Asian Development Bank

Greater Mekong Subregion

Capacity Building for Efficient Utilization of Biomass for Bioenergy & Food Security in the GMS [TA7833-REG]

Output 4: Knowledge Product Series

Biochar

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CONTENTS

ACRONYMS

ADB	Asian Development Bank
BCP	Biochar Compound Products
CH_4	Methane
CO_2	Carbon Dioxide
GMS	Greater Mekong Subregion
H_2O	Water
Ha	Hectare
HHT	High heating temperature
ICS	Improved Cookstoves
IRRI	International Rice Research Institute
K	Potassium
LCA	Life Cycle Assessment
N or N_2	Nitrogen
N_20	Nitrous Oxides
NO_2 / NO_x	Nitrogen dioxide / 'NOXs'
NPK	Nitrogen, Phosphorus and Potassium
P	Phosphorus
PDR	People's Democratic Republic (of Lao)
pH	Measure of acidity or alkalinity
SOC	Soil Organic Carbon
t/ha	tonnes per hectare
µm	Micrometer - one thousandth of a millimeter (mm)

EXECUTIVE SUMMARY

1. Biochar is the solid product of burning biomass in very low or oxygen-free conditions - a process called ***pyrolysis***[1]. It is a black, carbon-rich and porous material with potentially important benefits for soils and plant growth in addition to potentially storing carbon in a stable form for hundreds of years.

2. **Benefits for soils and plant growth:** Consisting of a large proportion of carbon, biochar adds ***soil organic matter (SOM).*** SOM derives from biomass and improves the quality of many soils. It does this by: increasing the soils water holding capacity and the availability of water for plants during periods of water stress; reducing their bulk density (helping ploughing, plant root development and drainage); and enhancing the soils ability to hang-on to essential nutrients enabling their provision to growing plants.

3. Many soils have very low amounts of organic carbon due to many years of culivation without sufficient replacement of the removed biomass. Because of its high number and volume of pores (spaces), biochar stores water and nutrients that are dissolved in that water, some of which derive from the ash component of the biochar. Chemical bonding occurs between molecules on the biochar surface and nutrients that are vital to healthy plant growth such as nitrates, ammonium, phosphates, potassium, magnesium, sodium, calcium and so on. Evidence suggests that such chemical reactions act to improve the availability of nutrients to the plant, potentially reducing loss by run-off and leaching[2] (thus decreasing agricultural pollution of waterways). This means that added nutrients, such as from ***synthetic***[3] or ***organic fertilizers***, are potentially utilized more efficiently by plants grown in soils containing suitable types of biochar.

4. Biochar is usually alkaline, adding a further positive property by countering the acidity of many soils which acts to reduce their fertility.

5. **Storing carbon – mitigating climate change.** Most biomass is readily and rapidly broken down by ***microorganisms***, releasing its carbon into the atmosphere as carbon dioxide (CO_2). The vast majority of biomass decomposes to CO_2 in this way within 10 years in warm conditions. Since the carbon in the CO_2 originally came from the atmosphere via photosynthesis, there is usually no net effect on atmospheric carbon concentrations. Everything that is absorbed is released back into the atmosphere.

6. The chemical structure of biomass changes when heated in the absence of oxygen to produce biochar, resulting in an overall loss of hydrogen, nitrogen and oxygen relative to its carbon content. The carbon atoms become strongly bound to one another, making it very hard for microorganisms to break them apart. Biochar addition to soils ensures that this stable carbon delays the release of CO_2 into the atmosphere, slightly reducing the atmospheric concentration of CO_2. While biochar can contribute to ***climate change mitigation*** in this way, there are key constraints in

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[1] *Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. In general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content – char. Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen or water.*

[2] *Leaching, in this context, is the loss of water-soluble plant nutrients from the soil.*

[3] *Synthetic fertilisers are those made by chemical synthesis. i.e. chemical (man-made) fertilisers*

terms of the amount of biomass available for producing biochar and the overall economics of the operation.

7. Biochar has the potential to contribute to climate change mitigation because of the area of cultivated land that could incorporate biochar to store carbon for long periods. The size of biochar's contribution is defined by the availability of spare biomass and the extent that this is aggregated both in space and time and where the costs of collection, preparation and biochar production provide sufficient benefits.

8. **Challenges.** Considerable challenges remain in demonstrating the sustainability and effectiveness of biochar as a soil amendment and climate change mitigation technique. There is still no robust methodology for calculating how long biochar remains stable in soils and without a clear measurement of its stability, biochar cannot be traded in carbon markets. The agronomic performance of biochar remains highly uncertain, though the evidence supports an average positive influence of a 10% increase in yield. More reliable and predictable effects of biochar in different soils with specific crops is necessary to promote biochar and help support a market for its commercial production and use. At the same time, technologies for biochar production need further research and development to encourage a reduction of the unit cost of production, whether at household, enterprise, or larger scales.

9. Earlier ideas which involved applying biochar at application rates of 10 to 40 tonnes per hectare (t/ha) have largely been shown to be uneconomic due to the large amounts of biomass required and the processing costs. The possible exception to this is if the biochar is a waste by-product and would otherwise be discarded (depending on calculation of the variable costs and benefits). From an economic perspective, biochar application rates of 1 to 5 t/ha or lower are now being more widely accepted. There are several ways in which the agronomic value of low rates of biochar application can be maximized.

10. Firstly, biochar can be concentrated in the soil by ensuring it is applied close to the growing plant roots (without being so close that chemicals contained in biochar may interfere with root development). In this way, biochar is employed in that part of the soil where it has most benefit to the plant. The resource productivity of a given quantity of biochar is, in this way, increased.

11. A second potential approach to enhancing the value of biochar is by mixing biochar with a range of chemicals before and / or after pyrolysis to promote the chemical reactivity and performance of mixed biochar products. Evidence has been accummulating which indicates the benefits of mixing biochar and synthetic NPK fertilisers and of co-composting biochar and organic materials. In both cases, there is the prospect of producing biochar that is charged with nutrients that can be kept available to plants for longer to improve the efficiency of nutrient use.

12. **The Report.** This report defines what biochar is (***Section 1***), explains the reasons for the growing interest in biochar (***Section 2***), provides an introduction to the utilization of biomass for biochar, including the current uses of biomass (***Section 3***), explains the key production processes and technologies (***Section 4***) and its benefits (***Section** Error! Reference source not found.**)** -ncluding its functions when added to soil, including carbon storage and a critical assessment of evidence from field trials of biochar effectiveness in agriculture. The report points to key challenges for research and innovation in the biochar sector.

13. The report's geographical focus is primarily on the Greater Mekong Subregion (GMS), giving examples of potential approaches from agriculture and agri-processing activities on a range of

scales, from household to large rice mills, across Cambodia, the People's Democratic Republic of Lao (Lao PDR) and Viet Nam.

1. WHAT IS BIOCHAR?

Figure 1: ***Definition of biochar*** *(Source: British Biochar Association)*

Biochar is a solid material obtained by burning biomass in oxygen-restricted conditions which is used for soil improvement and for the long-term storage of stable carbon.

14. Biochar is the solid product of burning biomass in very low or oxygen-free conditions. It undergoes a process called ***pyrolysis*** whereby carbon in the biomass is concentrated while other elements are emitted as vapor, becoming diluted in the solid residue. Biochar is made via a similar process to ***charcoal*** and the two are indistinguishable in physical and chemical terms. The key difference is that charcoal is intended to be burnt as a fuel[4], whereas biochar is made to be added to soil, where it remains in a stable form for hundreds or even thousands of years. Increasingly other applications of biochar are emerging, such as use as a waste water filter, as an animal feed supplement and as a buidling material: in all these cases the biochar will end-up in the environment however.

15. The structure of biochar is shown in **Appendix 2**.

[4] Charcoal is a smokeless fuel which has approximately twice the energy content per unit mass of the wood from which it is produced, hence is a preferred everyday fuel in towns and cities in many developing countries, as well as used in recreational barbeques in most countries.

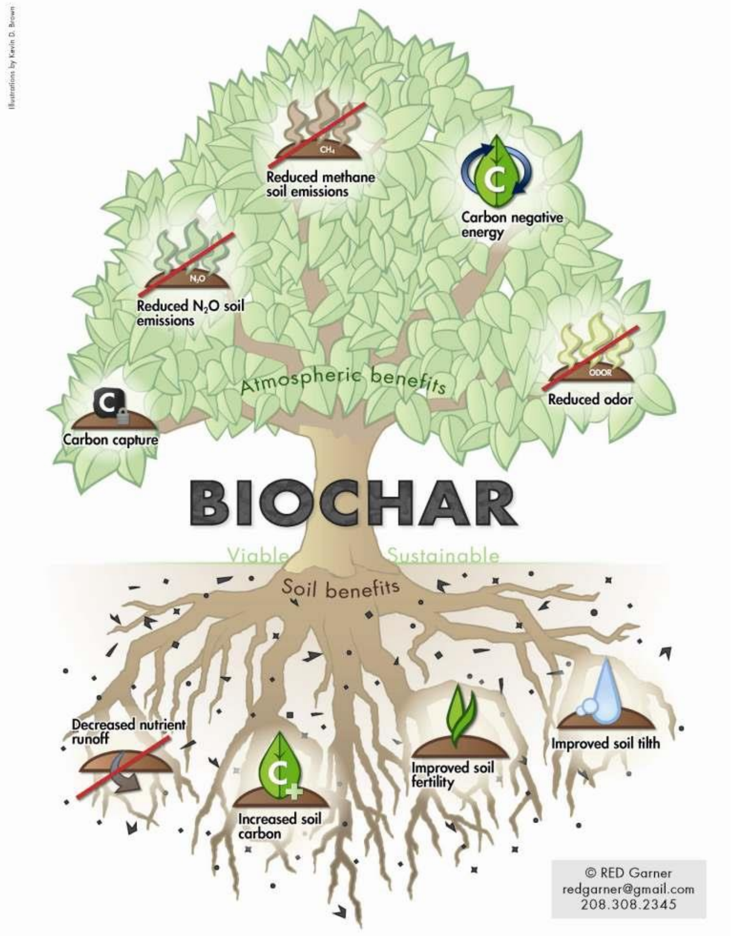
2. WHY IS THERE INTEREST IN BIOCHAR?

16. Interest in biochar can be traced back to observations of the ***terra preta*** soils of the Amazonia region, which were made by human societies living more than 500 years ago, through adding considerable amounts of charcoal, pottery, bones and other human-derived wastes to the soil. The *terra preta* soils are noticeably more fertile than surrounding soils which are often highly 'weathered' - i.e. depleted of nutrients that are vital to healthy plant development and prone to erosion. *The terra preta* soils are noticeably darker than the typical soils of the region due to the presence of charcoal and other organic matter. There is good evidence that the presence of charcoal in the soil has increased the amount of *other* types of soil organic matter, increasing further the carbon richness of such soils.

17. Combining the benefits of healthier, more productive soils with that of carbon storage in soils to reduce atmospheric concentration of CO_2, raises the prospect of a **win-win scenario**. Where there is spare biomass, such as agricultural residues not already fully utilised, it may therefore make sense to turn some or all of this into biochar.

18. The potential benefits of biochar to both soils and the atmosphere are many, as shown in the figure below. Some of these benefits are reasonably certain, while others are much more context-specific.

Figure 2: Some of the key benefits and functions of biochar



Source: International Biochar Initiative (IBI), 2010 (www.biochar-international.org/sites/default/files/CHARTREE2.jpg) (used with permission)

19. In addition, if more advanced pyrolysis technologies[5] can be used to generate ***syngas***[6] and heat, there is the prospect of bioenergy generation from pyrolysis, offsetting use of other fuels to produce heat and even electricity. This would constitute a reduction in existing fuel use and a reduction in net carbon emissions to the atmosphere. Along with addressing climate change and soil health, adding bioenergy generation to the mix would make biochar a **triple-win** option.

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[5] *The technologies used to produce biochar – see further details in section 4.*

[6] *Syngas, or synthetic gas, is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. The name comes from its use as intermediates in creating synthetic natural gas (SNG) and for producing amm9onia or methanol.*

3. BIOMASS, CURRENT USES, AND WHAT HAPPENS WHEN IT IS BURNT

20. ***Biomass*** is defined as *"the biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry, and related industries including fishing and aquaculture, as well as the biodegradable fraction of industrial and municipal waste (including municipal solid waste)".* [7]

21. The residues that are grown alongside the main agricultural crop, such as straw, are not waste but an important by-product. Agri-residues are currently used as bedding and feed for animals, as a fuel and as a soil amendment amongst other things. Manures and urine are residues from animals that are important soil amendments.

22. A separate report from TA-7833 examines the current utilization and resource availability of biomass in the Lao PDR, Cambodia and Viet Nam.[8] A key finding is that there are large potential sources of biomass in the three countries; however, whether they are economic to utilise will depend upon the usual factors of supply and demand, in particular how concentrated is the supply and are the end-use options able to meet the demands for, say, heat and power.

23. Burning of large quantities of biomass such as straw is still common in some parts of Asia. This is usually because the farmer wants to clear the land quickly to establish the next crop but it also reflects the underlying low value of the straw and often the lack of labour in rural areas and / or machinery to remove the straw quickly. Straw burning has many negative environmental impacts and has been implicated in many episodes of poor urban area quality.

24. Most biomass consists of three primary elements which, by weight, include approximately 50% carbon, 40% oxygen and 5% hydrogen. The remaining biomass consists of nitrogen (N) (0.3%), sulfur (0.1%), chlorine (0.1%) and trace amounts of phosphorus, potassium, calcium, silicon, sodium and other elements. The precise constituents of biomass will vary depending on species, growing conditions, soil conditions, etc.

25. If biomass is burnt in plenty of air with good mixing (aerobic conditions), the carbon, oxygen and hydrogen react with oxygen (O_2) and converted into carbon dioxide (CO_2) and water vapor (H_2O). Nitrogen will also be emitted as N_2 or, at higher temperature, as nitrous oxides (NO_x).

26. If biomass is burnt with somewhat limited air or mixing, other gases such as carbon monoxide (CO) will be formed, along with solid particles and hydrocarbons. Carbon monoxide is highly toxic, whilst particulate matter has a range of potential negative health impacts. The overall effect of biomass burning on climate change is zero, though there are still many uncertainties.[9]

27. If biomass is burnt in air-restricted (anaerobic) conditions, as in charcoal-making kilns, methane (CH4) and nitrous oxide (N2O) with be formed, along with black soot (unburned carbon) and organic carbon particles. CH_4, N_2O and black carbon (BC) are all causes of global warming (so-

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[7] *European Commission Agriculture and Rural Development (2010), Biomass Potential http://ec.europa.eu/agriculture/bioenergy/potential/index_en.htm*

[8] *TA7833 Technical Report: Agricultural Biomass Resource Assessment in Cambodia, Lao and Viet Nam, June 2013*

[9] *page 683, IPCC (2013)*

called ‘climate forcers’). CH_4 lasts in the atmosphere on average 12 years and is 28 more powerful a greenhouse gas than CO_2 per molecule. N_2O is 265 times more powerful a greenhouse than CO_2 and lasts for 121 years on average. BC lasts in the atmosphere for one week and is 345 more powerful as a greenhouse gas than CO_2.[10] Because BC acts as a climate forcer for such a short-time compared to CO_2, its reduction is not easily compared to reducing CO_2 emissions.

28. Most of the other elements in biomass end up in the ash, with the smaller particles as fly ash and larger particles as bottom ash, usually as salts or metal oxides. Such ashes are alkaline (pH above 7). Too much chlorine in the feedstock can result in the production of toxic compounds such as dioxins.

29. As discussed, agricultural residues such as straw, husks, stalks, shells and cobs have frequently been burnt in the field. Where the ***feedstocks*** are air-dried and in contact with air, ash is produced. Ash has some useful properties, such as returning some nutrients to the soil and increasing the pH of excessively acidic soils (pH below 7).

30. On the other hand, burning to ash results in the loss of most of the carbon, hydrogen and nitrogen from the biomass. Agricultural residues are frequently somewhat moist and anaerobic conditions occur in parts of the straw or husk pile when burnt in the field. This results in the production of smoke, soot particles, methane and nitrous oxide, causing local air pollution and contributing to climate change. Smoke drifting into urban areas of China from surrounding fields where straw is being burnt has resulted in bans on straw burning in some provinces or in incentives to collect rather than burn straw. Examples of rice straw burning are shown in the figures below.

31. An alternative to burning is pyrolysis to produce biochar along with by-products. Smoke and pollutants can be reduced and useful bio-products produced. These bio-products have the potential to improve soils, store carbon on climate change relevant timescales and replace fossil fuels as energy carriers. The next section will explore how biochar is produced.

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[10] *Values here all taken from Chapter 8, IPCC (2013)*

Figure 3: Burning of straw in the field, simulating the widespread farmer's practice. The left picture shows the initial process with open flames, the right picture shows a later stage when the heap is smoldering without open flames (from IRRI in Karve et al. 2010)

Figure 4: Aerial view of rice fields in the surrounding of IRRI, Los Baños, Philippines, showing the concentration of harvested rice in the center of each field, and burning of the residues after threshing, a widespread practice amongst farmers (from IRRI in Karve et al. 2010)

4. HOW TO PRODUCE BIOCHAR

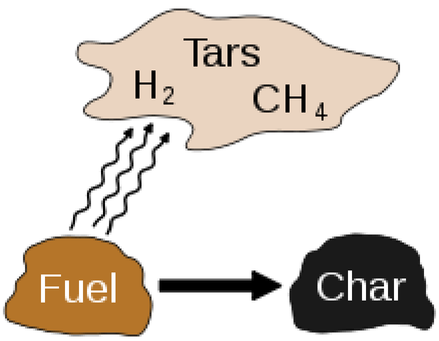
4.1. THE PYROLYSIS PROCESS

32. Biochar is created by a process called pyrolysis, in particular ‘slow’ pyrolysis which can be separated into traditional charcoal making and more modern processes. The biomass is heated slowly to high heating temperatures (HHT) of 450 to 750^{o}C. The heating rate is up to 100^{o}C per minute but is frequently much lower than this. The vapour and solid char remains in the equipment for 5 to 30 minutes[11] but residence time for the char can be up to several days in traditional charcoal making.

33. Slow pyrolysis splits biomass into three parts: solid char (typical range 25 –40% by mass), ***syngas*** (typical range 20-50% by mass) and condensable vapours (***pyrolytic liquids***) (typical range 20-50% by mass).[12] Temperatures of c. 400°C produce more char (c. 40% by mass) while temperatures above 750^{o}C produce less char (c. 25% by mass).[13]

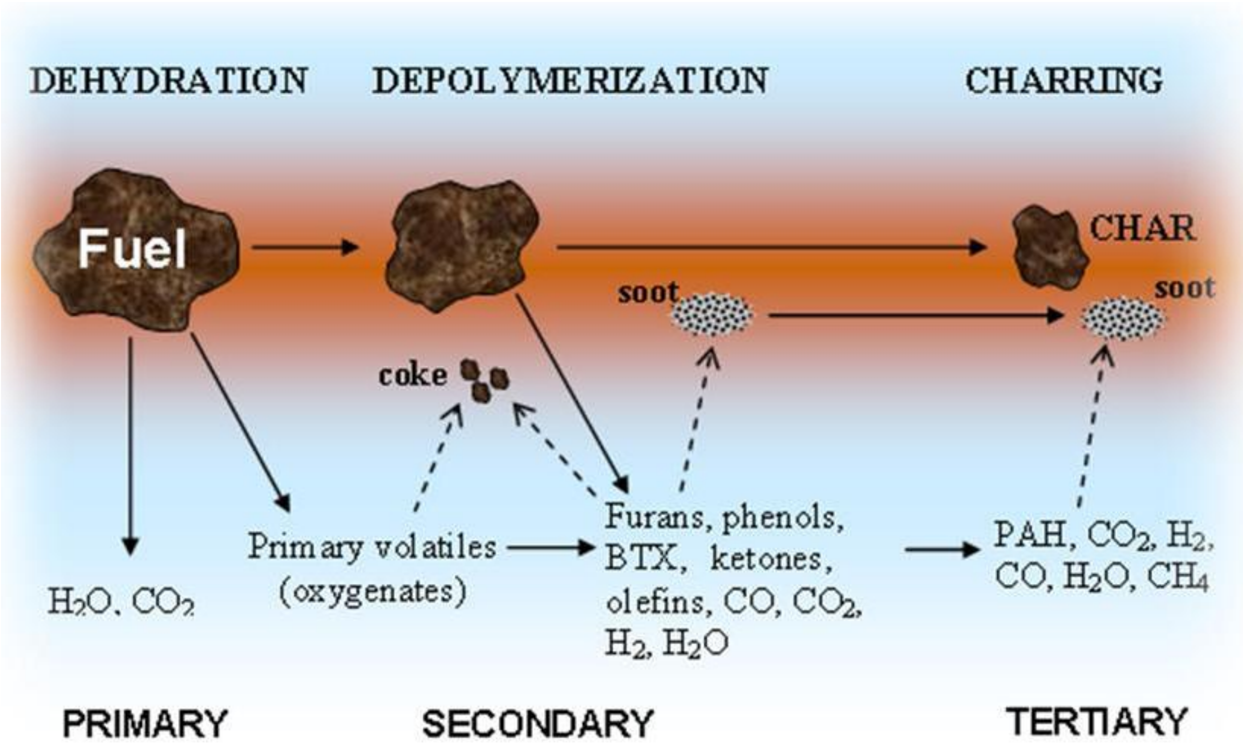
34. The properties of biochar produced at a high heating temperature (HHT) of 400^{o}C are quite different from those produced at above 700^{o}C due to the presence of more condensed ‘secondary’ char at the lower temperatures which ‘clogs-up’ the pore space. At the lower HHT the condensates contain longer, more complex hydrocarbon chains while at the higher HHT, these longer compounds have been broken-down into smaller molecules some of which are released as gases.

Figure 5: A simple depiction of the pyrolysis process (Source: Wikipedia)



[11] *Brown (2009).*
[12] *Shackley, S. et al. (2012)*
[13] *The terms ‘slow’, ‘intermediate’ and ‘fast’ pyrolysis do not refer to the ‘high heating temperature’ at which pyrolysis takes place but to the **residence time** of the vapour in the pyrolysis equipment. In the case of ‘fast pyrolysis’ the vapor is removed very rapidly from the char (in under one second) giving much higher bio-liquid by mass (75%) and an equal mass of gas and char.*

Figure 6: A more detailed depiction of the pyrolysis process



35. The properties of biochar vary greatly depending on: feedstocks used in its production, feedstock preparation pre-pyrolysis (e.g. pelleting, particle size), production conditions (temperature, additives such as clay or other minerals) and post-production treatment (quenching, pelleting, etc.) (Novak et al. 2013). Many different variables influence the properties of biochar but precise predictable knowledge of the relationship between feedstock, production conditions and biochar properties remains incomplete.

36. Biochar produced at a lower temperature (approximately 400^{o}C) will tend to have a lower specific surface area and porosity. Biochar produced at a higher temperature (700^{o}C) will tend to have a higher surface area, porosity and more negatively-charged surfaces. Since there are several useful properties of biochar, it may be possible to combine the benefits of biochar made at both lower (400^{o}C) and higher (700^{o}C) temperature by mixing. Due to feedstock properties, selecting straw and similar agri-residues for pyrolysis at the lower temperature and woody materials for pyrolysis at the higher temperature might make good sense. Such a biochar blend will have high porosity and high specific surface area, hence high internal volume for water and the chemicals dissolved in water (solute) and for microbial associations to develop. The lower-temperature biochar adds positively charged surfaces and less stable organic matter to fuel microbial growth.

37. Addition of other minerals and elements during pyrolysis is also important to control temperature (clay additions) and introduce iron (by adding rusty water) that is reduced and precipitates on the surface of the biochar and may act as a catalyst for biochar surface chemistry. Ash, produced using low-temperature ashing, introduced post-pyrolysis adds metal ions, cations (+ve charged ions) and increases the neutralizing capacity (pH ↑). Analysis of co-composted biochar which has been in the soil for one year has shown increased reactivity and nutrient retention (especially for nitrate) compared to the same one-year old biochar in the same soil but not added during compost production and added to the soil ‘pure’.

4.2. TECHNOLOGIES FOR PRODUCING BIOCHAR

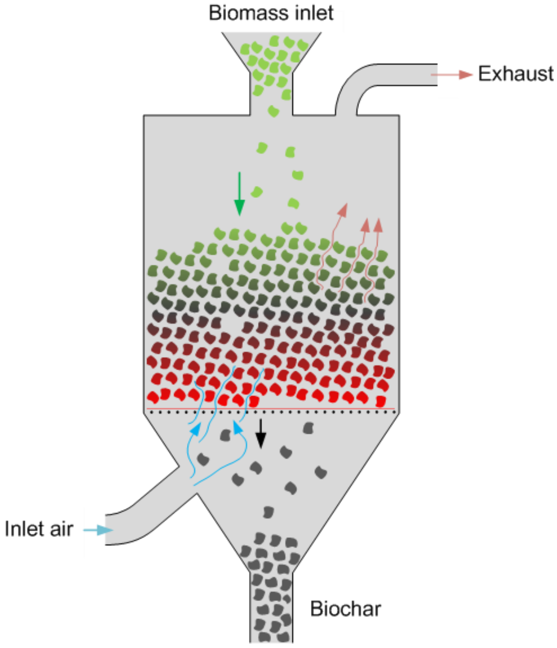
38. Technologies for producing biochar are available at a wide range of scales – from tin-can sized units to industrial-scale units processing tons of feedstock per hour. However, despite several years of research and development, there are rather few examples of standardized biochar-producing equipment available to customers. The most common units are at three scales.

a) Improved Cook Stoves (ICS) produce biochar as a by-product of cooking - either with an inner combustion chamber and an outer pyrolysis chamber or a single chamber design with inner chimney.[14] These units typically produce 100 to 1000g per run.
b) Oil-drum kilns come in a range of different designs and sizes (approximately 100 to 200 liter capacity) and typically produce 7 to 15 kg of biochar per run.
c) Retorts such as the *Adam Retort*[15] are static brick and metal units which can produce up to 400 kg biochar per run (over two days operation). Also at this scale, are much more expensive, highly engineered metal retorts such as the *Exeter Retort*, *Carbon Gold twin-retort*, *BigChar* and the *BigRoo*. A new design at the 400 kg biochar scale per run is the *Kon Tiki* metal cone retort, which does not require physical exclusion of air, keeping the cost down.[16]

39. Most charcoal and biochar producing technologies can be polluting if not designed and operated correctly. The better designs feature adjustable air inlets, allowing the reaction to start in plenty of air, which can then be shut-off to promote pyrolysis. Good designs also include adjustable secondary air inputs at the outlet of the kiln or retort, or fire boxes where hot temperature combustion is underway, to burn-off fugitive emissions of greenhouse gases and particles. An example of a contemporary design for producing biochar is provided in the figure below.

[14] *Such as the Sampada*
[15] *A retort is a container in which biomass is placed and heated from the outside, either indirectly through metal or directly by recirculating hot gas through the biomass (FAO 1987).*
[16] *Schmidt, H-P. and Taylor (2014)*

Figure 7: The Schottdorf kiln as used by Carbon Terra (Germany) for commercial production of biochar



40. ***Gasification*** is a different process from pyrolysis but qualifies as a legitimate biochar-producing technology according to some, but not all, specialists, even though the purpose is to produce gas, not char. It occurs at a high enough temperature (>800 to 1100^{o}C) that most of the char and vapour breaks down into gas (yields by mass c. char 10%, liquid 5% and gas 85% respectively). Since the purpose is to produce gas, the objective is to minimise production of char and liquids and modern designs can reduce char to 2% yield by mass. In exceptional circumstances char yields can be higher than 10%. This is the case where feedstocks containing a large amount of silica are used, such as rice husks and rice straw. The silica does not break-down at gasification temperatures and it also appears to protect the carbon from thermal decomposition such that char yields can be 35% with 35% carbon content (both by mass).[17]

4.3. OTHER USES FOR PYROLYSIS EQUIPMENT AND THE BY-PRODUCTS OF THE PYROLYSIS PROCESS

41. While this report concentrates on the production of biochar, it is useful to briefly mention other uses of pyrolysis equipment and the by-products of the pyrolysis process. The main use of pyrolysis at present is waste treatment and management e.g. on ships, for clinical hospital wastes and for sewage sludge treatment prior to end disposal. In these cases, the char produced is usually too contaminated for consideration as a soil amendment.

42. In the simplest pyrolysis equipment the purpose is solely to produce charcoal or biochar. While this retains approximately 50% of the energy value of the feedstock and approximately 50% of the carbon, if the pyrolytic vapours are simply burnt-off, then the efficiency of the use of the biomass is limited. If there is a use for the excess heat, then the overall efficiency of use of the biomass is

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[17] *Shackley et al. (2012 a & b)*

much improved. More advanced pyrolysis systems use excess heat for feedstock drying, including feedstocks other than those used in pyrolysis itself, potentially generating a further benefit.

43. Pyrolysis syngas use for electricity generation has proven difficult, in part due to variability in the composition of the produced gas. The pyrolytic liquids are potentially a source of both chemical feedstocks and tars for energy. However, to be viable this requires these to compete with the petro-chemical industry as a source for chemicals such as acetone and methanol and is not easily achieved. Niche uses for pyrolytic liquids may exist e.g. as bio-pesticides, but further product testing and validation is required.

5. THE BENEFITS AND USES OF BIOCHAR

5.1. BIOCHAR AS A SOIL AMENDMENT – IMPROVING AGRICULTURAL PRODUCTIVITY

5.1.1. Biochar Addition to Soils

44. In order to comprehend the use of biochar in soils, it is important to consider its structure. This is shown in **Appendix 2**.

45. Biochar is not a fertilizer. It is not intended to supply the key nutrients required by plants – nitrogen, phosphorus and potassium (NPK). Supply of NPK occurs through adding synthetic fertilizer and/or organic fertilizer. Biochar is, instead, a soil amendment, which is a material added to soil to improve its physical, chemical and biological properties, such as water retention, drainage, aeration, permeability, ability to retain nutrients and diverse and resilient micro- and macro-fauna. ***Soil amendments (or conditioners)*** aim to enhance the health of soils in the long-term. Healthy soils tend to be more productive and beneficial from the perspective of what humans want from them and require fewer chemical inputs and irrigation.

46. There have been hundreds of separate pot and field trials testing biochar and biochar-organic mixtures in many different countries in Asia, the Americas, Australasia and Europe. The method of meta-analysis has been employed by scientists, whereby all the studies with sufficiently comprehensive information have been collated and powerful statistical methods used to draw out general conclusions regarding the effectiveness of biochar as a soil amendment, including identifying the key factors which influence the response.

47. Four such meta-analyses of the research to date[18] regarding the impact of biochar on plant growth and soils have been published which show that, *on average*, there is a statistically significant increase in harvestable crop yield from biochar-based soil amendments of approximately 10%.[19]

48. While a powerful technique, meta-analysis ends-up comparing a lot of very different situations and contexts. The results reveal just how much uncertainty there is associated with the impact of biochar upon plant growth, with the average yield effect concealing a wide range of cases, from exceptionally high yield increases (100%+) to minimal or no impact and some reporting negative results. Change in crop yield varied from -28% to 39% in one meta-analysis (Jeffery et al. 2011). Crane-Droesch et al. (2013) note of the results of their meta-analysis that: "Variability in this response is high, ranging from cases where biochar reduced yields to cases with large relative increases (commonly from cases with near-failure in zero-biochar controls." Of 62 separate trials analysed by Biederman & Harpole, 65% showed a positive response, 3% no response and 32% showed a negative response.

49. The meta-analyses could not identify any clear correlation between the biochar application rate and the plant response.[20]

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[18] *as of December 2014*

[19] *Jeffery et al. (2011); Crane-Droesch et al. (2013) specifies that this 10% increase is for a 3t/ha application rate in the first year after application; Liu et al. (2013) report a 15% average yield increase for pot and field trials, but 10% for field only. For rice fields, they report a mean increase of 5%.*

50. Jeffery et al. (2011) found that the greatest impact on crop yield occurred in soils which were acidic and neutral, with a coarse or medium texture, leading them to propose that the main mechanisms by which biochar works are liming (increasing pH), increased availability of nutrient to crops and improved soil water holding capacity.

51. Biederman & Harpole (2013) found that plant productivity in biochar trials varied significantly with latitude – yields were higher at low latitudes (0-30^o) (tropics and sub-tropics) compared to yields at higher latitudes (>30^o) (temperate zones). Biochar produced at temperatures of 450 to 650^{o}C had more positive impacts upon yield than those produced at a lower temperature (<400^{o}C). Biochar pH had a significant impact upon productivity with alkaline biochar enhancing above-ground growth, while acidic chars decrease above ground-production. There was a significant increase in concentration of potassium (K) and phosphorus (P) in the soil following biochar application. Biochar produced from grassy and animal-derived feedstocks (manure, sludges) had significant benefits over those derived from woody material.

52. Crane-Droesch et al. (2013) concluded from their meta-analysis that: *"We find that yield response increases over time since initial application, compared to non-biochar controls. High reported soil clay content and low soil pH were weaker predictors of higher yield response. No biochar parameters in our dataset - biochar pH, percentage carbon content or temperature of pyrolysis - were significant predictors of yield impacts. Projecting our model onto a global soil database, we find the largest potential increases in areas with highly weathered soils […which tend to have low cation exchange capacity, low soil organic carbon, low pH, and relatively non-reactive clay minearology….], such as those characterizing much of the humid tropics. Richer soils characterizing much of the world's important agricultural areas appear to be less likely to benefit from biochar."*

53. The findings of Crane-Droesch et al. differ somewhat from those of other meta-analyses which have promoted soil pH as a primary determining factor in understanding the response of plants to alkaline biochar additions. Crane-Droesch et al. also found little evidence that the plant's response to biochar is mediated by nitrogen additions to soil (consistent with Biederman & Harpole). They did not find any significant difference between animal-waste derived biochar and plant-based biochar; this is a quite different finding from other meta-analyses in which animal-derived biochars tend to result in significantly greater plant growth than plant-derived biochars.

54. One experiment in upland rice fields in northern Lao PDR demonstrated that 'pure' woody biochar addition to soil (4, 8 and 16 t/ha application rates) reduced rice yield compared to the control of no biochar (and where no additional source of plant-available N was added) (Asai et al., 2009). The reason is likely to have been that the biochar sucked-up the already-present N in the soil and reduced its availability to the growing rice plant. The conclusion is that pure biochar additions will either have no effect or will reduce yields unless there is sufficient plant available N and P.

55. As a contrast, a field trial in Zambia using maize cob biochar at 4 t/ha in an acidic, sandy soil led to a harvestable yield increase for maize of 444% (Cornellisen et al., 2013). Synthetic fertiliser was also added but at 50% of recommended fertiliser rates. The biochar was added close to the root zone of the plant so that its effective concentration is 30 t/ha. It is not entirely clear why the yield gain was so great – the best guess is that it is due to biochar improving the availability of water to the plant at a time of severe water stress and to the improvement in nutrient retention.

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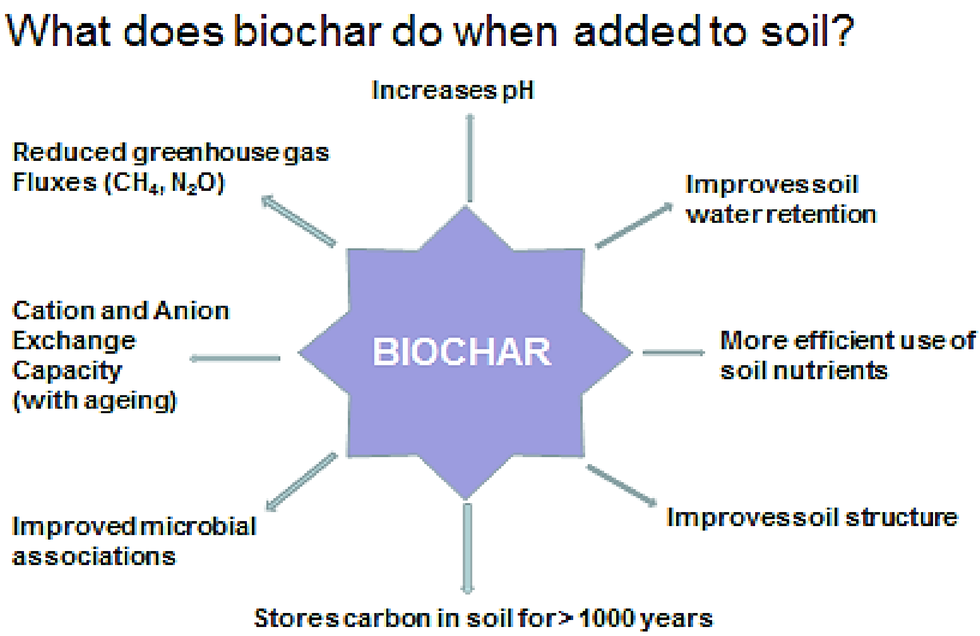
[20] *Ibid., Biederman & Harpole, 2013; Liu et al., 2013b.*

56. A further complication is the time-scale. According to some experts, biochar is not anticipated to work straight away but needs time in the soil to begin to have positive effects – for example, as biochar weathers and ages, the particle size breaks down and it slowly oxidizes, which increases its capacity to retain nutrients. Crane-Droesch et al. (2013) found in their meta-analysis that there was a significant increase in crop yields in the second season after biochar application and even more so in the fourth season after application (average increase of 7% and 12.3% respectively). There are, however, few biochar field trials which extended over a number of growing seasons and/or years.

5.1.2. Function of Biochar in Soils

57. How exactly biochar works in enhancing crop productivity is not fully understood, although there is an emerging consensus on some of the mechanisms involved. The single or multiple properties of biochar when applied to soil (Spokas et al. 2013) are illustrated in the figure below.

Figure 8: The diverse functions and properties of biochar



Note: these are potential functions and properties which will occur in some situations and contexts but not in all.

58. For weathered acidic soils, typical of the sub-tropics, a key benefit of biochar addition is likely to be an increase in soil pH. The increase in pH of acidic soils is important in improving nutrient exchange and, in particular, in enhancing the availability of phosphorus which, at low pH, reacts with iron oxides and becomes unavailable to plants. At higher pH, more of the iron and aluminium dissolves into solution releasing the P. An increase in soil pH is also important in reducing toxicity of Al, Cd and Mg ions on plant roots.

59. Biochar produced at a lower temperature has a lower pH than that produced at higher temperature. This is because the pH of biochar is a function of the base ion (Ca, Na, K, Mg) content

within the ash which will be more concentrated at a higher temperature. The ash content will dissolve in the soil water and be dissipated, so the pH of biochar will reduce over time. The composition of base ions in biochar also varies by feedstock.

60. There is no straight forward relationship between soil pH and biochar. This is because soil pH is determined by the so-called buffering capacity of the soil – that is the ability of the soil to replace H^+ when concentrations decline. Clayey-soils have a high buffering capacity and are able to replace H^+ over extended periods. This means that the pH of these soils is very hard to change despite the addition of alkaline or acidic chemicals. Sandy soils have much lower buffering capacity, however, and their pH will respond much more rapidly to acidic or alkaline soil amendments. While adding biochar to a sandy soil should increase the buffering capacity, a very large amount would need to be added to make the effect significant. Even for a sandy soil with low buffering capacity, many tons of biochar per hectare would need to be added to increase pH by one unit.

61. In a number of experiments where pH change has been controlled for by liming the control, biochar addition still led to a significant yield increase (Steiner et al, 2003). Therefore we know that the mechanism by which biochar works is not solely through pH modification.

62. Biochar has a low bulk density of 0.3 to 0.5 t m^3, which is about one-third to one-fifth that of most soils. Adding biochar will reduce bulk density, increasing soil volume which enhances water holding capacity and permeability to excess water (improving soil drainage). Increasing the spaces within and between the soil particles promotes better gas exchange, allowing organisms to flourish. A less compact soil is easier to plough and is less prone to damage from the effects of heavy machinery, animals and/or rainfall. However, some of the biochar particles may end up occupying the existing spaces (pores) within the soil in which case a reduction in bulk density and increase in soil volume from biochar addition do not automatically follow.

63. If plenty of water is poured onto dry biochar held in a funnel and allowed to drain out the bottom, the amount of water that remains held by the biochar is typically from one to six times the weight of the dry biochar. This ability of biochar to hold on to water is called the ***Water Holding Capacity (WHC).*** The WHC of biochar mixed with the soil is not the same as 'pure' biochar tested in a laboratory. Biochar mixes with the other constituents of soil and some particles may occupy existing soil spaces reducing the space for water.

64. WHC is a crude measure of the water actually available to the plants growing in the soil. This is because what determines *plant-available water* is the tension with which water is held by the soil as it dries out (Ashman & Puri, 2002). The tension is determined by the size of the pores in the soil. If these pores are larger – as in sandy soils – then water will move rapidly through the soil but the tension holding onto water is lower and therefore plant-available water less than for soils where the pores are much smaller and the tension is much greater – as in clayey soils.

65. The effect of biochar addition on the plant-available water depends on the type of soil. If it is a sandy soil, smaller pores are added which will increase the tension and plant-available water. If it is a clayey-soil, the plant-available water will not be increased, though larger pores in the soil will allow better gas exchange within the soil. For a loamy soil, the plant available water might increase, though many loamy soils already enjoy a good balance of plant-available water and gas exchange.

66. Biochar holds very little nutrient value, though in some cases it has been suggested that the provision of a micro-nutrient (such as zinc, molybdenum or selenium) that was deficient in the soil by biochar addition is likely to be the key factor explaining its benefit.

67. Biochar frequently has a very large internal surface area and high pore volume, meaning that it has the capability to adsorb and retain nutrients added from either synthetic NPK fertilizers or compost/manure.[21] These nutrients and ions are dissolved in pore-water. The surface area of biochar is frequently in the range 200 to 600m^2 per g, though it can be as low as 1m^2 per g.

68. The chemical reactivity of these surfaces helps to explain the capacity of biochar to retain nutrients such as K^+, Na^+, Ca^{2+}, Mg^{2+} that can be provided to the growing plant via suction by plant roots. There is growing evidence that negatively ions such as nitrate (NO_3^-) and phosphate (PO_4^{3-}) can also bind to the surfaces of biochar. If that is the case, the plant roots would also be able to access these primary plant nutrients via their roots.

69. Biochar has been shown in several studies to improve the efficiency of the utilization of nutrients when added as fertilizer.[22] *Terra preta* soils have been shown to have high levels of nitrogen and phosphorus but do not necessarily hold on to further added nitrogen. Several biochar field trials have measured how productive nitrogen addition is in biochar-amended plots compared to control plots and have reported an increase in such productivity.

70. The mechanism(s) behind enhanced nitrogen productivity are not fully understood. It has been suggested that biochar reduces the conversion of mineral nitrogen fertilizer into gaseous forms of N such as N_2 and N_2O. Gaseous forms of N are readily lost to the agricultural system. It has also been proposed that the ammonium ion (NH_4^+) which splits off from fertilizers such as ammonium nitrate attaches to the negatively charged biochar surfaces, thereby reducing N loss. Work recently submitted for publication suggests that nitrate ions (NO_3^-) which split off from fertilizers may be attracted to *positive* charges on the biochar surfaces. This is possible because biochar surfaces contain both negative and positive charge. Leaching of nitrates from the soil into water ways is a common source of pollution. Reducing the conversion of fertilizer N into N_2O, NH_3 or N_2 and/or retaining NH_4^+ and NO_3^- for longer in the plant-root zone means that the plant can make better use of a limited supply of N fertilizer which would account for increased nitrogen productivity.

71. Adding biochar to soil is also known to result in changes to soil microbiology. The impact of such changes is still being investigated but it is known that the microbial communities around plant roots are extremely important in plant growth and development. More diverse and resilient microbial communities would tend to enhance the prospects for healthy plant growth.

72. Biochar addition increases soil organic carbon (SOC) levels[23].

73. Biochar can assist in the remediation of contaminated soils through removal of heavy metals and, potentially, organic contaminants.[24]

74. A further potential role of biochar is that it reduces the negative effect of pests or diseases on plant development (Graber et al., 2014). There is some evidence of ‘U’ shaped response with respect to the effects of biochar addition on the capacity of certain species of microbes or viruses to cause a disease – i.e. at high and very low biochar doses there is no benefit in terms of reducing the

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[21] *Joseph et al., 2013, Novak et al., 2013, Joseph et al., in preparation, Kammann et al., in preparation.*
[22] *Steiner et al., 2008; Chan & Xu, 2009; van Zwieten et al., 2010*
[23] *Kimetu et al., 2008; Zimmerman et al., 2011*
[24] *Beesley et al., 2011; Bian et al., 2013; Houben et al., 2013*

adverse effects of plant pests/diseases. At intermediate biochar doses (0.5 – 1% by weight in pot trials) however, there appears to be a benefit to the plant (Graber et al., 2014).

75. The low bulk density of biochar (a third to one fifth of the receiving soil) and the presence of very small particles, some of which are water repelling, mean that there is a high potential for lateral movement of biochar compared to other soil components. Where biochar is applied to soil subject to intensive rainfall, there is the prospect of high rates of movement of the biochar off the land on to which it was applied. The loss has been calculated as up to 25% over two years, while it was calculated as 66% over 30 years in one study.[25] As biochar becomes more water accepting and forms associations with mineral particles, it appears to become better 'anchored' within the soil matrix which reduces loss from the application site.

5.1.3. Biochar Compound Products

76. The majority of biochar pot and field trials have used application rates of 5 to 40 t/ha.[26] 10 t/ha equates to 1kg of biochar per m^2 and is only a third of one percent of topsoil mass. Because of this dilution, it was originally assumed that pure biochar additions needed to be in the order of > 5 tons per hectare to have any effect. Farmers are also used to adding organic amendments such as manure, sewage sludge and digestates from brewing and anaerobic digestion facilities at rates of approximately 10 t/ha, in part driven by need to dispose of such materials efficiently. Adding 1 t/ha of pure biochar would equate to 100g per m^2 and would only be 0.030% of topsoil mass.

77. At present, the precise chemical reactions which occur within - and on biochar - are not fully understood and additional research is necessary before a more complete understanding of mechanisms and processes is acquired. However, the latest recommendations on how to use biochar have changed.

78. There has been a move away from adding 'pure' biochar and a trend, instead, towards mixing biochar with organic matter, clay, ash and / or synthetic chemicals such as NPK fertilizers. These mixtures have become known as ***biochar compound products*** (BCP). The biochar component may be a relatively small percentage by mass or volume - from 1 t/ha to several tons per ha. There are *hypothesised* to be synergistic effects from mixing biochar with other materials such as compost, manure, NPK, clay and other chemicals which stimulate the reactivity of the biochar pores and surfaces (Joseph et al., 2013). This effect on the biochar surfaces is known as ***biological or chemical activation*** of biochar.

79. Chemical activation of biochar is hypothesised to occur through reaction of biochar with compounds such as urea, phosphates, potash, ammonium sulfate, metal compounds, etc.

80. Biochar also undergoes slow oxidation during storage, increasing its capacity to retain nutrients once applied to soil. Physical and chemical changes occur as biochar is broken down in the soil into smaller-sized fractions –reducing its capacity for retaining plant-available water.

81. Biochar mixed with nutrient-containing materials such as manure, compost, bio-slurry, or with synthetic NPK, is hypothesised to combine the benefits of a stable carbon matrix with those of

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[25] *Major et al. 2010; Nguyen et al. (2008)*
[26] *Jeffery et al., 2011, Hammond et al., 2013, Biederman & Harpole, 2012, Crane-Droesch et al., 2013.*

organic matter, including available nutrients.[27] During mixing, and once in the soil, biochar associates with minerals and other sources of organic matter. The biochar-mineral-organic matter complexes formed appear to protect non-biochar soil carbon from oxidation, adding to the enhancement of the Soil Organic Matter content.

82. It is hypothesised that the combination of biochar which has a high internal surface area and internal pore space with nitrogen-containing bio-wastes or synthetic chemicals creates a slow-release fertilizer. A slow-release fertilizer will increase nutrient-use efficiency and reduce the loss of N and P as nitrates, ammonia, N_2, N_20 and phosphates through the soil profile or to the atmosphere.

83. The sheer problem of producing sufficiently large quantities of biochar to meet a 10 t/ha demand has added a strong incentive for a reduced biochar application rate. At least 3t of feedstock are required to produce 1t of biochar, yet feedstocks are frequently not available because of competing demands (see section 3) and/or because of their high price. In many Asian countries, there is a steady trend towards mechanization of agriculture which has reduced the number of animals kept, in turn reducing the amounts of manure than can be ploughed back into fields. This has meant that animal-based feedstocks have become scarcer, hence more valuable.[28] Larger wood pieces for producing charcoal and agri-residues such as rice husk are increasingly briquetted and sold as fuel.

84. Another trend has been the growth in employment opportunities in many cities and towns over the past two decades which has reduced the rural labour force. The lack of labour – and its higher cost - means that the collection of feedstocks and their conversion into other materials such as biochar has become more challenging and expensive.

85. Producing large quantities of biochar is difficult with current technologies. Oil-drum kilns may produce 7 to 20 kg biochar per run. Hence 50 to 100 runs are required to produce just one ton of biochar and this is very time consuming and labour intensive. Larger biochar-producing units are available, producing 400 to 600 kg of biochar per operation and these include the Adam Retort, BigChar, BigRoo, the Kon Tiki and various other designs under development. The cost of such units varies widely from US$200-300 for the Adam Retort, several thousand US$ for the Kon Tiki and up to US$70,000 for the most advanced designs.

86. There is presently debate concerning how to treat biochar and organic and inorganic amendments. Many practitioners believe that it is not sufficient to mix biochar with other materials just prior to addition. Rather, some believe that the biochar has to go through some type of reaction which occurs over a number of weeks. It is suggested, for example, that in order for the nutrients to be mineralized, and in a form where sorption[29] by biochar can take place, it is necessary to compost the biochar with organic matter (***co-composting***) for approximately 6 to 8 weeks. The decomposition process should be thermophilic[30] (60 – 70°C). There is some evidence that, if so processed, ammonium (NH_4^+), phosphates (PO_4^{3-}) and nitrates (NO_3^-) will adsorb onto the biochar surfaces and absorb into its pores to be released slowly for the benefit of plant roots seeking out nutrient.

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[27] Kammann, et al., in prep., Carter et al. 2013, Partey et al., 2014
[28] Lao PDR is something of an exception due to the larger number of animals per capita in that country.
[29] Sorption is a physical and chemical process by which one substance becomes attached to another
[30] i.e. a temperature that is optimum for the growth or thermophilic microorganisms

87. Analysis of field trials have aimed to identify synergistic effects from treatments combining biochar with organic or chemical fertilizers. The meta-analyses have not identified strong evidence of such synergies. Individual field trials have, however, shown good evidence. In one experiment, wheat straw biochar was combined with synthetic NPK and bentonite clay and pelleted before application to the field in China. The crop showed a 75% increase in nitrogen productivity (rice-yield (kg/ha) divided by total N input (kgN/ha)). Surprisingly, these benefits occur with additions of only approximately 120 kg biochar addition per hectare (12g per m^2) (Joseph et al., 2013). Microscopy has been able to demonstrate that the chemicals in the NPK react with the carbon lattice of the biochar and this could explain the slow release of nutrient.

88. Kammann et al.'s (submitted) analysis of co-composted biochar particles added to the soil and then removed after a period of one year suggests that such particles contain approximately 5g of N per kg of biochar (compared with pure biochar amendment, which retains very little). [31] Most of this N is present as nitrate.

5.1.4. Applying Biochar to soils

89. The question of how to apply biochar most effectively has, to date, received much less attention that it deserves. Most researchers have adopted the conventional application regime of the farm or crop with which they are working. Where mechanization occurs, methods such as fertilizer spreaders have aimed to apply biochar evenly over a given area, followed by discing or harrowing. Inversion ploughing has been found to move a layer of biochar from the top soil to the sub-soil where it is below the root zone and unlikely to be as effective (though the biochar layer re-emerges in the next inversion ploughing operation). Direct seeder technology including a scalloped-shaped vertical disc and winged tine soil opener has been used to apply biochar into the root zone (Graves 2013).

90. Hand application has been common in many research and development trials, usually involving weighing biochar quantities, accounting for the moisture content, or using volumetric measurement, followed by hand spreading with rakes, etc. All these methods have limitations, especially in spreading biochar evenly. Hence, the actual biochar concentrations in the root zone remain a key uncertainty and experiments which report application rates of 10 t/ha may, in reality, have very different effective concentrations in the root zone. In that sense, application rates are not reliable, making comparisons and establishment of dose-response relationships problematic.

91. Biochar can be concentrated in the root zone of the growing plant, e.g. by placing it in a bole into which a seedling is planted or in a trench for horticultural and other row crops. The effective concentration of biochar can be increased, such that a 4 t/ha application effectively becomes a 30 t/ha application rate.[32] This technique works where seedlings are taken from a nursery and planted in field and where Conservation Farming techniques are employed. It is a more productive way of utilising limited supplies of biochar.

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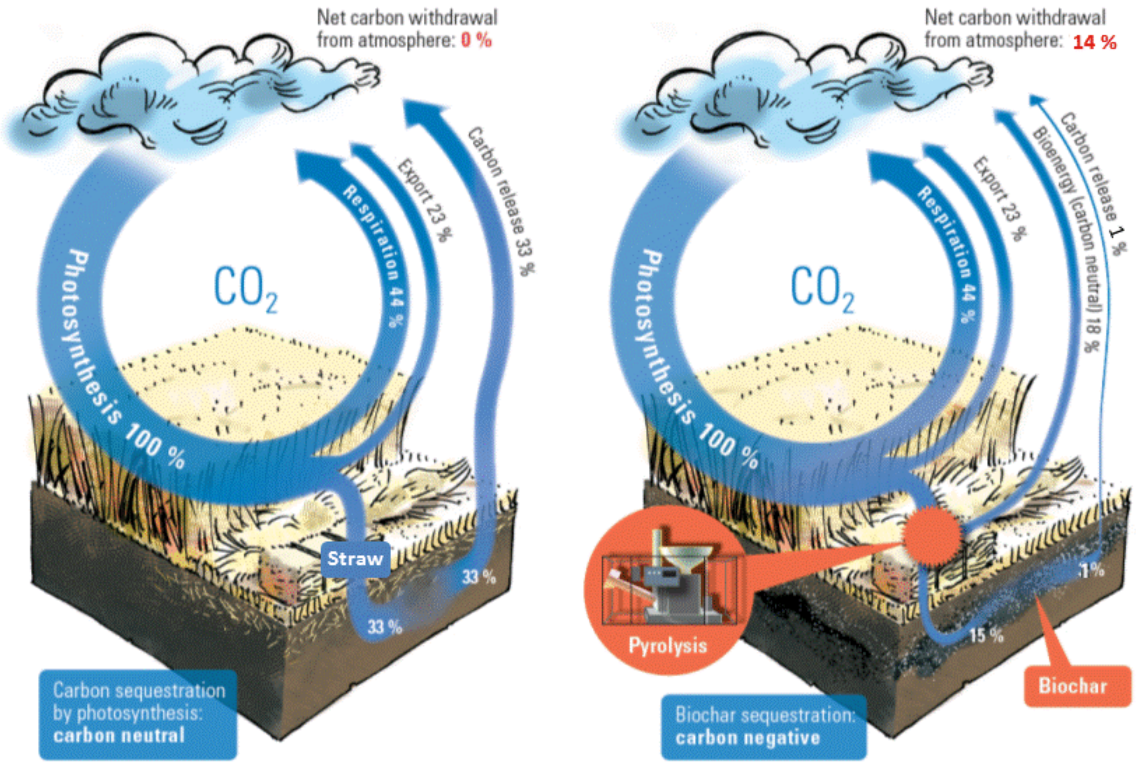
[31] *For a 10 t/ha co-composted biochar addition containing, say, 50% biochar (i.e. 5 t/ha biochar), this would equate to 25 kg of N, representing 25% of the N demand of rice or wheat. However, this would be reduced to 2.5% of the N demand with a 1t/ha addition or only 0.25% for a 100kg/ha application rate.*

[32] *Cornelisen et al. 2013*

5.2. CARBON STORAGE IN SOILS – MITIGATING CLIMATE CHANGE

92. Plants grow through the process of ***photosynthesis***, by which they use CO_2 from the atmosphere, energy from sunlight and water and nutrients from the soil to grow and reproduce. If the plant material is burnt in the open then the carbon in the biomass is returned directly to the atmosphere as CO_2. There is no net removal or gain of carbon in the atmosphere since the carbon removed during photosynthesis as CO_2 is then returned to atmosphere as CO_2 during burning. This is shown on the left hand side of the figure below and is called the 'short carbon cycle' because the removal and return of carbon dioxide occurs in the space of a few years.

Figure 9: Principle behind carbon sequestration with biochar soil application (right) compared to a normal agricultural system (left). The wheat carbon cycle is based on Aubinet et al. (2009). Copyright E.W. Bruun, Department of Chemical and Biochemical Engineering, Danish Technical University (DTU), Denmark



93. Plants use up approximately half of the carbon that they take-up during the day time to provide energy during the night time (***respiration***). In the case of cereal crops, a quarter to a third of the carbon is removed from the field as grain which will be converted back into CO_2 when the grain is consumed by humans or other animals. Approximately a third of the carbon is locked-up in the straw and, if this is dug into the soil, it will emerge as CO_2 in just a few years' time. The overall effect is no net change in CO_2 in the atmosphere, hence no net effect on decreasing or increasing climate change.

94. If we were to convert the cereal straw into biochar through pyrolysis (right hand side of Figure 9 figure above), the effect is that approximately 50% of the carbon in the straw is released as CO_2 while the other half is converted into biochar. The overall effect is that up to 14% of the overall carbon taken-up by the crop is stored in the form of stable biochar for a very long time. This portion

of the carbon enters the 'long-carbon cycle', so-called because the carbon is removed from exchange with the atmosphere for >100 years.

95. What is remarkable, and unique, about biochar is that most of the material cannot be broken down by microorganisms in <100 year timescales. The very strong bonds within the biochar matrix mean that the molecules that comprise biochar are very resistant to decomposition. For this reason, the carbon remains in biochar for hundreds to thousands of years.

96. For a woody feedstock such as forestry residues, approximately one ton of CO_2 is removed from the atmosphere for each ton of feedstock converted into biochar. This equals approximately 3 tons of CO_2 removed per ton of biochar.[33] The amount can be a lot less for non-woody feedstocks, such as rice husk, straw and bio-wastes such as those from anaerobic digestion which typically remove between 0.5 and 1.0 ton(s) of CO_2 per ton of feedstock.

97. There is no 'magic number' which defines an acceptable carbon storage period for the purposes of mitigating carbon dioxide emissions. If most of the biochar carbon leaks back to the atmosphere as CO_2 within 50 years, however, it may be contributing to global atmospheric CO_2 concentrations at a time when accumulative carbon emissions are close to reaching a level which will result in exceedance of the 2^oC safe threshold for mean global surface temperature change.

98. The desirable maximum ***leakage rate*** of CO_2 from biochar to the atmosphere will depend upon the extent to which biochar is adopted as a carbon mitigation option and on the risk of other carbon mitigation options not working as intended. For example, if biochar becomes widely deployed globally, the risk of CO_2 leakage from biochar in the next 50 years becomes more important. The ***mean residence time (MRT)*** is the average time that the carbon in the biochar remains in a stable form as opposed to decomposing to CO_2. The MRT for charcoal in soil produced from natural fires has been measured as c. 1000 to 1,500 years. [34]

99. Production and use of char may result in a net increase in carbon emissions to the atmosphere where: a) land-use change to grow biomass to produce biochar results in the loss of large amounts of carbon in biomass and soils. The 'carbon debt' from converting carbon-rich forest and soils to agricultural land can be up to 400 years[35]; and b) 'dirty' char production results in emissions of powerful greenhouse gases, namely N_20 and CH_4. An example of a simple charcoal producing technology that produces particulates and fugitive greenhouse gases is illustrated in the figure below.

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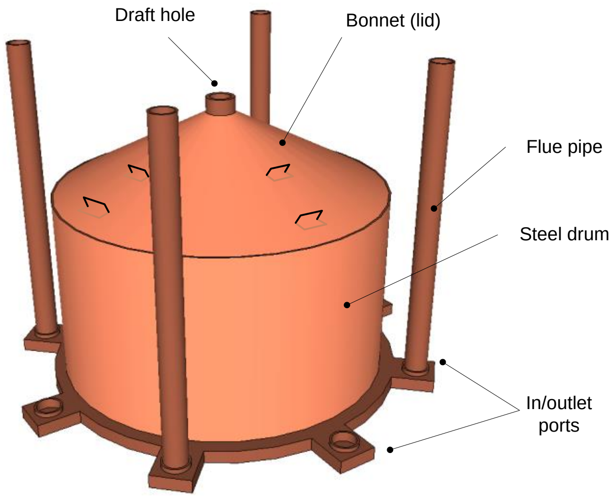
[33] *Shackley et al. (2012)*
[34] *Lehmann, J. (2008); Lehmann, J. et al. (2009)*
[35] *Shackley et al., 2012.*

Figure 10: Example of a simple steel charcoal kiln (New Hampshire kiln)



100. ***Life Cycle Assessment (LCA)*** is a tool for evaluating the environmental aspects of a product or service system through all stages of its life.[36] It can be used to examine how much carbon is abated through different biomass conversion pathways, such as producing biochar for biofertilisers.

101. LCA has demonstrated that conversion of biomass to biochar without using clean burning methods can make the climate change problem *worse* not better. [37] This is because under low-oxygen conditions, some carbon is converted into methane and some nitrogen into nitrous oxide, both more powerful greenhouse gases than CO_2. From a climate change perspective, biochar production only makes sense if sustainable feedstocks (i.e. spare agri-residues and bio-wastes) are used rather than virgin biomass *and* if clean production methods are applied.

[36] *www.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx*
[37] *Shackley et al. (2012); Sparrevik, et al. (2013)*

6. KEY POINTS

102. **Uses of Biomass.** Comparison of biochar production with other options for using biomass should be undertaken to ensure the most effective use of limited biomass resources. Comparisons should not look at energy efficiency only but should also consider economic costs and benefits, net carbon abatement and environmental impacts.

103. **Producing Biochar.** Biochar is produced in a range of kilns or retorts which can vary greatly in cost, performance, size and durability. Biochar can be produced over a wide range of scales, from household, to village-scale to factory-scale.

104. **Biochar as a Soil Amendment.** Biochar has been widely tested around the world through research and development and its agronomic impact is, on average, positive (approximately 10% yield increase) but the averaging of many different soils, crops, climate and management regime, means that this is not an accurate prediction of any given biochar, soil or crop trial.

105. If current pyrolysis technologies are used, only about a third of the feedstock is utilized in producing biochar. The remainder is lost as vapour and gases. It is important to improve the efficiency of biomass conversion by finding a use for the heat, syngas and pyrolytic vapours produced from pyrolysis. Uses could include heat for drying feedstocks, syngas for electricity generation and production of bio-pesticides.

106. Pure biochar is not a fertilizer. Pure biochar contains very little plant macronutrient (N and P) and could even reduce plant-available N in the soil.

107. Biochar might sometimes contain micro-nutrients (required by plants in very tiny amounts) which are deficient in a specific soil and improve plant productivity through supplying the missing micro-nutrient.

108. Pure biochar additions are generally considered to be too expensive given feedstock scarcity, production and/or labor costs. Mixtures of biochar with organic matter or with NPK fertilizers are regarded by many experts as economically more promising than pure biochar. Mixtures mean using less biochar per hectare so reducing costs, while aiming to create slow-release fertilizers by exposing N and P containing materials to biochar.

109. The application of biochar and compound biochar mixtures into soil requires attention so as to maximize the concentration of biochar / mixtures in the root zone of the growing plant. This can be done by placement in root boles or in rows and effectively increases the effective concentration of biochar in contact with the growing plant.

110. **Biochar for Climate Mitigation.** Biochar is produced by a change in the composition and structure of organic molecules which makes it much more resistant to attack by microorganisms than conventional organic matter. It is this change which accounts for the long residence time of biochar in the soil, with an average residence time of 1000 – 1500 years. The longevity of biochar is what makes it of interest as a carbon storage technology. i.e. Biochar has a high proportion of very stable carbon content – stable on climate change relevant time scales.

111. Clean production of biochar is vital if it is to have a beneficial net impact on climate change rather than adding to the problem. The key factors here are to ensure that the feedstock does not contribute to direct or indirect carbon emissions through land-use change (creating ‘carbon debt’)

and that production does not generate black carbon particles (which also causes health problems) and greenhouse gases such as methane and nitrous oxide. Clean production is a design issue not a technical challenge.

APPENDIX 1: REFERENCES

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APPENDIX 2: THE STRUCTURE OF BIOCHAR

In order to comprehend the use of biochar in soils, it is important to consider its structure. The most common materials found in plants are ***cellulose***, hemi-cellulose and ***lignin***. Cellulose consists of carbon and oxygen arranged in ring-like structures containing four carbon atoms and two oxygen atoms. These rings are joined together to create long chain-like structure (C-O-C). Hemicellulose is similar to cellulose, although it consists of shorter, weaker chains. Lignin is found in woody plant cells and is a more rigid material than cellulose.

Biochar is derived from cellulose and lignin with their chemical structures changing due to heating causing the loss of hydrogen, nitrogen, oxygen and other elements through vaporization and subsequent ***condensation***. The carbon atoms fuse together in structures which are much stronger than in raw cellulose or lignin. It is this transformation from 'ordinary' plant organic matter to a sheet-like carbon-rich lattice which explains the far greater stability of the carbon in biochar compared to normal organic matter.

Biochar consists of carbon lattice sheets of varying sizes, arranged in irregular layers. Biochar also contains residual H, N, O, S, metals and ash - a complex mixture of different elements.

The figure below shows the structure of biochar and the next figure presents highly magnified images of biochar produced from rice husk (left) and rubber tree (right). The unit of measurement is a micrometer (µm) equal to one thousand of a millimeter. Hence 50 µm is the same as 0.05 mm. To give an idea of scale, most bacteria are from 1 to 10 micrometers in length. The space between biochar sheets is in the order of a few Angstroms, where 10,000 Angstroms equal one micrometer.

Figure 11: Structure of biochar (Source: bekbiochar.pbwork.com)

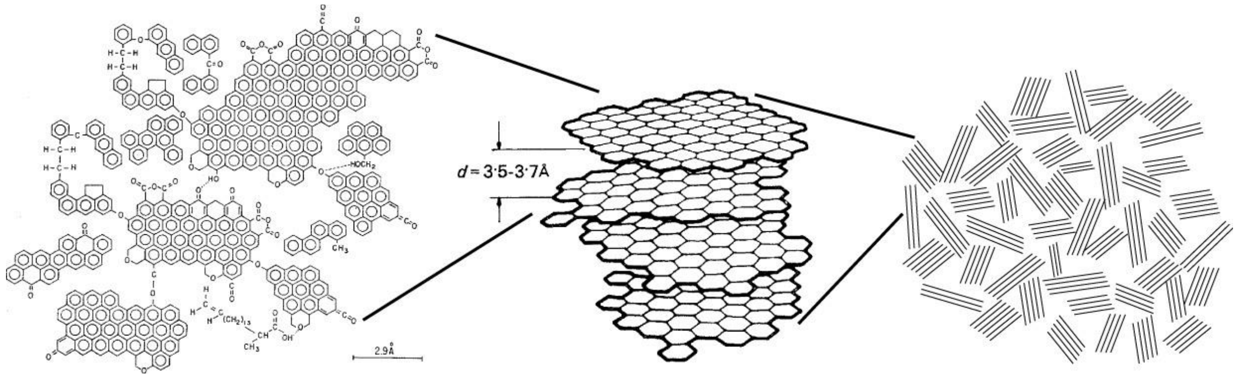
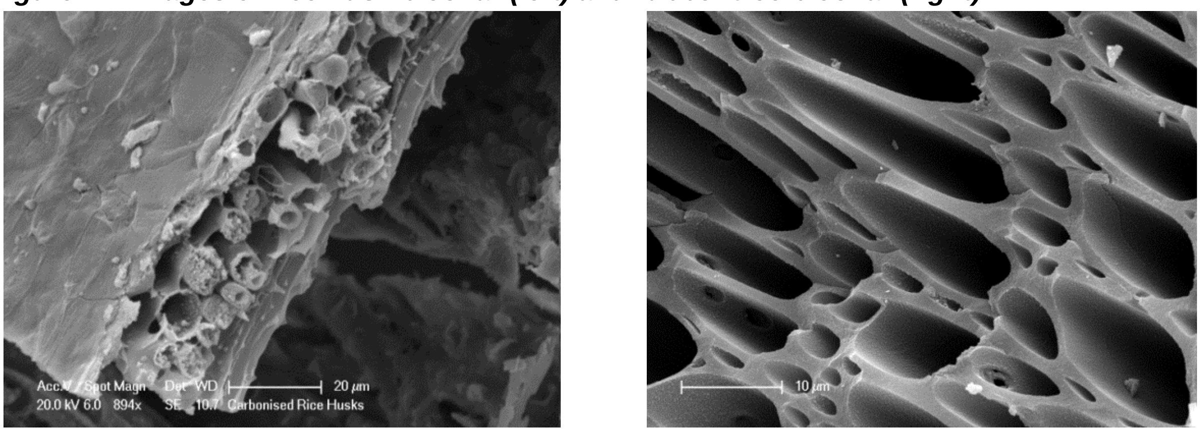


Figure 12: Images of rice husk biochar (left) and rubber tree biochar (right)



When converted at a higher temperature (>700^{o}C), ‘fresh’ biochar tends to have a clean and clear carbon matrix which reflects the structure of the organic matter from which it was created - including the cells and the tube structures in plants which convey water, energy and nutrients within the plant. This is nicely illustrated by the image on the right hand side the figure above. The high temperature also means that other pieces of biomass which have not formed into strongly bound-together carbon-ring structures will break-down and be released as vapour. Biochar produced at much lower temperature (c. 400^{o}C) tends to contain more pieces of biomass within the pores, as shown in the left hand image of the figure above.

When fresh biochar is added to soil for a year or longer, or when it is composted along with organic materials, a far more complex structure is created. This is illustrated in the figure below, where the presence of bacteria and fungi, along with elements and molecules attached to the biochar surface can be clearly observed. The surface of the biochar becomes ‘activated’, meaning that there is more chemical and biological activity taking place. This is usually regarded as improving the performance of biochar in enhancing soil fertility.

Prior to soil addition, biochar is usually crushed to have a reasonably uniform particle size which can vary from a few cm’s to a few mm’s. If the particle size is too small, then a dust is created which will blow away easily during or after application. Once in the soil, biochar is subject to stresses and shearing effects caused by movement within the soil induced by micro-fauna and flora, plant roots, decaying plant matter and physical processes (wind, water, etc.). Since biochar is frequently brittle along one axis, particles will tend to break down into smaller pieces < 50 µm (0.05mm). However, charcoal fragments hundreds of years old have been recovered from soil and these can be a few cm’s in length. More heavily worked soils, such as ploughed agricultural ones, are likely to accelerate the diminution of biochar particle size compared to less disturbed soils.

While biochar particles decrease in size by about a thousand times, it does not follow that the molecular carbon structure of biochar decomposes and loses its structure and integrity. This is because the molecular scale is about one hundred thousand times smaller than a 50 µm biochar particle. The carbon in the smaller particles therefore remains as tightly locked-up in the biochar as it is in the larger particles.

As particles become smaller, the properties will change, for instance capacity for holding water is likely reduced. There may be more available surfaces so increasing reactivity but fewer internal spaces for holding water and dissolved ions. On the other hand, there is substantial evidence that biochar reacts with minerals in soil, such as clay particles, forming ‘biochar-mineral complexes’. The minerals protect the char from decomposition and will also change the surface chemistry.

Figure 13: Analysis of biochar - compost mixture used in the Cambodian TA-7833 field trials showing clear evidence of micro-organisms on the surface. (Courtesy of Professor Stephen Joseph) This area is magnified on the right hand-side panel to reveal fungal hyphae and mineral aggregates

Biochar From Comped Mixture; High Concentration of Fungi and Bacteria on the biochar. Internal Surfaces are coated withK, Ca, P, Si, Mg, S and Cl