts for more than one growing season, the annual soil sampling should occur at the same time each year, to match nutrient availability that changes across the course of a year.
- Sampling before planting or after harvesting tends to be the easiest, logistically.
- Soil that is very wet or very dry can be hard to sample.
- Soil can vary greatly within a small area.

Where to sample?

- Within one plot (roughly 4 by 4 metres), you should take soil from 3–5 locations to average soil variability.
- Avoid plot edges.
- A random or a regular pattern will work.
- If using crop rows, consider where fertiliser may be concentrated when choosing soil sample locations. Within one plot you could choose three locations on crop rows and two between rows, or pick all sample spots within the root zone if the soil within the root zone is of overriding interest.

How to sample?

- A trowel or shovel can be used; there are many augers and corers made for this specific task as well.
- Use an aluminium core if you are sampling to determine the soil's bulk density.

- Use the same tool each time and use it in the same way.
- Ensure you are replicating the depth reached when taking the soil sample each time (crucial, since there can be a rapid change of properties with depth, especially when transitioning out of the root zone).
- Surface soil (first 10–20 cm) is often preferred as it is the most influential to nutrient availability to crops.
- Label each sample in its container or tray or bag as soon as it is sampled, to avoid mislabelling or losing samples.
- Start air-drying the soil as soon as possible, by spreading each sample out over pieces of plastic or paper and leaving it for several days until it looks and feels dry. Do not air dry if you are sampling to do tests that require moist soils (i.e. inorganic nitrogen or soil biota). Note: Avoid keeping samples in plastic bags, which encourages mould.
- Archive your samples if possible after finishing tests. This will enable a re-run analyses or further tests later.

Composite sample

A composite sample is made up of samples taken from various locations within one experimental unit. Place all subsamples from one experimental unit into a bucket and mix thoroughly by hand, breaking large clumps. Accumulate 300 g from multiple places in the bucket and discard the rest of the soil. Make sure to accurately label the bag the soil is put in.

Quantifying carbon

Quantifying the increase in carbon sequestration due to farming practice changes is important to qualify for carbon credits. Specific methods for quantifying biochar in soil are being developed. Until such tests become available to the public, the best current alternative is to analyse the soil for total carbon, and to compare how much total carbon is in biochar-amended soil versus the control soil (the soil that did not receive biochar). The control soil will tell you how much non-biochar carbon is present in the soil. However, biochar does not easily degrade, and not all routine analyses for soil carbon or organic matter detect it. Therefore, it is important to specifically request a total carbon analysis, which is accomplished via dry combustion in a C/N analyser. If in doubt, contact the lab and explain what you need.

Analysing samples

Do-it-yourself kits are available to analyse some properties of soils (for example, pH). However, for those seeking a more reliable analysis of soil fertility, a specialised laboratory is recommended. A regional soil-testing lab can conduct analyses specifically designed for the soils of your region. To find a soil-testing lab in your region, you can contact cooperative or government extension services, universities with agronomy departments, or gardening stores. Many labs have online order forms and offer analysis packages.

Environmental Analysis Laboratory (EAL)

The Environmental Analysis Laboratory at Southern Cross University (SCU) specialises in range of quality analytical services covering:

- Agricultural soil testing
- Contamination testing
- General soils and solids testing
- Plant testing
- Waters and other liquids testing
- Acid sulfate soil and acid rock testing
- Compost, potting mix and landscape soils testing
- Scanning Electron Microscopy (SEM) Unit

EAL can providing detailed analysis of biochar and soils from samples sent in or can send qualified staff to undertake on-site sampling. www.scu.edu.au/environmental-analysis-laboratory---eal/

A variety of tests recommended for biochar are given on page 33 of the following document: www.scu.edu.au/media/scu-dep/services/environmental-analysis-laboratory/pricelists/Full-analytical-services-price-list-2023.1.pdf

FURTHER INFORMATION

This chapter is abridged and updated from two chapters in the book The Biochar Revolution[1] (from Chapter 8, Characterising Biochars: Attributes, Indicators, and At-Home Tests by Hugh McLaughlin, and from Chapter 14, Simple Biochar Tests for Farmers & Gardeners by Julie Major & Kelpie Wilson), and from other published articles by the same authors.[2,3] It also draws from work published by the International Biochar initiative (IBI)[4,5], the European Biochar Certificate (EBC)[6], and the ANZBIG Code of Practice.[7] More details and tests can be found in those resources. For more complex testing of biochar to generate data valid for analysing the statistical significance of results, see the IBI Guide, which is available online at http://www.biochar-international.org/ publications/IBI.

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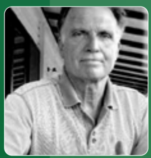

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