



BIOCHAR: TAKING COMMERCIAL APPLE PRODUCTION TO NET ZERO

An Innovate UK funded and British Apples & Pears Limited commissioned consortium research study to assess the feasibility of using pyrolysis techniques for growers to manage the end-of-life of apple orchards.

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STOCKS FARM

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EXECUTIVE SUMMARY

- Tree fruit, apples and pears are a reasonably low emission crop today. Orchards are planted and most will be productive for 15-20 years, in the case of pears as long as 40 years. During that time the soil is not turned over to release carbon unlike annual crops which require some loss of carbon from the soil each year.
- The LCA analysis of British grown Gala undertaken as part of this project, measured from orchard establishment to the delivery of packs of apples to the supermarket distribution centre, provides us with a clear guide as to the key aspects of production that need attention in order to reduce carbon footprint:
 - o Packaging (specified by retailers)
 - o Plant protection products
 - o Storage energy
 - o Nitrogen (fertiliser)
 - o Fossil fuels (for vehicle movement in the orchard)
- The carbon emission of each of these aspects will be solved by the wider agricultural industry or retailers through: the adoption of new packaging formats; the production of biological plant protection products; renewable energy adoption; creation and adoption of bio-fertilisers; vehicle development to run on hydrogen, electric or bio-fuels. No individual grower can solve these carbon emissions without whole system change.
- But one key challenge facing the fruit sector is the grubbing and burning of orchards at the end of orchard life. This releases the carbon that has been sequestered over the lifetime of the orchard and may impact neighbouring farms, housing and wildlife.
- The top fruit industry is striving to meet carbon reduction targets and to reduce emissions.
- Orchard wood is a logical fit as a feedstock for Biochar pyrolysis kilns; the process has the prospect of being able to offer a circular solution for growers - the trees are used to create Biochar and the Biochar is returned to the soil of an orchard or another part of the farm to provide benefit to the soil and/or to create a value as a carbon credit.
- The project team was built to give us a good mix of academic expertise, practical on the ground orchard experience (two farms), practical orchard removal experience (orchard contractors) as well as excellent project and technical management experience from the UK Agri-Tech Centre. The funding from IUK was a critical factor in terms of being able to bring the consortium together and deliver a really collaborative project.
- Project subcontractors Cranfield produced the LCA of British grown Gala and Carbogenics undertook literature reviews in order to better inform the project and the wider sector.
- Will orchards reach net zero? We believe that all of the major emission factors can be addressed and that biochar will be part of the solution to ensuring that apples and pears become one of the lowest carbon footprint foods available to the shopper. They may even become a way to “offset” the emissions of other food choices.



SECTION 1 – WHAT IS BIOCHAR?

1.1 Introduction to Biochar

The use of biochar as a sustainable solution for environmental problems has gained growing interest throughout the world. The purpose of this report is to provide a detailed and comparative analysis of different kiln technologies, biochar yield, syngas production, biochar purity, likely emissions, and cost considerations of various biochar production companies. Via this evaluation, we intend to give an outline of various methods and technologies used by these companies which may be useful for the interested stakeholders involved in biochar production and its environmental applications.

The application of biochar was already known from ancient times when native communities employed it as a soil improvement of fertility and yield crops. Ancient civilizations like the Amazonian tribes in South America created fertile “terra preta” soils through the incorporation of biochar (1). Lately, biochar has been repeatedly mentioned for its ability to fight climate change, utilize soil nutrients, and sustainable waste management. At present, biochar has become one of the subjects that attracted renewed interest in terms of climate change mitigation and agriculture sustainability (1). The unexpected finding of biochar in the soils from the past opened the eyes of scientists to the fact that biochar could be used for carbon sequestration, soil restoration, and crop yield improvement.

Following these early trials, researchers and entrepreneurs around the world began to develop various biochar production methods, ranging from primitive kilns to sophisticated pyrolysis reactors, trying to improve biochar characteristics and make it more efficient from the environmental point of view (2). Nowadays, biochar is viewed as a useful solution for global problems, including soil deterioration, nutrition security, and climate change. However, through research and development, more applications of biochar are continuously discovered.

1.2 Difference between Pyrolysis and Gasification

Definition of Pyrolysis: Pyrolysis is a thermochemical decomposition process that takes place under the conditions of low oxygen levels (either oxygen-free or oxygen-limited). In pyrolysis biomass, a solid material comprising of organic materials, is heated at high temperatures ranging from 400°C to 800°C, which breaks down a complex molecule into simple molecules like biochar, liquid bio-oil, and gaseous syngas (3). Pyrolysis is not just a means to biochar, bio-oil, and syngas but it applies to different sectors like waste management, feedstock for biofuels and chemicals production, as well as materials processing. This waste management technique has been successfully applied in the area of pyrolysis to convert organics to useful products whose container sizes help reduce landfill anaerobic decomposition emissions minimizing methane emissions (4).

The process of pyrolysis can be categorized into three main types based on the heating rate: slow pyrolysis, fast pyrolysis, and flash pyrolysis. Slow pyrolysis is practicing slow heating of biomass (300°C to 500°C) over a longer time aiming for larger biochar outputs with lower production speed. Fast pyrolysis occurs during approximately 0.6-0.8 seconds at temperatures of 450°C- 600°C, resulting in most oil production. The heating of biomass to over 800°C for a second through flash pyrolysis will form on the major level of syngas. Many properties of the Biochar can be adjusted by adjusting the parameters such as temperature, time of residence, and feedstock in the process of pyrolysis (4). These traits are surface area, pore size distribution, and chemical composition which are the characteristics that enable biochar to serve as a handy remedy for soil contamination or to purify water or as an energy storage.

Definition of Gasification: Gasification is the mechanism by which organics raw materials either biomass or coal are processed into syngas. Gasification is the opposite process of

pyrolysis in that it takes place in the atmosphere with a controlled amount of oxygen and/or steam (3). The biomass is heated to higher-than-usual temperatures (above 700°C) in a gasifier where it reacts with the selected gasification agent to form a syngas that contains primarily carbon monoxide (CO), hydrogen (H₂), and carbon dioxide (CO₂). Gasification is a flexible technology that can use many feedstocks with varying compositions, such as biomass, coal, municipal solid waste, and even plastics to generate syngas (5). Syngas from gasification may serve as a fuel for power generation, and heating, and also serve as a source for the production of chemicals and fuels for transportation.

This leads to one of the gasification benefits, which is its ability to process alongside other systems, for example, CHP and biorefineries, to enhance energy efficiency and resource utilization. The reactor systems can be created with the aim of CCU or CCS. but the mission of these two systems is to cut greenhouse gas emissions and combat the consequences of climate change. Further development of gasification processes is ongoing, and worldwide research is mostly focused on the performance increase, reduction of capital and operating costs, as well as increased environmental performance (3). High-technology gasification systems, like plasma gasification and supercritical water gasification, have the virtue of providing the conditions to overcome the identified problems of low-technology gasification, such as tar formation and reactor fouling.

1.2.1 Table: Difference between Pyrolysis and Gasification

Oxygen Presence	Pyrolysis is performed when oxygen is absent or present at very low levels, at the same time that gasification requires a certain amount of oxygen or allowable steam.
Product Composition	Usually, the pyrolysis produces biochar, bio-oil, and gases, but gasification boils down to syngas.
Temperature Range	By-products are produced in the conditions of low temperatures (400°C to 800°C) whereas gasification operates above 700°C (above 700°C temperature).
End Products	Pyrolysis and gasification generate different product proportions with the former producing a higher content of solid biochar and the latter a higher amount of gaseous products.

1.3 Definition of Biochar and Charcoal

Biochar is a carbon-rich black solid material obtained from the pyrolysis process of biomass under limited air or reductive environments. It has a sponge-like feature, as well as it is high in carbon, these make AAC great for many environmental uses such as soil conditioning, carbon sequestration, and wastewater treatment (6). Charcoal, on the other hand, is a low-carbon-containing solid waste that is formed through the incomplete combustion of woody matter under a limited amount of oxygen. Biomass is fed into the kiln and then burned to produce charcoal under controlled pyrolysis conditions (7). On the other hand, traditional methods like kiln burning and earth mound burning are used to make charcoal.

Difference between Biochar and Charcoal
Although both black carbon and charcoal are black carbon-rich materials from biomass, they have different production methods, properties, and applications. Biochar, which is made by controlled pyrolysis and has specific properties that are optimized for use in environmental remediation applications such as soil improvement, carbon sequestration, environmental remediation, and sustainability, is produced (8). Charcoal instead is mostly utilized as a fuel for both cooking and heat either through the traditional methods which often produce lower purity and high emissions compared to the environmentally friendly production of biochar (9). But charcoal production technologies like retort kilns and

improved combustion methods are the way forward and they have been able to produce clean and sustainable charcoal products. Besides the different applications, biochar, and charcoal will also affect the carbon cycle and climate change in their own ways. Biochar when used as a soil amendment can store carbon for as long as several thousand years, effectively reducing carbon dioxide in the atmosphere and, hence, climate change. Charcoal, while it can temporarily serve as a carbon sink when it is buried or used for biochar production, fundamentally releases carbon dioxide into the atmosphere when it is burnt as a fuel (10). This, in turn, contributes to greenhouse gas emissions.



1.3.1 Table: Difference between Biochar and Charcoal

Production Process	Biochar is manufactured by controlled pyrolysis of biomass while charcoal is mainly produced in conventional kilns or mounds using incomplete incineration
Intended Use	Biochar has been applied primarily as a soil improver or carbon store, while charcoal has most frequently been used as a cooking and heating fuel.
Carbon Content	Biochar being a more stable product, contains higher carbon content as compared to charcoal.
Purity	The production of biochar is based on considerable filtration and the resulting higher purity of the product rather than the raw charcoal.

Section 1 - References

- (1) Kamarudin, N. S., Dahalan, F. A., Hasan, M., An, O. S., Parmin, N. A., Ibrahim, N., ... & Wikurendra, E. A. (2022). Biochar: A review of its history, characteristics, factors that influence its yield, methods of production, application in wastewater treatment and recent development. *Biointerface Res. Appl. Chem*, 12(6), 7914-7926.
- (2) Cheng, H., Yang, S. O. N. G., & Bolan, N. (2023). Biochar for future and futuristic biochar. *Pedosphere*, 33(5), 680-682.
- (3) Mavukwana, A. E., Stacey, N., Fox, J. A., & Sempuga, B. C. (2021). Thermodynamic comparison of pyrolysis and gasification of waste tyres. *Journal of Environmental Chemical Engineering*, 9(2), 105163.
- (4) Alcazar-Ruiz, A., Ortiz, M. L., Dorado, F., & Sanchez-Silva, L. (2022). Gasification versus fast pyrolysis bio-oil production: a life cycle assessment. *Journal of Cleaner Production*, 336, 130373.
- (5) Glushkov, D., Nyashina, G., Shvets, A., Pereira, A., & Ramanathan, A. (2021). Current status of the pyrolysis and gasification mechanism of biomass. *Energies*, 14(22), 7541.
- (6) Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar role in the sustainability of agriculture and environment. *Sustainability*, 13(3), 1330.
- (7) Zhou, Y., Qin, S., Verma, S., Sar, T., Sarsaiya, S., Ravindran, B., ... & Awasthi, M. K. (2021). Production and beneficial impact of biochar for environmental application: a comprehensive review. *Bioresource Technology*, 337, 125451.
- (8) Saletnik, B., Zagała, G., Bajcar, M., Tarapatsky, M., Bobula, G., & Puchalski, C. (2019). Biochar as a multifunctional component of the environment—a review. *Applied sciences*, 9(6), 1139.
- (9) Oni, B. A., Oziegbe, O., & Olawole, O. O. (2019). Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, 64(2), 222-236.
- (10) Gan, X., & Zhang, W. (2021). Application of biochar from crop straw in asphalt modification. *PLoS One*, 16(2), e0247390.

SECTION 2 - SCENARIOS FOR BIOCHAR INTEGRATION

2.1 – In-field Processing and Orchard Removal



This Innovate UK funded project brings together a varied consortium comprised of two English commercial orchard growers (Stocks Farm and Adrian Scripps), experts in end-of-life orchards processing.

Adrian Scripps Ltd. Currently farms over 250 ha of top fruit this requires a rolling program of orchard renewal which involves the grubbing (tree removal) out of the old orchard and structure and the replacement with a new structure and tress.

For this reason, we were selected as representative growers with orchard systems that as current “state of the art” and are representative of commercial trees that are likely to be grubbed out going forward. To replicate this in the West Midlands, Stocks farm were similarly selected so that the work could be replicated in that region.

Our role within the project was to produce biomass for processing from the end-of-life orchard trees, once the Biochar had been produced from this biomass, we would then set up trial plots within newly planted orchards to investigate the possible on farm use of the Biochar.

Project change brought about other areas of involvement for Adrian Scripps. The Life Cycle Analysis that was to be carried out by Cranfield University, would require Adrian Scripps Ltd. to provide both representative modern orchards for Green House Gas emission analysis as well as our input to look at energy and fuel usage and inputs to the production system so that a full analysis of carbon production within UK apple production could be produced.

Current farm practice for end-of-life treatment

The whole project was born from AHDB Trees Fruit Panel discussions that regard suitable carbon calculation models that were available to the industry.

The Panel had been tasked with looking at the various Carbon Calculation Tools that were then available to industry, in order for them to work out their carbon footprint, this was increasingly becoming a requirement of retail customers. What became obvious very quickly was that the industry standards were very good up to the point of orchard removal. Currently it can be expected that orchards would have a 15-to-20-year commercial lifetime, during which the tress would be capturing carbon from the atmosphere through photosynthesis and turning it into solid carbon in the form of leaves wood and bark.



Picture 1. A representation of current practice orchard growing system

Current industry practice however, at the end of orchard life was to grub both tree and root out of the ground and burn this in the field in the open air. This gasification subsequently released the carbon locked up in the trees and roots and released it back into the atmosphere.

Due to the pressure from retailers wanting suppliers to share their carbon calculations and a drive towards Net Zero by 2050, and directly from end consumers is becoming a problem for the industry. Furthermore, the actual practicality of burning large amounts of trees outside with increasing pressure from farming on the urban fringe, and local authority intervention, was and is becoming more difficult. Growers having to predict wind speeds and direction for a minimum of 12 hours in order that they don't cause a statutory nuisance.



Picture 2, 3. Current industry practice of grubbing an orchard

From this position alternative processes were investigated and the only viable storage solution available to the industry was to lock up the carbon for a time significant period in the form of biochar.

End of life Biomass and Carbon Conversion

As this was only to be a two-year project, one of the first parts of WP2 for us as partners, was to produce biomass from end-of-life trees. To do this we processed orchards trees along with our contractor Ellis Contract Services Ltd. To produce a G30 standard wood chip. This was already a process that we had the capability of doing.

Chip was then produced at our Wenderton Farm in East Kent from Braeburn trees that were being grubbed out. We had kindly been lent a stillage to process this chip from Pressvess when we had visited their factory in the West Midlands very early in the project. Having located a local Charcoal producer in the form of Ashdown Logs and Charcoal based in East Kent.



Picture 4. Ashdown Logs and Charcoal's Pressvess batch kiln.



Picture 5. Orchard grubbing in progress at Wenderton Farm Ellis Contracting Services

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Picture 6. Tree chipping by Ellis Contracting Services.

Biochar In-field Assessment

The ability to produce good quality Biochar from our G30 chip was then proven by processing our chip. This Biochar was also sampled by University of Edinburgh in their laboratory to confirm the quality. We also obtained sufficient Biochar from the same processor to allow us to set up the in-field assessment for two methodologies: the first applied to the tree planting hole and the second, for the retro application to the surface of an established orchard.

These trials were set up at Wenderton in Heart Delight Block 2 and Dambrige West. The second site was Hononton Farm in Target East and in 9 acres.

Prior to the trial areas being set up on each of the two sites in Kent we undertook soil surveys of both fields carried out by consortium colleges Hutchinsons using their Omnia Terramap system which can show soil nutrition and water availability. (see Section 3.1 Biochar in field assessment report for more details on field trial analysis)



Picture 7. Trial plot at Wenderton Farm



Picture 8. Planting of trial plot at Wenderton Farm

Knowledge exchange and field visits

From the onset of the project, we have tried to gain as much knowledge and understanding of the process that we can through involvement in technical project discussions and visits to relevant sites both in the UK and Europe.

Early visits were to Ashdown Logs and Charcoal where we discussed batch production at length with proprietor Norman Donaldson and he introduced us to the idea of continuous flow

production, the simple Pressvess retort amply demonstrated the pyrolysis process. We have subsequently revisited his site on numerous occasions to collect samples from processing and Biochar for the in-field trials work, throughout 2022.

In 2022 we also undertook a visit to the Pressvess manufacturing facility in Dudley, West Midlands. Here along with other consortium members we were hosted by owner and Managing Director Roger Bannister. Pressvess are one of the only UK based manufacturers of charcoal retorts, these are however all based on a batch manufacture process although they can provide a form of continuous production using their double retorts and their cooling covers. These were interesting to observe as one side to the retort could effectively fuel the processing of the other side through the volatiles that are given off during the process.

November 2022, we participated in the fact-finding visit to Germany to see Biochar plants in use and to visit the production facilities of both Pyrag and Biomacon. This demonstrated how advanced the use of pyrolysis is in Europe. It also brought about the fundamental change in the direction of the project as we no longer needed to pursue the design and production of our own retort system as competitively priced units were available to order from these manufacturers depending upon the size of the plant required.

January 2023 brought us to an introduction to the Energy and Bioproducts Research Institute which is part of Aston University. The subsequent site visit to their research facility at the university and their commercial partner Combind Industries based nearby at Crofton on the outskirts of Birmingham. Following this we provided orchard feed stock for both lab analysis and trial production in their pre-production test unit. This proved to be important as from this feedstock, they were able to develop and prove the ability to successfully produce biochar from the G30 chip feedstock. Again, the lab results showed that a good quality biochar could be produced. The system developed by Combind is interesting as it attempts to capture all the biproducts from the pyrolysis process and they can amply

demonstrate that the product can be used directly in existing pressure jet water boilers and gas systems. The electricity used in production can be renewably sourced and offset by PV solar panels in a farm packhouse/cold storage scenario. (See section 2.2 and 2.3 for more detail on energy usage assessment)



Picture 8, 9. Combind Industries and Aston University

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Picture 10. Cranfield's in-field greenhouse gas emission monitoring equipment in orchards.

Finally, Adrian Scripps would undertake a wood chip storage trial. During the visit to Germany trip to an on-farm unit by Biomacon, the owner demonstrated their winter storage of chip outdoor. This required us to produce two suitably sized storage clamps of G30 chippings from our own orchard feedstocks. Gala and Braeburn trees were grubbed on one of our West Kent sites at Moat Farm. Having researched the available cover systems, a set of covers and anchor bags were purchased from Silostop in the UK. These are intended to be water repellent and breathable, to store chipping outdoors on farm with little capital investment needed. Again, Ellis Agricultural Contractors were engaged to grub the trees, this time however we were able to prove that a modern post and wire system could remain in place while the trees were removed. A specialist forest machine was hired to allow this work to be done successfully.



Picture 11. Forestry machine



Picture 12. Steelwrist at work removing trees with structure in place under hail net system



Picture 13. Storage trial of G30 chippings showing both covered and uncovered clamps for analysis.

Root Treatments

The final part of the project for Adrian Scripps Ltd. has been to look at the options available for handling the root balls.

Due to the equipment that is used to chip the biomass from the grubbed orchard trees it has been deemed that is not commercially possible to process the tree root ball. This is due to the abrasive effect of the soil contamination

on the blades of the chipper machine. The contamination from the soil would also pose a problem in the pyrolysis process. It was therefore decided to remove the roots from the trees at grubbing, so that the "clean" above ground part of the tree can be chipped, and the roots are left on the surface in the field. Ellis Contracting Services are already equipped to be able to do this with their 360' machines as they are fitted with a "Steelwrist" which allows the operator to handle the trees suitably. During our production of the chip for the storage trial in March 2024, we set aside the roots on the surface of the orchard so that we could investigate a method of treatment.

A suitable machine was sourced from a manufacturer in Italy, Seppi, arrangements were made to ship the machine to the UK from Spain so that its suitability could be assessed. Trials were then carried out in July 2024 on various root types. These were mostly successful in that they dealt with the material into a product that we felt could be suitably incorporated back into the soil without any detrimental effects. More investigation of machinery however is required as operation of this was difficult due to poor visibility.



Picture 14: Forestry mulcher from Seppi, Italy

SECTION 3 – ASSESSMENT OF KILN TECHNOLOGIES AND OUTPUTS

3.1 Kiln Assessment of Known Companies

This section summarises an analysis carried out at point of writing of current available technologies, their appropriate uses, outputs and energy uses. Kiln units described are in no particular order and with no stated commercial preference.

Pyrolysis kilns come in different models with varying designs though generally comprised of a chamber that is heated in the absence of oxygen to produce biochar, bio oil, aqueous phase and/or syngas. They are usually grouped into batch kilns, continuous kilns, and rotary kilns, each having varying capacities of throughput and efficiency levels (1). This section comprises of kiln assessment of known companies based on pyrolysis methods, biochar yield, syngas production and other outputs, purity of the biochar, likely emissions and unit costs. If a range of unit sizes is offered by a manufacturer, the 1t/hr feedstock intake is used as a base line for performance data. Reactor output is affected by the type of feedstock so in most cases either wood chip or a woody biomass is used as a reference where possible. All financial information given is correct at the time of publication

Wilson Biochar - Ring of Fire Kiln

The Ring of Fire Kiln Company is US based (Oregon) initially operating throughout North and East American states especially in heavily forested areas and employs a practical and efficient way of making biochar using the constant pyrolysis process that converts the biomass to biochar and syngas. Unlike a regular kiln, this kiln is accomplished by manually strategically placing the biomass into a horizontal drum that is indirectly heated to 500°C (2). The drum has an air draft skin around it, allowing the air to be drawn up and over the open top kiln creating a flame curtain to secure oxygen exclusion. Overall, the controlled heating makes the thermal decomposition of biomass possible without oxygen and generates biochar and syngas.

Biochar Yield: The Ring of Fire Kiln is notable for its high yield of biochar of around 30% by weight since biomass feedstock is efficiently converted into useful biochar, but the biochar quality can be variable. One unit can process between 2t – 5t biomass (wood/brush) per 8hr period depending on dry matter content. Due to its compact size and operational requirements, it presents a perfect alternative for producing biochar and dealing with biomass in difficult and inaccessible areas such as forests and more remote agricultural units, making it a realistic option for potential applications in the environment.

Syngas Production: The Ring of Fire Kiln reports a syngas production rate, which stands at about 800 cubic meters per ton of feedstock. Plus, the utilization of biomass residues in this process creates an extra source of syngas, which not only expands the kiln's value proposition but also helps improve the energy efficiency of the process. However, the unit has no means of syngas collection and given its potable design, this would be challenging to achieve.

Biochar Purity (C: Ratio of C: H): The biochar obtained from the Ring of Fire Kiln shows a C: H ratio of 15:1. While this ratio could show a slight loss of carbon against more complex kiln technologies, the biochar still retains multiple good eco-friendly characteristics such as soil improvement, and carbon sequestration.

Likely Emissions: The Ring of Fire Kiln emits little once it is in full operation. The exhaust is a very clean byproduct, making sure that the particulate matter and the volatile organic compounds are up to the stringent environmental standards. Therefore, this condition complies with the regulatory context and minimizes the environmental footprint of biochar production resulting in the clean environment option. However, it still emits more than complex fully enclosed units.

Cost of Unit: At current prices each unit is \$2,400 US plus delivery and offers a very cheap start up or low-cost solution in more challenging environments. The kiln remains attractive because of its efficient operation and high-rate biochar yield. Hence, the possibility of successfully competing in the market is high. The modular model also lends itself to have several units all running at the same time as long as they are within close proximity.

The modular structure of this technology also allows for hassle-free integration into existing biomass processing facilities, prompting the biochar production market to expand and be flexible.

Conclusion

The Ring of Fire kiln with its relatively high biochar yield and relatively low emissions offers a cheap flexible, portable solution to producing biochar in remote and inaccessible areas. Although the capital costs are extremely low compared to more complex unit designs the kiln requires constant manual input and monitoring which may inhibit the financial yield potential. However, its modular design could reduce this if several units can be operated at the same time.

Woodtek Ltd

Woodtek Ltd is a UK based (Shropshire) family-based company who design and manufacture a range of continuous flow, horizontally rotating pyrolysis and drying units.

Biochar Quality: The Woodtek Biochar Kiln generally produces high-quality biochar with carbon content typically ranging from 70% to over 90%. The purity of the carbon largely depends on the feedstock used, the pyrolysis temperature, and the residence time as per most kilns. The unit is capable of processing wood/wood-based biomass at rates between 1.5t and can process certain manures after some processing. Further work on manure processing is being carried out.

Temperature Control: The kiln's ability to maintain consistent high temperatures (usually between 400°C and 700°C) is crucial for achieving high carbon purity.

Outputs

Biochar: The primary output of the Woodtek kiln is biochar, which is used for soil enhancement, carbon sequestration, water filtration, and even as a component in building materials.

Syngas and Bio-oil: The pyrolysis process also produces syngas (a mixture of gases including hydrogen, carbon monoxide, and methane) and bio-oil. The syngas can be used as an energy source to sustain the pyrolysis process or for other energy needs, while bio-oil can be condensed and used as a fuel or chemical feedstock.

Residue and Ash: A small amount of non-carbonized residue or ash is also produced, depending on the feedstock.

Likely Emissions

Greenhouse Gases: Properly operated, the Woodtek kiln minimizes the release of greenhouse gases (GHGs) like CO₂ and methane. However, incomplete combustion or poorly managed pyrolysis could lead to higher emissions of these gases. Like most kilns this especially occurs when dealing with variable feedstocks.

Particulate Matter: Depending on the efficiency of the kiln and the nature of the feedstock, some particulate matter (PM) might be emitted, but this can be controlled with proper filtration systems.

Volatile Organic Compounds (VOCs): Pyrolysis can emit VOCs, but these are typically captured and combusted within the system or condensed into bio-oil.

Cost

Capital Cost: The initial investment for a Woodtek Biochar Kiln can vary widely depending on the size, capacity, and additional features (like emission controls and automation). Small to medium-scale kilns might range from tens of thousands to many hundreds of thousands of pounds.

Operational Costs: Operational costs include feedstock supply, energy inputs (if not self-sustained by syngas), labour, and maintenance. The energy efficiency of the system, the local cost of labour, and feedstock availability are key factors influencing operating costs.

Conclusion

The Woodtek Biochar Kiln is a reliable option for producing high-quality biochar with high carbon purity. It offers useful byproducts like syngas and bio-oil while keeping emissions relatively low when operated correctly. The cost of acquiring and operating the kiln can be justified by the economic and environmental benefits, particularly in regions with high demand for biochar and renewable energy solutions.

Pressvess: Dual Batch Kiln UK

The Pressvess Dual Batch pyrolysis kiln is manufactured in the West Midlands (UK) by family-owned company who also specialise in large steel tank manufacturing. The kiln is a cartridge-based batch system with a central wood fire box which acts as a primary heat ignition and also maintains energy input if needed later in the process.

Carbon Purity

Biochar Quality: The Pressvess Dual Batch Kiln is known for producing high-quality biochar, with carbon content typically ranging from 70% to 90%, depending on the feedstock and operating conditions. It is best suited to even sized wood feedstocks such as logs with an open cartridge or smaller wood chip with a baffled cartridge to allow 'air' flow for even pyrolysis. The kiln's design allows for precise control of the pyrolysis process, which is crucial for achieving high carbon purity, but constant monitoring and experience are required.

Temperature Control: The kiln is capable of reaching and maintaining high temperatures (usually between 400°C and 700°C), which is essential for producing biochar with a high percentage of fixed carbon. The dual-batch system allows for consistent operation and

the ability to optimize the process for different feedstocks. Best efficiency is achieved if the energy from the 'finishing' cartridge is used to initiate the fresh or new cartridge

Outputs

Biochar: The primary output of the Pressvess Dual Batch Kiln is biochar, which is used for various applications, including soil amendment, carbon sequestration, water filtration, and as a component in construction materials. The biomass processing rate is between 2t-4t per 8hr day depending on how many batches are fitted in on continuous turn around.

Syngas: The pyrolysis process generates syngas as a byproduct, which can be captured and used as a fuel to sustain the process itself or for other energy needs.

Bio-oil/Aqueous Phase: Depending on the feedstock and process conditions, bio-oil can also be produced. This can be condensed and used as a fuel or chemical feedstock.

Ash and Residue: A small amount of ash or other non-carbonized residue is typically produced, which varies depending on the feedstock.

Likely Emissions

Greenhouse Gases: If properly managed, the Pressvess kiln minimizes the release of greenhouse gases such as CO₂ and methane. The kiln's design includes features to ensure efficient combustion and gas management, reducing the likelihood of significant emissions. Emissions at the beginning of the process are difficult to avoid.

Particulate Matter (PM): The kiln may emit some particulate matter, depending on the efficiency of the pyrolysis process and the nature of the feedstock. However, this can be controlled with appropriate filtration or gas scrubbing systems.

Volatile Organic Compounds (VOCs): The pyrolysis process can release VOCs, but these are typically managed by the kiln's design, which may include systems for capturing and reprocessing these gases into bio-oil or syngas.

Cost

Capital Cost: The Pressvess Dual Batch Kiln is generally a significant investment, with costs depending on the size, capacity, and additional features such as emission control systems and automation. For medium to large-scale operations, the initial capital cost can range from tens of thousands to several hundred thousand dollars.

Operational Costs: Operating costs include expenses related to feedstock procurement and processing, energy consumption (though this can be offset by using syngas generated by the kiln), labour, and maintenance. The kiln's dual-batch system is designed to optimize efficiency, potentially lowering operational costs by allowing continuous operation with minimal downtime.

Return on Investment (ROI): The ROI depends on the market value of the biochar produced, potential savings from waste management, energy recovery from syngas, and income from carbon credits. Given the high quality of biochar produced, the kiln can provide a solid ROI in markets where biochar and sustainable waste solutions are in demand or where biochar is used as charcoal into a premium market although there is a loss of carbon credits and the environment benefits are lost in that circumstance.

Conclusion

The Pressvess Dual Batch Kiln is a robust and efficient system for biochar production, offering high carbon purity and multiple useful outputs such as syngas and bio-oil. It is engineered to minimize emissions and operate efficiently, though it requires a relatively significant initial investment. The system's design is particularly suited for small to medium scale operations where consistent biochar quality and process efficiency are critical. Overall, it is a competitive option for enterprises looking to produce high-quality biochar with environmental benefits.

Takachar USA

The Takachar Biochar Kiln is a small-scale, portable continuous flow system designed to convert agricultural and forestry waste into biochar. Takachar is known for its focus on low-cost, accessible technology, particularly for use in rural and underserved areas. Here's an assessment of the Takachar Biochar Kiln based on carbon purity, outputs, likely emissions, and cost:

Carbon Purity

Biochar Quality: The Takachar Biochar Kiln produces biochar with a carbon content typically ranging between 60% and 85%, depending on the feedstock and operating conditions. While it may not achieve the extremely high carbon purity of larger, more sophisticated systems, it still produces biochar suitable for many applications, particularly in agriculture.

Temperature Control: The Takachar kiln operates at lower and more variable temperatures compared to industrial-scale kilns (typically between 300°C and 600°C). This can result in slightly lower carbon content, but the design prioritizes simplicity and adaptability in the field.

Outputs

Biochar: The primary output is biochar, which is used for soil improvement, carbon sequestration, and water filtration. The biochar produced is generally well-suited for these purposes, especially in small-scale agricultural settings. This kiln can achieve relatively high rates of feedstock through put, especially given its portable design, of up to 1t per hr.

Syngas: The pyrolysis process generates syngas, but in the Takachar kiln, this is typically used to sustain the process itself, with any excess syngas being minimal and less frequently captured for other uses.

Minimal Byproducts: Unlike larger systems, the Takachar kiln is designed to focus on biochar production with minimal byproducts like bio-oil or ash. This is in line with its goal of simplicity and ease of use in low-resource environments.

Likely Emissions

Greenhouse Gases: The Takachar Biochar Kiln is designed to minimize greenhouse gas emissions. However, due to its small-scale and less controlled operation compared to industrial systems, there is a potential for some CO₂ and methane emissions, particularly if the process is not carefully managed.

Particulate Matter (PM): Given its portable and low-tech nature, the kiln might emit some particulate matter, especially if used in open environments. However, its design aims to keep these emissions low to meet environmental standards and be suitable for rural use.

Volatile Organic Compounds (VOCs): The kiln may emit some VOCs during operation, but these emissions are generally low due to the relatively simple and efficient design of the system.

Costs

Capital Cost: The Takachar Biochar Kiln is designed to be affordable, especially for small-scale farmers and rural communities. The cost is significantly lower than industrial-scale kilns, with units typically costing below \$100,000, depending on the model and features.

Operational Costs: Operating costs are minimal, as the kiln is designed to be fuel-efficient and low maintenance. The primary costs involve labour (which is often minimal), and feedstock, which is usually agricultural or forestry waste that would otherwise be discarded.

Return on Investment (ROI): The ROI for users of the Takachar kiln is generally high, particularly in rural and low-income settings. The production of biochar can significantly enhance soil fertility, leading to increased agricultural yields when applied correctly, and the kiln's low cost makes it accessible even to small-scale farmers. Additionally, there is potential for income from selling biochar or carbon credits.

Conclusion

The Takachar Biochar Kiln is a practical and cost-effective solution for small-scale biochar production, particularly in rural or underserved areas. While it may not achieve the highest carbon purity compared to industrial kilns, it produces biochar that is effective for agricultural and environmental applications. The system is designed to be low-emission and easy to use, with minimal operational costs, making it an excellent option for communities looking to improve soil health and manage waste sustainably. Its affordability and portability make it a valuable tool in promoting sustainable agriculture and carbon sequestration in low-resource settings.

Future Energy UK

The Future Energy Biochar Kiln is designed and manufactured in the West Midlands (UK) as a continuous flow, versatile, efficient system for producing biochar through the pyrolysis of many types of biomass. This type of kiln is often used in both agricultural and industrial settings, with a focus on sustainability, leading design and technology and energy efficiency. Here's an assessment of the Future Energy Biochar Kiln based on carbon purity, outputs, likely emissions, and cost:

Carbon Purity

Biochar Quality: The Future Energy Biochar Kiln is known for producing high-quality biochar, with carbon content typically ranging from 70% to 97% but mostly in the upper percentiles of performance. The exact carbon purity depends on factors like the type of feedstock, pyrolysis temperature, and residence time. The kiln's advanced design allows for precise control over these variables, along with a patented nitrogen fixing and injection system that eliminates all oxygen from the pyrolysis process leading to consistent and high-carbon biochar. The company look at each individual client requirement and bespoke the build of the pyrolysis unit to those requirements.

Temperature Control: The kiln operates at high temperatures, generally between 400°C and 700°C, which is ideal for producing biochar

with high carbon content. The system's ability to maintain stable temperatures ensures the production of biochar with a high degree of fixed carbon. Heat process initiation is by way of electric elements which surround the reactor insulation jacket.

Outputs

Biochar: The primary output of the Future Energy kiln is biochar, used in applications such as soil improvement, carbon sequestration, and environmental remediation. The biochar produced is typically of high quality, with properties that enhance soil fertility and water retention but can also be used in more demanding applications where consistency and high carbon purity levels are required.

Syngas: The pyrolysis process also generates syngas which can be used to generate electricity or be utilized in other energy applications or be condensed into an aqueous phase. Specific syn gases can also be targeted and captured if required depending on the initial testing of feedstocks. The efficient capture and use of syngas are key features of the Future Energy kiln, making it energy self-sufficient or even net positive in some cases.

Bio-oil: Depending on the specific configuration and operation of the kiln, bio-oil can also be produced. This bio-oil can be condensed and used as a renewable fuel or chemical feedstock, providing an additional revenue stream or energy source.

Aqueous Phase: Extensive work is being carried out to identify specific uses for the aqueous phase which has known but untested qualities.

Ash and Residue: Minimal ash or residue is typically produced, as the kiln is designed to maximize the conversion of biomass into biochar and other useful outputs.

Likely Emissions

Greenhouse Gases: The Future Energy Biochar Kiln is engineered to minimize greenhouse gas emissions, thanks to its efficient combustion and gas management systems. The kiln design includes mechanisms to ensure complete combustion of volatile gases, thereby reducing the release of CO₂ and methane. The unit works well within the emission requirements of all areas.

Particulate Matter (PM): The kiln is equipped with emission control technologies that help reduce particulate matter emissions. Filtration systems or gas scrubbers are often included to capture any particulates before they are released into the atmosphere.

Volatile Organic Compounds (VOCs): The kiln's design effectively manages VOC emissions, either by capturing and condensing them into bio-oil or by ensuring they are fully combusted within the system. This reduces the environmental impact and improves the overall efficiency of the pyrolysis process.

Cost

Capital Cost: The initial investment in a Future Energy Biochar Kiln can be substantial, particularly for larger models designed for industrial use. Costs start at over £1,000,000, depending on the size, capacity, and additional features such as specific condensing and control systems increase costs further.

Operational Costs: Operational expenses include feedstock procurement, electric, labour, and regular maintenance although this is kept to a minimum due to the efficient running of the unit. However, the kiln's high efficiency and ability to utilize syngas for energy can significantly reduce operational costs. The longevity and durability of the equipment also contribute to lower long-term expenses.

Return on Investment (ROI): The ROI is influenced by the value of the biochar produced, potential revenue from bio-oil and syngas, savings from waste management, and possible income from carbon credits. Given the high quality of the biochar and the kiln's efficient energy use, the Future Energy kiln offers a strong ROI, particularly in markets with high demand for biochar and sustainable energy solutions.

Conclusion

The Future Energy Biochar Kiln is a high-performance system designed for efficient, large-scale biochar production. It excels in producing biochar with high carbon purity, and its ability to generate useful byproducts like syngas and bio-oil enhances its value proposition. The kiln is designed to minimize emissions, making it a sustainable choice for both agricultural and industrial applications. While the initial cost is significant, the kiln's efficiency and the high value of its outputs make it a worthwhile investment, particularly for operations that can take full advantage of its capabilities.

Biomaccon Germany

Biomaccon Company is a family-owned business based in Rehburg/Germany and they manufacture pyrolysis units ranging from 160kw to 500kw. Their units are based on a continuous pyrolysis process in the fluidized bed reactor, where the particles of biomass are continuously fed into the heating reactor (3). In the process of the reactor condensation, the biomass starts to encounter an extremely hot and anoxic environment thus not only guaranteeing the art of complete thermal decomposition, but also production of biomass.

Biochar Yield: The Biomaccon pyrolysis system developed by Biomaccon Company with a fluidized bed has an excellent biochar yield at the rate of about 35-40% by weight depending on the dry matter feedstock. Biochar production efficiency using the Biomaccon technology could be mixed with varied feedstock properties and processing values, yet this data represents how the technology performs.

Syngas Production: The Biomaccon-based fluidized pyrolysis system is computationally predicted to result in gas production rates ranging from 100 to 150 cubic meters per ton of biomass consumed. This further output of syngas also improves the total energy output or efficiency of the process, allowing the generation of energy and its possible utilization. That and carbon credits are the primary outputs of these units.

Biochar Purity: (C: Ratio of H to C (H/C): Biomaccon has an excellent C: H ratio (max. 55:1) for biochar which demonstrates high purity and contains a lot of carbon. The key benefit of this property is that it widens the scope of use of biochar in different environmental-related applications like soil amelioration and carbon fixing.

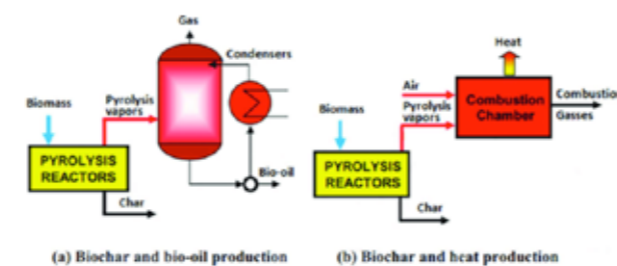


Fig 3: Flow diagrams for simplified pyrolysis units. (a) Simplified biochar and bio-oil flow diagram. (b) Biochar and gas flow diagram (Jouhara H. 2019) <https://www.researchgate.net>

Likely Emissions: Efficiency in both the combustion and gas cleaning processes is obtained by the utilization of modern techniques in the Biomaccon system. Direct pollution in the form of CO, CO₂, and NO_x is measured and can be adjusted to meet the local requirements.

Cost of Unit: The Biomaccon fluidized bed range of pyrolysis units with capacities of between 100kg to 300kg of feedstock per hour based on the possible configuration of the project cost relative to the kw output of the units. The simplistic design allows for self-maintenance helping keep operational costs to a minimum. Although the initial investment may be more or less, the long-term profits and paybacks from the economical ecosystem of biochar production validate the cost spent.

Conclusion

Biomaccon has a workflow of fluidized technology to reduce energy and the size of the unit, as it provides higher efficiency in large-scale production. The company focuses on customer approval through the provision of extended technical customer service, and optimization services, thereby looking to ensure that clients get a better experience, which handouts better yields from their biochar production units. The units are aimed at the biomass boiler replacement market (especially agricultural) and larger commercial units.

Pyreg Germany

Pyreg is a corporate business based in Dorth/Germany. Their units apply a continuous rotary kiln process that allows for the constant feeding of biomass feedstock to a rotating kiln where the resulting high temperatures are achieved in the absence of oxygen (4). This technique provides for uninterrupted and fast thermolysis of the biomass, resulting in biochar production.

Biochar Yield: The burn-off rotary kiln pyrolysis system (Pyreg) raises its yield of biochar to about 30-35% by weight. This can be different from one to another based on the content of feedstock and the process conditions. However, it indicates that it is a very effective technology to generate biochar from biomass.

Syngas Production: Generally, when it comes to Pyreg's rotary kiln system, bioenergy production rates are around 120-150 cubic meters per ton of biomass processed. This additional syngas combustion improves the general process energy efficiency making it possible for wasted energy recovery and disposal.

Biochar Purity: (C: Biochar of Pyreg which is mainly carbon with a ratio of C: H reaching up to 50:1 confirms high carbon content and purity. The fact that this feature makes the biochar suitable to be used for many different environmental purposes, such as soil improvement and carbon sequestration as well as industrial applications, is one of its quality aspects.

Likely Emissions: The rotary kiln pyrolysis process emissions are thoroughly minimized using the combined effect of efficient combustion and a gas cleaning system which is considered to be a key technology by Pyreg. Primary emissions that are CO, CO₂, and PM are monitored and compliance with strict environmental regulations relative to location is achieved.

Cost of Unit: The range of units supplied is between 500 – 1500kw and can be bespoke for individual needs. The annual feedstock requirement is between 300 – 1000kg per hr depending on feedstock and the unit. Costs are relative to the output of the unit and due to the efficiency and complexity of the reactors are on the upper end of the capital outlay scale. The initial investment amount could be different while the long-term effects and the gained benefits from more efficient biochar production plus the extra outputs generated more than make up for this expenditure.

Conclusion

The Pyreg Biochar Kiln is a highly advanced and environmentally friendly system designed for the production of high-purity biochar. It offers significant outputs, including biochar, energy recovery, and potentially useful by-products like syngas. The system is designed to operate with very low emissions, making it suitable for use in regions with stringent environmental regulations. While the initial investment is high, the long-term benefits, including high-quality biochar production and energy savings, can make it a cost-effective choice for many applications, particularly for large-scale or commercial operations.

Arti

Bio-Columbia is a family-owned business based in Des Moines Iowa, USA. Their kilns are continuous flow auger driven reactor units and can operate in tandem with a drying and processing unit along with delivery out.

Biochar Yield: Retort kiln system is the caliber of the production by Arti Company that guarantees the production of biochar of around 20-30% by weight. This value may differ due to the ingredients' structure and technical process parameters, yet it proves Arti's technology feasibility in biochar processing. Operating temperatures range from 400 – 700 degrees and due to the straightforward design can be simple to run but achieves slightly less performance on more challenging feedstocks. However, throughput and processing speed are high achieving 25t feedstock input (6t biochar output) per day.

Syngas Production: The gasification rate of Arti's batch retort kiln varies according to the process environment and the corresponding cubic meter per one ton of biomass used in the process. However, this plume together with other outlets which do not emit so much carbon is still often the source of overall energy efficiency losses.

Biochar Purity (C: H Ratio): Prospect: Arti sort of biochar is shown to have a high value of 45:1 in C: H, which represents the high amount of carbon as well as the purity. The decomposability of the biochar is one of its attributes; thereby presenting it as a diverse range of environmental applications.

Likely Emissions: Through optimizing combustion parameters and secondary combusting gas cleanup systems, the emissions from the batch retort kiln pyrolysis process of Arti are controlled. Monitoring of primary polluting emissions such as carbon monoxide (CO), carbon dioxide (CO₂), and trace amounts of organic vapors (VOCs) is carried out and is treated to comply with the provided standards.

Cost of Unit: The cost of the burner-reactor kiln system used for the production of 4t/h is between \$800,000 and \$1,200,000. It slightly fluctuates depending on the capacity and

customization requirements. This capital is inexpensive in comparison to some other systems; hence it is quite a viable option for biochar production by both small-scale and middle-sized enterprises.

Arti batch retorts coil kiln technology stands out for the characteristic of its simplicity and ease of operation, and it is therefore ideal in smaller-scale to middle-scale biochar production lines. An educational service, including training and support, is also available to certify operations efficiency and quality of the products, making the company more attractive to potential members.

Beston Group China

Type and Method of Pyrolysis: Beston Group China adopts a continuous rotary kiln vis-à-vis process where feedstock is continuously fed into a rotating kiln and heated to very high temperatures in the deficiency of air (5). This process, unlike other traditional methods, is both efficient and uniform in biochar production.

Biochar Yield: Beston Group's rotary kiln pyrolysis system yields about one-third of the source material as biochar, which is a remarkable percentage. This can also fluctuate with the feedstock characteristics and various process conditions; however, it illustrates the ability of the Beston group to produce biochar from biomass.

Syngas Production: Generally, Beston Group's rotary kiln system can produce syngas in the amount between 120-150 cubic meters/t (a ton of biomass processed). The extra syngas generated herein lead to higher overall operation efficiency together with the possibility of useful energy recovery.

Biochar Purity (C: H Ratio): The carbon content and purity level of Beston Group's biochar is as high as 50:1(C: H ratio), which can be achieved. Thus, this environmental feature makes the biochar an alternative solution for diverse soil improvement and C storage purposes.

Likely Emissions: The emissions of the rotating kiln pyrolysis method are efficiently managed through high-performing gas burning systems and gas cleaning systems which are implemented by Beston Group. Primary pollutants like CO, CO₂, and PM are closely monitored and controlled to the environmental standards without exception.

Cost of Unit: The costs of a Beston Group rotary kiln technology for processing 4t/hr of feedstock are from \$1,200,000 to \$1,800,000 depending on the size and the configuration. The cost of investment in an efficient biochar production process may differ but the long-term benefits and returns make the spending reasonable.

Beston Group's rotary kiln technology is reliable and scalable which works just great for large-scale biochar production operations. The company excels through our ability to provide complete technical support and customized options to suit the specific needs of clientele so that they can get the maximum value and satisfaction out of the products purchased.

ReCor South Africa Kilns

Type and Method of Pyrolysis: The ReCor South Africa pyrolysis process uses critical parameters including the batch retort kiln and pyrolytic chamber, sealed with no oxygen, for feeding biomass feedstock to indirectly heat to very high temperature (6). This technique enables culinary programs in biomass; thus, biochar production efficiency is guaranteed.

Biochar Yield: ReCor South Africa's batch retort kiln method succeeds in producing a 25-30% yield in weight of biochar although its figure is still considered good. The output may fluctuate regarding the characteristics of feedstock and processing parameters. The above-mentioned example demonstrates the operation of ReCor South Africa related to biochar production; however, it does not mean that the technology of this company is the best one.

Syngas Production: Different factors such as biomass type, retort duration, weather conditions, and hiring of skilled labourers may affect the Syngas production rates with the

batch retort kiln system. The scale of production with this system is generally between 80 to 120 cubic meters per ton of biomass. Nonetheless, this is only a fraction of how much other systems produce, therefore this rate still ensures that the system is more energy efficient.

Biochar Purity (C:M: C Ratio): The biochar generated by ReCor South Africa indicates a high carbon content and purity from C: H ratio = approximately 45:1. The high calibre limit provides this biocarbon its suitability for application purposes in various environmental areas.

Likely Emissions: Combustion of emission from the batch retort kiln pyrolysis process in the region belonging to ReCor South Africa is achieved through the application of efficient fuel combustion and gaseous purification processes. The primary emissions from tailpipes including CO, CO₂, and trace amounts of VOCs are supposed to be controlled and adjusted to meet regulatory standards.

Cost of Unit: Our package of up to 4t/hr feedstock retort kiln system, ReCor South Africa, costs from \$800,000 to \$1,200,000 depending on the processed item, batch capacity, and necessary customization measures. Moreover, the amount of capital that is needed to get these systems going is relatively less than that needed to launch some other systems and hence is appealing for small to medium-scale biochar production operations.

In comparison to other technology in use by ReCor South Africa, batch retort kiln offers an easier-to-operate and less complicated technology, which can be used by even small to medium biochar plants. What distinguishes the performance is sustainable procedures and several training services and support systems which ensure a smooth running of the system and are of high quality, creating even more necessity for the company among the potential customers.

3.2 Tabular Summary of Kiln Process for Companies

Company	Type and Method of Pyrolysis	Biochar Yield	Syngas Production	Biochar Purity (C:H Ratio)	Likely Emissions	Cost of Unit (4t/hr)	Other Relevant Info
Ring of Fire Kiln	Continuous rotary kiln	30%	800 m ³ /ton	15:1	Low emissions	\$1.5 million	Offers automated control systems and easy integration
Wilson Biochar LLC	Batch pyrolysis	35%	700 m ³ /ton	20:1	Advanced emission control	\$2-\$3 million	Customizable designs and waste heat recovery options
Pressvess Dual Batch Kiln	Batch pyrolysis	35-40%	80-120 m ³ /ton	55:1	Efficient combustion systems	\$800,000 - \$1,300,000	Versatility for batch processing and medium-scale production
Takachar USA	Continuous pyrolysis	30-35%	100-150 m ³ /ton	50:1	Monitored emissions	\$1-\$1.5 million	Emphasis on sustainability and support services
Combined Industries UK	Rotary kiln	25-30%	120-150 m ³ /ton	45:1	Controlled emissions	\$1.2-\$1.8 million	Robustness and reliability for large-scale operations
Biomacon Germany	Continuous fluidized bed	35-40%	100-150 m ³ /ton	55:1	Efficient gas cleaning	\$1.5-\$2 million	High efficiency and scalability for large-scale production
Pyreg Germany	Continuous rotary kiln	30-35%	120-150 m ³ /ton	50:1	Controlled emissions	\$1.2-\$1.8 million	Reliability and flexibility with extensive support
Arti Columbia	Continuous auger flow kiln	25-30%	80-120 m ³ /ton	45:1	Efficient gas cleaning	\$800,000 - \$1,200,000	Simplicity and ease of operation for small to medium-scale production
Beston Group China	Continuous rotary kiln	30-35%	120-150 m ³ /ton	50:1	Controlled emissions	\$1.2-\$1.8 million	Reliability and scalability with comprehensive support
ReCor South Africa	Batch retort kiln	25-30%	80-120 m ³ /ton	45:1	Efficient combustion	\$800,000 - \$1,200,000	Simplicity and sustainability for small to medium-scale production

3.3 Conclusion

The analysis of the choice biochar units indicates a multiplicity of technologies and methods used in biochar development. Specifically, whether continuous rotary kilns will work for large scale or batch retort kilns for smaller requirements, a variety of enterprises provide bespoke solutions. Of course, yield factors such as biochar, syngas production, and purity are mandated in your decision-making in the determination of biochar production system, environmental as well as cost is a factor to consider. Through knowledge of the advantages and disadvantages inherent in each technology, stakeholders can make exact informed decisions to upgrade biochar as a longer-lasting solution for soil improvement, carbon sequestration, and waste recycling. As it moves from struggling to thriving, the biochar industry's future looks bright with more collaboration, innovation and solving global environmental issues.

Section 3 References

- (1) Okoji, A. I., Anozie, A. N., Omoleye, J. A., Taiwo, A. E., & Osuolale, F. N. (2022). Energetic assessment of a precalcining rotary kiln in a cement plant using process simulator and neural networks. *Alexandria Engineering Journal*, 61(7), 5097-5109.
- (2) Williams, P. T. (2021). Hydrogen and carbon nanotubes from pyrolysis-catalysis of waste plastics: A review. *Waste and Biomass Valorization*, 12, 1-28.
- (3) Garcia-Nunez, J. A., Pelaez-Samaniego, M. R., Garcia-Perez, M. E., Fonts, I., Abrego, J., Westerhof, R. J. M., & Garcia-Perez, M. (2017). Historical developments of pyrolysis reactors: a review. *Energy & fuels*, 31(6), 5751-5775
- (4) Tutturen, K. A. (2013). Industrial charcoal production with power generation at Mully Children's Family Yatta, Kenya (Master's thesis, Norwegian University of Life Sciences, Ås).
- (5) Ai, J., Zhang, W., Chen, F., Liao, G., Li, D., Hua, X., ... & Ma, T. (2019). Catalytic pyrolysis coupling to enhanced dewatering of waste activated sludge using KMnO₄Fe (II) conditioning for preparing multi-functional material to treat groundwater containing combined pollutants. *Water research*, 158, 424-437.2.3.4
- (6) Wei, H., Luo, K., Xing, J., & Fan, J. (2022). Predicting co-pyrolysis of coal and biomass using machine learning approaches. *Fuel*, 310, 122248.

SECTION 4 – ASSESSMENT OF ORCHARD BIOMASS AS BIOCHAR

4.1 Summary from EBRI Material Assessment report

Executive Summary

This report summarises the analysis of materials derived from pyrolysis of mixed apple and pear wood from the 300 g/hr Pyrolab™ and pilot-scale Comkiln-200™ system.

- Derived material yields, 450°C and 550°C test with 20 minutes residence time.

	Pyrochar	Liquid (total)	Pyrogas
450°C	25 wt.%	51 wt.%	19 wt.%
550°C	19 wt.%	28 wt.%	46 wt.%

- Pyrogas yields increased significantly with temperature with corresponding reductions in solid and liquid products.
- Processing at 550°C or higher derives a lower pyrochar yield but the higher H:C (hydrogen to carbon ratio) ratio provides a better-quality pyrochar that is more suitable for agricultural applications.
- The summary below indicates compliance of derived pyrochar with respect to the physical, trace element, H:C ratio and PAH limitations of the three established biochar standards:

Pyrochar compliance		450°C	550°C
BQM	Standard	✓	✓
	High	x	✓
IBI	All	✓	✓
	Basic materials	✓	✓
EBC	Consumer Materials & Urban	✓	✓
	Agro	x	x
	Agro Organic	x	x
	Feed & Feed Plus	x	x

- BQM High standard is not met at 450°C due to trace levels of Nickel and Chromium exceeding limitations.
- EBC Agro, Argo Organic, Feed & Feed Plus certifications are not met due to high polyaromatic hydrocarbon levels.

- The pyro-liquid obtained from the Comkiln-200™ at both temperatures was aqueous phase, pyrolysis oil made up just 1.4 wt.% of the liquid mass or 0.7 wt.% of the feedstock mass at 450°C and at 550°C negligible organics were observed.
- The aqueous phase density and viscosity was similar to water and was mildly acidic in nature at an average of around four. Major compounds including acetic and propionic acid alongside a range of phenolics and some alcohols.
- The pyrolysis liquid has a low heating value of ~ 31MJ/kg, high viscosity, high flash point and a water content of 8.77 wt.%. With the exceptionally low yields this makes it unsuitable to process the feedstock for volume production and utilisation of the oil as a fuel.
- The phenolics present in the oil could be of value to the bio-chemicals industry.
- Pyrolysis gas heating value:

	H ₂ proportion	MJ/kg	kWhr/kg
450°C	6.86 vol.%	21.03	5.84
550°C	13.96 vol.%	22.20	6.16

This equates to slightly under half the heating value of natural gas.

- The proportion of hydrogen increased at the higher processing temperature of 550°C in conjunction with over double the volume of gas with the higher heating value.

Recommendations

In summary it is recommended that future processing under controlled conditions should take place at 550°C as this will:

- Produce a high-quality biochar for the BQM standard making soil applications easier while fulfilling the same criteria within IBI and EBC.
- A much higher volume and increased heating value of pyrolysis gas is derived than at lower processing temperatures.
- The physical characteristics of liquid products are similar at either temperature with little to negligible organics at the higher temperature.
- The chemical composition of the aqueous phase pyrolysis liquids were different with a wider variety of phenolic compounds present at the higher temperature of 550°C.
- Lower temperatures could be investigated, e.g., 500°C, to optimise the amount of energy used whilst still potentially meeting the same standards as at 550°C.
- The effects of variability in the feedstock with respect to trace elements concentration will need to be considered as levels are close to limit.
- Adjustments to the materials residence time should also be considered, longer and shorter, as this may provide beneficial effects in both derived products and energy balance.

4.2 Durability of Carbon Storage in Three Apple Wood Biochars: Comparison of Three Project Biochars Via Accelerated Ageing (the Edinburgh stability tool)

Abstract

Three biochars made and used in the Innovate project were assessed for their stability, indicating their possible extent and trajectory of decay over approx. 1000 years in soil. The idealized product from the UK Biochar Research Centre showed the highest level of durability with 81% of initial carbon surviving the highest level of degradation. The Aston sample showed a high level of resistance and a similar pattern of degradation but was ultimately reduced to ash (<5% carbon remaining). The sample used in the field in comparison showed low resistance from the outset, with 45% of the carbon eliminated in the first treatment, equating to approx. 100 years.

Dr Saran Sohi
Email: saran.sohi@ed.ac.uk

Introduction

Microbial degradation of charcoal and biochar in soil is oxidative, and we previously defined a method to simulate the ageing that occurs in the soil environment by the controlled application of the oxidant chemical hydrogen peroxide under laboratory conditions. Increasing doses of oxidant expose the same fixed amount of biochar carbon to higher oxidative pressure, simulating increasing levels of degradative ageing. This presents a full profile for the reactivity of carbon in biochar as it ages, from the perspective of soil micro-organisms viewing biochar rather in terms of “substrate quality”.

Oxidations were conducted for all three biochars used in the project, at the UK Biochar Research Centre, University of Edinburgh. Each biochar was treated at incrementally higher doses of 0.05, 0.10, 0.20, 0.30, 0.40 or 0.50 mol hydrogen peroxide, in triplicate. The measured carbon concentration of each biochar was used to weight out sub-samples that each contained exactly 0.1000 g (0.008 mol) of carbon.

BIOCHAR

TAKING COMMERCIAL APPLE PRODUCTION TO NET ZERO

Each biochar was milled to a fine powder before oxidation. This was to remove physical impediments to oxidation that are presented by a complex physical microstructure, and provide a 'worst case' picture for durability in the soil environment. Under natural soil conditions it is known that charcoal, an analogue for biochar, remains present over the long-term, but fragments into fine particles quite quickly.

Shortly after adding the oxidant to a biochar sample, the reaction temperature is increased to 80°C and held, such that the sample progressed gradually to dryness. Chemical determinations of carbon concentration were made on each weighed residue, enabling us to establish the amount of carbon that was oxidised to CO₂ (mimicking microbial utilisation) in each case.

The resulting curve shapes (reactivity profiles) reveal large differences between the biochars.

This may be because pyrolysis reactions reached different equilibria at the set heating temperature, and consequently different ageing patterns. It could also reflect non-equilibrium in pyrolysis, where overall distribution of reactivity is affected by variation in the completeness of pyrolysis within the sample (i.e., including fractions that are not could reflect fractions in the process of pyrolysis). Non-equilibrium is more likely to occur in biochars created at lower set temperature, owing to slower thermal transfer and/or slower chemical conversion.

Biochars made at high temperature are liable to be more evenly pyrolysed, as well as more completely pyrolysed. This has a large effect on durability, which is disproportionately sensitive to aromaticity, and indicators such as H:C ratio.

Results

The main results for each biochar are presented below in Figures 1–3. The x-axis scale corresponds to approximately 1000 years of ageing in the environment. The y-axis shows the proportion of initial carbon remaining as ageing is increased.

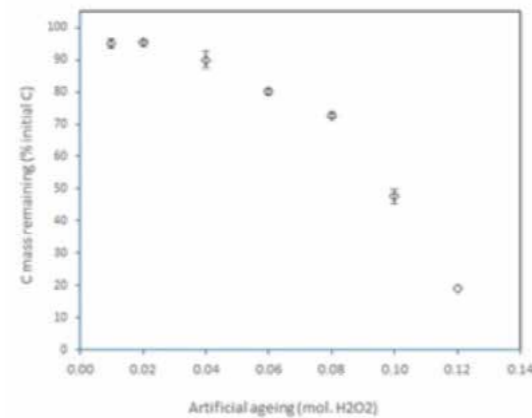


Figure 1a The idealized product from the UK Biochar Research Centre showed the highest level of durability with 81% of initial carbon surviving the highest level of degradation.

Mean values shown with standard error (n=3)

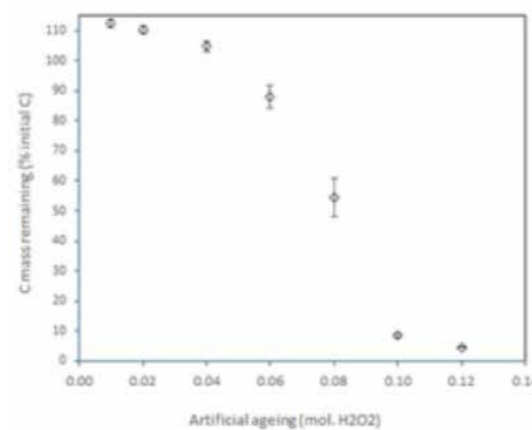


Figure 1b: The Aston sample showed a high level of resistance and a similar pattern of degradation, but was ultimately reduced to ash (<5% carbon remaining).

Mean values shown with standard error (n=3)

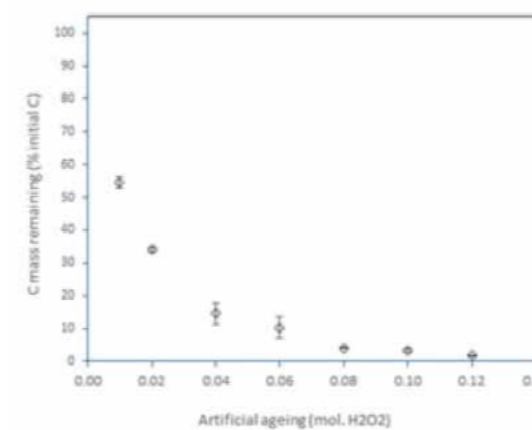


Figure 1c: The sample used in the field in comparison showed low resistance from the outset, with 45% of the carbon eliminated in the first treatment, equating to approx. 100 years.

Mean values shown with standard error (n=3)

Interpretation / Implications

Biochar has multiple functional properties in soil, but the availability and continuity of each function varies between biochar types and how / where it is used. Some functions are finite, such as direct provision of non-carbon nutrient elements. These are inherited from the biomass and carried within the physical matrix and may be mobilised independently of the carbon – chemically, physically or biologically.

Other functions emerge over time – surface reactivity increases rapidly as the outer molecules over the extensive surface area are partially oxidised, even though the progress of oxidation through the material may be extremely slow.

If carbon storage is an important property, complete pyrolysis at high temperature assures the highest durability. Although static assessment of fresh product may show lower function, the relevant functionality emerges in soil over weeks to months.

Functional tests are designed to mimic processes acting on biochar in soil over time, providing a measure of trajectory for a function as well as relative size. The results in Figures 1–3 above illustrate this point for carbon durability. The pattern as well as ultimate extent of decomposition is important to valorisation of biochar in CO₂ removal.

Appendix

Some supplementary data is provided in the Appendix, namely the H:C ratio of differently aged biochars. These provide an indicator of how ageing of residual biochar progresses in tandem with slow CO₂ emission.

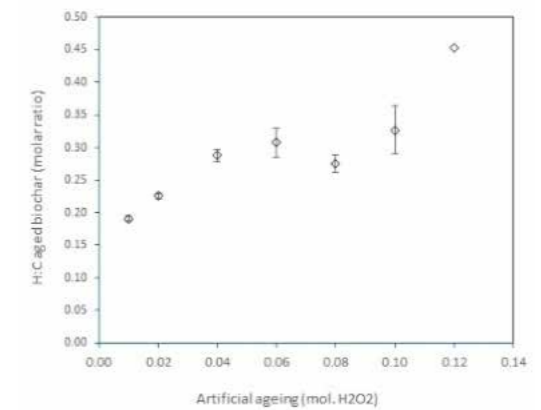


Figure A1a: H:C for the UK Biochar Research Centre sample starts at a low value below 0.20, consistent with highly-stable biochar according to commonly used accounting methodologies. It remains below the higher (acceptable) threshold of 0.40 until subjected to the highest dose of oxidation.

Mean values shown with standard error (n=3)

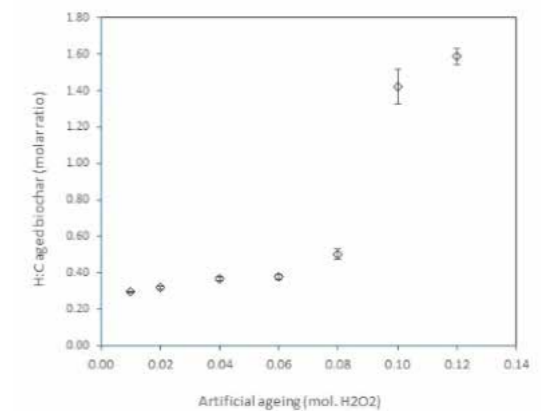


Figure A1b: It appears that the initial H:C of the Aston biochar does not meet the 0.20 threshold for highly stable biochar, and H:C increases rapidly, exceeding 0.40 with a medium level of ageing, equivalent to approx. 600 years.

Mean values shown with standard error (n=3)

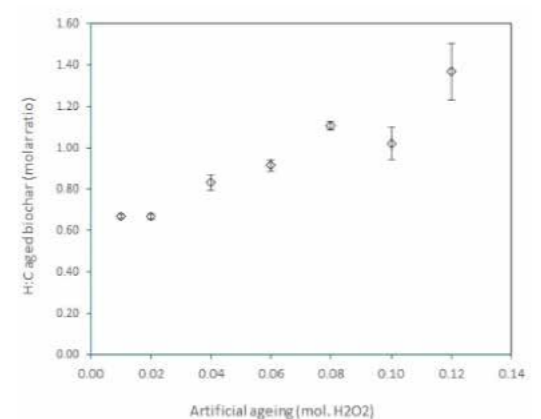


Figure A1c: The sample used in the field in comparison showed low resistance from the outset, H:C falling outside the qualifying ranges for permanence after basic ageing.

Mean values shown with standard error (n=3)

SECTION 5 – BIOCHAR IN-FIELD ASSESSMENT



5.1 Introduction

One of the key aspects is whether the addition of biochar as a soil amendment has a beneficial effect on orchard soils. As part of this project, we undertook to trial the use of biochar as an addition in the planting hole and also as an amendment in an established orchard. Whilst trials of two years are not long enough in a perennial growing system, we hope to be able to continue these trials in the future.

5.2 Overview

There is now a considerable body of literature (ca. 15,000 publications) concerning the use of biochar as a soil amendment, much of it published in the last 12 years. Meta-analyses of the studies indicate an overall trend of useful effects, variously characterised as, for example, increases in plant productivity, crop yield, photosynthetic rate, root length, root biomass, chlorophyll concentration, transpiration rate, stomatal conductance, and in the soil, increases in soil organic carbon, soil microbial carbon, and available water content.

That said, in already optimised high yield systems on fertile soils with sufficient precipitation and optimised fertilisation, further yield increases are difficult to achieve.

To build a compelling use-case to justify associated costs, it would be an advantage to identify parameters that are specific to tree fruit production which may be positively influenced:

- Can biochar amendment of planting holes accelerate early growth, or help to overcome replant disorder?
- Can amendment influence fruit calcium levels and storage characteristics or colour?
- Can it influence the prevalence of canker?
- Could the use of biochar enable previously marginal sites to be planted successfully?

Many of these tree fruit specific parameters, if they are affected, can be expected to develop over an extended period of time, likely beyond the duration of this pilot project. This creates a tension when considering the optimum approach: A replicated, randomised-block trial layout is optimum to provide scientific rigour and statistically reliable results – but it is intended to continue to monitor for treatment effects after the funded pilot project has ended, and complex plot layouts do not lend themselves to continued, unfunded observations and comparisons in commercial orchards. At one level, in agriculture, if effects can only be discerned after painstaking statistical analysis, the effect is not large or reliable enough to be of commercial interest.

It will only be possible to compare a limited number of variables, choosing from this (non-exhaustive) list

Post pyrolysis processing: (Grinding / particle size, +/- nutrient mixing)

Deployment: (Dose, planting hole (+/- AMF) vs. surface spread)

5.3 Trial Outline.

1. Terramap site to characterise baseline soil conditions of site, mapping variability.
2. Establish a plot layout in areas of minimal soil variability (plot size dictated by biochar availability, at least 30 treated trees)
3. Dose planting holes, in addition to the farms 'normal practice' (e.g. AMF)
4. Apply around tree bases with measured dose of biochar, (possibly in mixture with PAS100 compost, at a range of ratios, TBC)
5. Monitor for treatment effects:
 - Plant: Extension growth, trunk girth, canker prevalence, (later, brix, dry matter, firmness, colour, other parameters?)
 - Soil: microbial biomass, PLFA, soil organic carbon, available P (other parameters?)

Dose considerations:

Raw material available – sourced from on-farm, pruning's discounted.

Previously measured tree weights:

1: Parsonage Orchard 17.38kg X 1675 trees/ha = 29,111 kg (@ 21 years old).

2: Wingham Orchard 14.33kg X 1666 trees/ha = 23,875 kg

ca. 26.5 tonnes per hectare of 'trees'(mid-range value)

ca. 13.25 tonnes dry matter (taken as 50%)

ca. biochar yield per tonne of dry matter = 300 kg (range 250-350 kg)

ca. therefore biochar yield per hectare = 3975 kg/ha dry biochar

For a holding of 100 hectares, assuming a 14-year orchard life (range 10-18 years):

7 ha X 3975 kg = 27,825 kg Biochar per year.

27,825 kg divided across 93 ha = 299 kg/ha/yr. divided by 3077 trees = 97 g/tree if spread annually.

27,825 kg divided across 21,539 trees (7 ha X 3077trees/ha) = 1.29 kg per tree planted, if used as a planting hole supplement.

Rate? Some sources advocate 7.5% inclusion by volume, other sources 0.5 kg per tree, other sources suggest a maximum of 20% by volume of backfill soil. Previous studies have broadly tended to evaluate large doses over short periods of time. It would be useful to evaluate the effect of small additions.

5.3.1 Trial Design – Additions to planting holes. Plots 4 rows wide X 5 trees long.

Quantity of Biochar per planting hole	Row 1	Row 2	Row 3	Row 4	Total Req
Trees 1-5	15g	15g	15g	15g	300g
Trees 6-10	30g	30g	30g	30g	600g
Trees 11-15	60g	60g	60g	60g	1200g
Trees 16-20	120g	120g	120g	120g	2400g
Trees 21-25	240g	240g	240g	240g	4800g
Trees 26-30	480g	480g	480g	480g	9600g
Trees 31-35	960g	960g	960g	960g	19200g

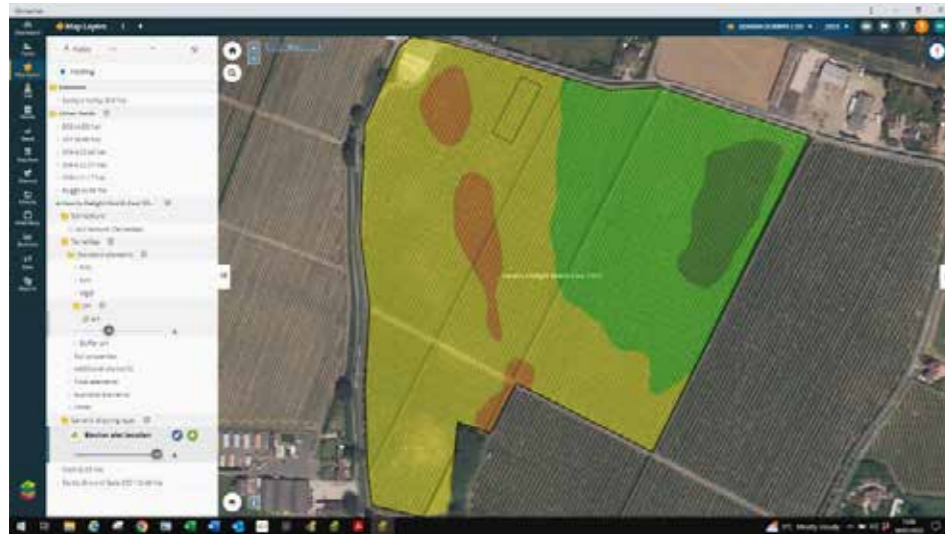
Total Biochar req = 38 kg, if plots extended to 10 long X 4 wide, 76 kg biochar req.

5.3.2 Trial Design – Surface application in established orchard

Quantity of Biochar per planting hole	Row 1	Row 2	Row 3	Row 4	Total Req
Trees 1-12	500g	500g	500g	500g	24kg
Trees 13-24	1000g	1000g	1000g	1000g	48kg
Trees 25-36	1500g	1500g	1500g	1500g	72kg
Trees 37-48	2000g	2000g	2000g	2000g	96 kg

5.4 Terramap examples used in planning location of treatment plots.

Plot location Hearts Delight orchard – Biochar addition at time of planting



Proposed plot location in Saxby's Valley – Biochar addition at time of planting



The trial plots have been established as follows:

Kent:
Wenderton - *Hearts Delight addition in tree planting hole*

Dambridge West - *surface application in young established orchard*

Hononton Target East – *biochar addition at time of planting*

Hononton 9 acres - *surface application in young established orchard*

Worcestershire:
Suckley, Sams Orchard - *surface addition in young established orchard.*

5.5 Trial Results

At the time of writing, there were no observable effects in any of the treated plots. This is to be expected, and any treatment effects are likely to become apparent in the years to come.

If no observable effects are apparent, it is likely a reflection that in already optimised high yield systems on fertile soils with sufficient precipitation and optimised fertilisation, further yield increases are difficult to achieve.

SECTION 6 – LIFE CYCLE ANALYSIS AND CARBON CONVERSION ASSESSMENT – BIOCHAR PRODUCTION

Biochar Production and Integration in UK Apple Orchard System: Comparison of integration options in accordance with the Puro Earth Standard

Abstract

In UK apple production the periodic renewal of old trees generates potentially harvestable biomass. New biomass chipping options offer an alternative to open on-site burning, which returns the carbon accumulated in the trees to CO₂. Pyrolysis would permanently sequester about half of the carbon by creating biochar. If pyrolysis is centralized, capex and opex costs are reduced (not an explicit part of the present analysis) and the associated heat product can be valorized. Co-location with a use for industrial heat is important because the efficiencies of small-scale electricity generation are very low, and the electricity grid is increasingly decarbonized.

Dr Saran Sohi, University of Edinburgh

Summary

This prospective life cycle assessment (LCA) estimates the CO₂-equivalent impact of producing and using biochar as part of the cyclical grubbing and replanting of UK apple orchards, which is traditionally achieved by open burning.

Grubbed biomass includes small diameter above-ground stems and branches of aged apple trees (wood and bark), a fraction that can be prepared for pyrolysis using suitable chipping equipment. It excludes below-ground biomass in roots and the root ball which have to be extracted prior to replanting but are not readily prepared for pyrolysis due partly to the stones and soil attached.

Carbon in wood is biogenic and can be stabilised during thermal conversion into biochar (the pyrolysis process). Wood has a very low mineral content, resulting in a high yield of stabilised carbon. It initially has a high moisture content, and the carbon content could be diluted by some soil contamination attached during grubbing and in-field handling.

Grubbing rotates around apple-growing land on a roughly decadal cycle. To convert harvested biomass into biochar at an efficient scale, chipped biomass would be aggregated across apple-growing landscapes and centrally converted to biochar. In-field drying to 30% moisture content precedes transport to the pyrolysis site, avoiding the need for active thermal pre-drying.

Pyrolysis is undertaken using a Biomacon 500 continuous feed pyrolyser with 85% up-time and biomass feed rate of approx. 340 kg / hr (240 kg / hr dry mass), 500 kW nominal heat output.

The heat required to sustain the pyrolysis is derived through combustion of the pyrolysis gas product in a linked thermal oxidiser. Surplus energy captured from the oxidiser via heat exchange offsets adjacent year-round demand for heat previously supplied from the gas grid.

Entry of chipped apple wood into the wider woodchip market is avoided, since the explicit goal is to inset CO₂ emissions in the apple supply chain via permanent carbon removal and to exceed the net cost through sale of heat and defined agronomic effects on the same source land. The latter still have to be identified / demonstrated at relevant dose, and quantified with the level of certainty required for sufficient economic valorisation

The LCA in this report aims to comply with ISO 14040 and 14044 as well as the Puro Earth biochar methodology, drawing on a previously published biochar-specific LCA model. The boundary of the analysis is cradle to grave, including the delivery of biochar back to orchards.

The calculation of CO₂-equivalent benefit includes consideration at each stage, where data is available, of two non-CO₂ greenhouse gas emissions – methane (CH₄) and nitrous oxide (N₂O).

Data used in the LCA calculations is variously sourced from within the project consortium, equipment manufacturers and users, official Government statistics and published academic literature. The unit of analysis is tonnes of net CO₂ removal / abatement per tonne of biochar produced, comprising a defined amount of permanent CO₂ removal and a less defined effect on energy emissions relative to baseline scenario. The analysis timeframe is 25 years (two rotations), with a time horizon of 100 years.

The pyrolysis site draws on 20 orchards with average apple-growing area of 100 ha and grubbed every 13 years. The average straight-line distance to the pyrolysis plant is 23 km, and the plant receives 2500 tonnes of chipped apple-wood biomass per year.

The system produces 457 t / yr of biochar and avoids 1147 tCO₂ emission through the supply of industrial heat, substituting for natural gas. The analysis provides an estimated net removal of 2.45 tCO₂ per tonne of biochar produced, with a higher net overall abatement of 4.96 tCO₂ once avoided fossil energy emissions are considered. The corresponding figures per tonne of dry biomass are 0.61 tCO₂ and 1.24 tCO₂, or 1.30 tCO₂ and 2.64 tCO₂ per tonne of biomass carbon.

The main emission sources were fuel sources for processing, handling and transporting biomass, and the initial and subsequent slow decomposition of biochar in the field.

Refinement of the LCA should validate the assumed / expected impacts of the biochar on the growth and efficacy of the orchard system, including defined effects of the product fertiliser use (and the CO₂-equivalent emissions avoided by this).

In addition, the net emissions arising from associated energy capture should be revised according to detailed operational data specific equipment and the utilisation scenario updated once potential siting is clearer.

6.1 Introduction

6.1.1 Scenario overview

British Apples and Pears Limited seek to profitably embed carbon removal into the UK tree-fruit sector, by making and valorising biochar within the orchard system. This will be achieved by chipping apple tree biomass gathered in the grubbing process, aggregating and transporting it to a centralised pyrolysis facility and returning it back to the orchard as part of the normal crop management. Sited alongside, e.g., apple processing facilities, the energy co-product from pyrolysis (heat) will contribute to wider decarbonisation of the supply chain.

Returning stabilised carbon into the orchard offers potential value from the associated recycling of crop nutrients and indirect effects on soil chemical and physical properties around tree roots. The aim is to integrate valorise biochar in the annual production cycle, probably through effects on efficacy of nutrient and water use, speed of tree maturation, and general tree health.

Siting pyrolysis adjacent to an end-user for industrial heat provides a second revenue stream from the heat co-product. The likely counterfactual to centralised pyrolysis of chipped tree biomass is its centralised combustion. Combustion yields more heat energy, so the net total value of the biochar has to exceed the opportunity cost of energy, plus the differential in opex and capex costs (which are higher for pyrolysis).

The combustion counterfactual has a larger effect on pre-existing energy emissions owing to higher heat output, but pyrolysis combines emission reduction with carbon removal. The net climate benefit depends on the source of pre-existing energy usage, and the efficiency of heat use. Avoiding emissions from the gas grid has less climate benefit than for gas-generated electricity due to inherent inefficiencies in power generation. Because renewable sources provide the majority (and increasing proportion) of grid-electricity, targeting gas-derived heat and CO₂ removal has the greater climate impact.

6.1.2 Scale and Scaling

The cost of biochar is highly sensitive to unit size of pyrolysis equipment. There is a strongly non-linear relationship between the cost of space, infrastructure and pyrolysis equipment and the 'capacity' of the equipment (potential throughput in tonnes of biomass per unit per day). To a lesser extent this is also true of site scale, if multiple smaller units are co-located. Key components of opex are essentially fixed with respect to unit size, and non-linear for aggregate (multi-unit) size of site. In some situations, a multi-unit site has indirect advantages related to continuity of biochar supply, i.e., if there is particular dependency on energy supply for example.

Transportation costs are relatively insensitive to distance owing to the high fixed time / cost of biomass handling (loading / unloading), and the higher tortuosity of short journeys.

Scale optimisation is most sensitive to the level of orchards engagement with the system – low engagement increases the average distance required to source the supply of biomass required to sustain a larger site. However, catchment area increases rapidly with radius, and it may be total regional area of orchard land that provides a relatively modest cap.

The scenario we used in LCA assumes a single pyrolysis unit on one site. The size of the unit and consequently heat output and transport emissions are based on capture of biomass up to a 50 km (30 mile) straight-line distance. It is imagined that the total area of orchard within this 8000 km² catchment is 8000 hectares (1% of the landscape), and that the level of engagement (participation) is 25%, i.e., one in four orchards supply their biomass for pyrolysis. This situation could reflect initial implementation in either of the two areas of concentrated dessert apple production in the UK, i.e., Kent, or Worcestershire / Herefordshire,

The boundaries of this LCA are cradle-to-grave for the biochar product. The analysis includes emissions associated with the acquisition of chipped apple tree wood, the manufacture

of biochar, the use of the pyrolysis heat co-product, and the transport and application of the biochar product back to orchard land.

An allowance is made for the emissions associated with the manufacture, installation and lifespan of the key fixed, mobile and haulage equipment used within the system.

The analysis is strictly attributional and developed by hand, drawing on the first-published LCA for pyrolysis-biochar systems (Hammond et al. 2011). The original spreadsheet model was developed and applied to the first national assessment of potential carbon benefits arising from widespread adoption of biochar in the UK, for UK Government in 2009–10 (Shackley & Sohi, 2010).

The owner of this specific analysis is British Apples and Pears Limited. The intended audiences for this analysis are the UK orchard industry, Puro Earth and wider stakeholders in the apple supply chain.

6.1.3 Scope of the Life Cycle Assessment

This LCA is to establish the potential carbon benefit of harvesting surplus biomass in dessert apple orchards, converting it to biochar, and using in back into the same orchard system. The indirect carbon benefits arising from improved fertiliser use (reduced application rates) or lower rates of water use are only scoped in this work and not included in the lead scenario.

Emissions from the manufacture of biochar and heat co-product are analysed across the whole life cycle, with their impacts categorised by life cycle stage. In the near-term, the life cycle model provides for scenario adjustment and system optimisation, drawing on refined information or adjusted targets. The analysis provides a basis on which to determine future audit and monitoring, in line with the Puro Earth market place.

The LCA calculations in this work follow the principles of ISO 14040 and 14044 (The British Standards Institution, 2020a; 2020b) and aim to align with the Puro Earth Biochar Methodology (puro.earth, 2024).

6.1.4 The Product System

Biochar cradle-to-grave LCA considers the impacts of biochar manufacture from acquisition of apple wood chip and its thermal conversion by pyrolysis, to the utilisation of the heat co-product. Pre-processing involves in-field chipping of above-ground tree biomass, after trees have been uprooted and cut. It is anticipated that air-drying in the field will reduce the initial moisture content of 50% (fresh mass basis) to 30%, reducing the demand on heat generated in the pyrolysis process.

Pyrolysis is conducted at 700°C to achieve even and near-complete conversion of degradable carbon into carbon permanently stored in recalcitrant chemical form (at molecular scale, fused aromatic carbon rings). Permanence is relative and measured as the proportion of solid carbon remaining after 100 years in soil, in an agricultural field environment.

A continuous stream of biochar and volatiles / gases is separated on exit from the reactor / kiln. Some of the gas-phase product is directed towards the outside of the kiln, providing the external supply of heat required to sustain the continuity of the process, i.e., heating further incoming biomass. The precise amount and proportion of gas used within the pyrolysis process adjusts continuously to allow for

fluctuations in biomass moisture content and chemical composition. The remaining heat is captured into water via heat exchange in the thermal oxidiser, an integral part of the pyrolysis system for handling the gas product. It is assumed that waste heat (10% thermal loss assumed) is dissipated and un-utilised.

The seasonality of orchard operations means the wood chip will not be continuously generated, but in-field drying should allow for more continuous collection across the catchment. Shutting down, re-starting and reaching stable operating conditions increases opex and accelerates wear in the pyrolysis system. High utilisation of capex is economically desirable, so the pyrolysis equipment will shut down only for planned and unplanned maintenance.

The initial input of heat required to start pyrolysis reactions after shutdown is provided from biomass with the system in aerobic mode, over a period of 1.0–1.5 hrs. Operation is continuous between maintenance shutdowns, with 85% up-time. It would generally be more efficient to supplement orchard wood chip with wood chip from other sources rather than to limit pyrolysis operations due to biomass supply. Biomass composition should not vary outside beyond the range permitted by Puro Earth, else new analysis of the biochar output is required.

6.1.5 Functional Units

The basis for operation of the system is the biochar product. The functional unit is tCO₂ per tonne of biochar produced, on a dry mass basis. The unit of measurement is greenhouse gas emissions expressed as tonnes of CO₂-equivalent emissions (t CO₂e).

6.1.6 Basic Parameters

The basic parameters outlined in the introduction and reiterated in Table 1.

Parameter	Status	Unit
Catchment area	800,000	hectares
Apple wood chip pyrolysed	1787	dry tonnes per year
Biochar produced	457	dry tonnes per year
Heat export	3888	MWhth per year

Table 1. – Basic project parameters

6.1.7 Analysed Impacts

The LCA considers the net emission of the greenhouse gases carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). The latest values for the global warming potential (GWP) of these gases are used, published by the Intergovernmental Panel on Climate Change and specified for a 100-year time horizon (IPCC, 2020). The GWPs for N₂O and CH₄ are expressed on mass basis relative to CO₂ as carbon dioxide equivalents (CO₂e), with CO₂ exhibiting a GWP of 1.0.

6.1.8 System Elements and Boundaries

A single pyrolysis (biochar production) site would be located within an 800,000-ha catchment, representing one of the two areas of concentrated dessert apple growing in the UK. The site would ideally be positioned centrally within the catchment, but this will be guided by the need for an existing (as yet unspecified) user for industrial heat. This is assumed to displace a current use of fossil energy (natural gas) and could be linked to a facility within the supply chain, i.e., an apple packhouse.

The cradle-to-grave boundaries for the system (Fig. 1.) includes the generation of wood chip in the field and its delivery to the pyrolysis site. The multiple processes taking place at the pyrolysis site includes drying and / or pyrolysis, and the delivery of the biochar fertiliser end-product to farms, substituting for conventional P/K fertiliser and delivered as part of the seed sowing process (the “grave”).

The following activities are inside the assessment boundaries:

- Apple biomass handling and chipping and air-drying in the field
- Apple wood chip transport to site of pyrolysis including loading / unloading
- Pyrolysis, gas combustion / heat capture and heat utilisation, biomass and biochar handling
- Transport of biochar to orchards, including loading / unloading.

Emissions resulting from the manufacture of the machinery and other infrastructure are included. At this stage there are no formal criteria or quantitative thresholds against which processes have been included or excluded.

A full inventory of final LCA elements is shown in the Appendix. It is unlikely that emissions arising from an unidentified activity would exceed the smallest elements considered.

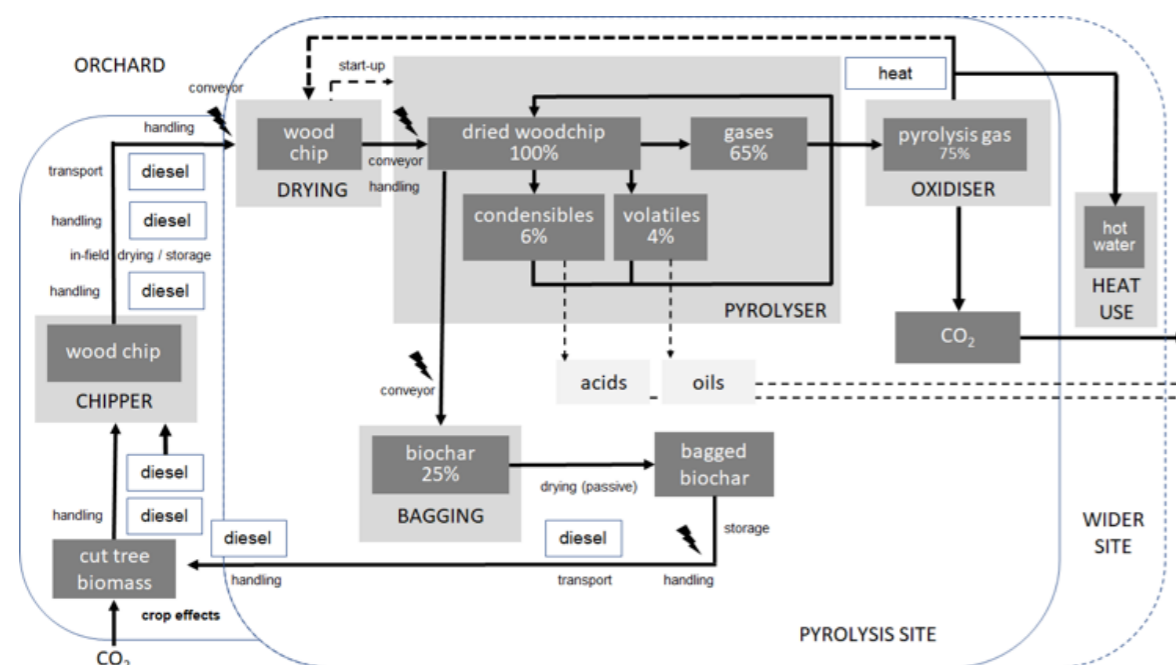


Fig. 1. – System components, boundaries and product flowchart

6.1.9 Baseline Scenario

Under the baseline scenario, the CO₂ in apple-tree biomass is instantaneously emitted to the atmosphere at the end of orchard life, through open burning. Burning directly emits emission of most of the carbon cumulatively removed from the air by the apple trees during their growth.

In LCA involving annual crops, the balance of CO₂ uptake and emission is conventionally ignored (treated as neutral) owing to the match between the crop cycle and the time step of the analysis, and decomposition (and utilisation) being predictable and rapid.

For tree crops these processes are explicitly distinguished, because accumulation and emission occur on contrasting timeframes. In the present LCA, the analysis timeframe (25 years) is a multiple of rotation length, so the net change in standing biomass can be assumed zero. Changes in apple varieties may affect the validity of the assumption, since the amount of woody biomass associated with the crop can decrease over successive rotations. This change affects the carbon balance of the baseline system, but independently of the project intervention.

It is similarly assumed that soil organic matter (and organic carbon in the soil) will have equilibrated with the management over successive cycles of tree growth and apple production, with the biomass to be removed for biochar production not directly influencing soil carbon under baseline conditions. The assumption of stable soil carbon could be changing over time owing to varietal change or changes or standard orchard management practices (e.g., management of grass strips), but this is also independent of the project intervention.

Open burning of tree biomass will have non-CO₂ climate effects through the emission of methane, nitrous oxide as well as airborne black carbon. On the other hand, approximately 1–2% of the carbon in biomass burned in each cycle will have been near-permanently sequestered on (or in) the soil through uncontrolled formation of charcoal. For simplicity it is assumed that the sequestration of carbon resulting from historical charcoal formation would be balanced by the GWP of is the emission of non-CO₂ greenhouse gases to air.

On the co-product side, it is assumed that the baseline source of industrial heat used on the pyrolysis site is provided by fossil methane, from the gas grid, and converted using a boiler that operates with 80% thermal efficiency.

6.1.10 Project Scenario

Apple tree biomass

The average apple farm in the catchment is assumed to have an orchard area of 100 ha, yielding 25 t cut biomass above-ground at the end of a 13-year rotation (one fallow year followed by 12 years of trees, including eight years of apple production).

The assumed moisture content of tree biomass is assumed 50% at time of cutting and (in this scenario) chipping. Allowing chipped wood to dry in the field involves heat from microbial utilisation of some carbon that would otherwise be available for pyrolysis. However, a moisture content to 30% meets the manufacturers limit for biomass in-feed.

In-field partial drying avoids the energy demand, capex (also opex) and footprint that would be required for thermal pre-drying at the pyrolysis site. An “in-field loss” of 5% is specified for microbial activity in piled apple wood chip under permeable membrane (for up to a year). This is treated as a reduced capture of biomass feedstock for pyrolysis rather than an emission and it is assumed the pile remains aerobic with no emission of methane.

Greenhouse gas emissions arising in the growing of the apple trees has to be estimated, since an allocation to the product intervention is required. This is because the use of the tree is diversified from producing apples only to producing woodchip with its own market value.

Financial allocation used in the present analysis attributes only 0.25% of embedded emissions to the project intervention, since the monetary value of apples (average 40 t/ha/yr for 8 of 13 years) dwarfs the corresponding value of 2 t / ha /yr of biomass accumulation.

Emissions in apple production are being more precisely assessed within the wider project, but a basic calculation for the tree-growing based on fertiliser usage only (25, 10 and 50 kg / ha / yr for nitrogen, phosphorus and potassium respectively) suggests approx. 38 kg CO₂e / t dry biomass. Sensitivity to this figure will be small, owing to the small project allocation.

Aggregating, chipping and piling biomass within the orchard involves considerable handling. It is assumed that moving biomass within the field will require tractor operation for up to 7 hr / ha, consuming 10 l / hr diesel fuel. This includes some time for loading chipped wood for transport to the pyrolysis site after the in-field drying step.

The appropriate technology for chipping fresh cut apple wood is uncertain at the moment, pending assessment of new equipment options within the wider project. The LCA uses a standard emission factor of 39 kg CO₂e / t fresh biomass.

Wood chip transport

It is assumed that wood chip would be transported using a 40 t articulated truck (120 m³ load volume). Based on orchard size, grubbing / replanting frequency and the assumed per hectare yield of chipped wood, a volume-based load factor of 80% has been calculated. This reflects the small number of trips per farm (three) and equates to an average load of 38.7 t (fresh mass).

The bulk density of chipped apple wood has a large effect on this calculation. It has been conservatively assumed that the chipped biomass will have a bulk density of 200 kg / m³ (dry basis) – which equates to approx. 400 kg / m³ as harvested, or 286 kg / m³ after field-drying (as loaded, 30% moisture).

The average road distance to a centrally positioned pyrolysis site is 23 km (14 miles), after applying a standard detour multiplier (1.40) to allow for tortuosity. The emissions factor used is from the latest UK Government data for articulated haulage (Defra, 2024), namely 1.04 kg CO₂e / km (fully laden), adjusted for projected load factor and distance to give a figure of 1.31 kg / t dry biomass. About 15% of the emissions from haulage are accounted for by nitrous oxide and methane.

An allowance is made for establishment for small storage capacity at the pyrolysis site, but on a week-to-week basis wood chip will be retrieved from the field at a rate to match by the pyrolysis process.

Receiving wood chip

Articulated trucks fitted with a walking floor will deposit biomass onto a perforated floor, taking waste heat from pyrolysis to (gradually) further reduce moisture content. An electric conveyor / feeder would then supply the pyrolysis system. An electric bagging system receives biochar from the pyrolysis system from the electric discharge auger. The further handling of the biochar is primarily undertaken using an electric forklift, averaging 10 kWh / day for intermittent operation.

Pyrolysis

Biochar production capacity is affected by the number and size of pyrolysis units, their individual capacity (potential biomass throughput), and their up-time in continuous operation. Utilisation is further affected by the continuity of feedstock supply.

The configuration of Biomacon pyrolysis systems have limited scalability. The Biomacon 500 has a maximum mass-based feed rate (throughput) of 300 kg / hr (dry basis), and a maximum thermal output is 500 kW when using a high feed rate and biomass of high calorific value.

In the present scenario the pyrolysis site operates a single Biomacon 500 unit with a feed rate of 240 kg / hr (dry basis). Assuming 15% downtime the unit processes 1787 odt / yr and is 102% utilised. Biomacon pyrolysis systems are assembled in Germany, near Hanover. There is currently one example operational in the UK.

Additional pyrolysis units could be commissioned on the same site to meet increased demand, if biomass supply was increased. This could arise within the initial scenario if, for example, new equipment was identified to render below-ground biomass an accessible resource. It would also involve integration of compatible biomass from sources outside the orchard system.

Increasing biochar production has a lower marginal cost, until demand for heat has been fully met. Site footprint does not scale proportionally with increasing capacity, while opex / energy integration costs are relatively fixed. Multiple units also offer flexibility around maintenance in/outside a planned cycle.

Initialisation

This concerns the net-endothermic part of the process, i.e., initiating the pyrolysis reactions that are later sustained by part of the syngas product. The Biomacon equipment does not rely on natural or liquified propane gas in this phase, rather a small amount of the feedstock is processed with the pyrolysis reactor in combustion mode, to build up heat. The reactor has high thermal inertia and can switch directly to pyrolysis. The small demand on wood chip over the lengthy maintenance cycle is neglected, as although biomass availability could limit biochar production, the net emission from biomass is close to zero.

Steady state operation

In stable operation electrical power is required to run two conveyors for supply biomass to the pyrolyser, and to transport biochar from the pyrolyser to the bagging facility. Electricity is also used to turn the internal augers of the pyrolysis unit. Electricity is drawn from the grid with a decreasing carbon intensity (the 2024 figure of 207 kgCO₂e / MWh was used). The average power consumption in operation is 50 kWe.

Heat is provided to both drier and pyrolysis from a controlled portion of the gas-phase product of the pyrolysis (syngas plus volatiles).

Product yield

The biochar yield is In stable operation electrical power is required to run two conveyors for supply biomass to the

Biochar distribution and application to land

It is assumed that biochar is delivered to orchards using the same vehicles collecting woodchip. Since the mass and volume of material is reduced through pyrolysis, only a portion of the trips will be loaded.

6.1.11 Allocation of Emissions

Biochar is the primary product of pyrolysis and heat is the sole co-product (valorised). In those analyses the CO₂ emissions arising in pyrolysis are allocated to the biochar product.

6.1.12 Caveats

Carbon accumulated in biomass from atmospheric CO₂ is ordinarily recycled to the atmosphere over relatively short timeframes, through turnover of plant material in or on the soil, and through the fate of harvested products.

In LCA for annual crops it is conventional to treat this cycle as balanced on an inter-annual basis and to omit the individual fluxes from calculations. It is usually also assumed that there is no change in soil carbon resulting from a change in the pace of organic matter recycling or a change in the proportion of carbon that is recycled through the soil versus other end-uses.

If biomass previously used in animal bedding is diverted to bioenergy uses the pace of recycling increases and the amount of stored solid carbon will re-equilibrate slightly lower. There is similarly much-discussed potential to achieve a modest increase in soil-stored carbon by diverting biomass away from (e.g.) burning towards soil incorporation (this occurred increasingly after the 1980s ban on in-field burning of straw).

This LCA assumes that apple wood chip is drawn only from orchards where cut wood is ordinarily burned in the field. The utilisation of apple wood in biochar manufacture will have impacts on multiple, transient end-uses that may result in no or small positive emissions of CO₂ from soil or elsewhere.

Should a counterfactual be analysed, a valid comparison would be between pyrolysis for biochar production and conventional use of wood chip for electricity generation through complete combustion.

6.2. Inventory Analysis

6.2.1 Software and Data Sources

This LCA draws on the first published life cycle model used to analyse biochar systems, initially in a national assessment for UK Government in 2009-10. The model was developed in Microsoft Excel and made publicly available upon peer reviewed publication in 2011. The original model has been updated, expanded and refined for the purpose of this LCA.

6.2.2 Inventory

Samples of biochar have been analysed for their chemical composition, notably in the context of this LCA, for the molar ratio of hydrogen to carbon (H:C). Biochars have also been assessed for their durability, i.e., susceptibility to degradation over longer timescales.

SECTION 7 – LIFE CYCLE ANALYSIS OF ORCHARD GROWING SYSTEM – GALA APPLES

Background

- UK Agriculture must meet its Net Zero targets by 2040 (NFU), which were estimated to be 46 Mt CO₂e (Defra, 2018) and account for 10% of all emissions in the UK.
- Exact emissions associated with British Gala apple production are unknown and existing C-Calculator tools e.g. AgRE Calc, Cool Farm Tool, Farm Carbon Toolkit are currently not able to take into account the complexities of British 'Post and Wire' Gala apple production systems.
- Cranfield University was commissioned in 2023 to undertake a detailed Life Cycle Assessment of 'Post and Wire Gala' apples in order to
 - Identify levers to reduce emissions;
 - Improve carbon calculator tools; To provide scope 1, 2 & 3 data;
 - Provide a clear global position for British apples

Summary

- The carbon footprint of British 'Post and Wire' Gala apple production from orchard Establishment to Farm Gate was approximately 70% and 38% lower than comparable productions systems in Spain and France
- Similarly, the carbon footprint of British 'Post and Wire' Gala apple production from orchard Establishment to Distribution Centre was approximately 80% and 30% lower than comparable LCA studies undertaken in South Africa and Belgium
- In terms of comparison with imported apples, the carbon footprint of British 'Post and Wire' Gala apple production from orchard Establishment to Distribution Centre was approximately 80% lower than growing and importing apples from New Zealand to Belgium (Establishment to Customer) and 50% lower than growing and importing apples from Chile to the UK customer.

Benefits of LCA

- Generates insights into:
- Carbon emissions around specific processes and activities of representative BAPL businesses
- Robust comparisons of carbon footprint against competing products e.g., New Zealand imports
- While majority of carbon calculation tools use global, aggregated data to generate estimates, this LCA developed and used a comprehensive inventory of site-specific primary data and information
- This work aims to enhance understanding and build the foundations regarding:
- How to improve business carbon footprint through targeted actions at farm level
- How to develop a competitive advantage considering sustainable fruit production and supply at industry level

What is Life Cycle Assessment (LCA)?

- Definition: A modelling perspective; a systematic approach to evaluating sustainability impacts associated with the different inputs and outputs of a product or service throughout their lifetime
- ISO 14040-14044: Sets out the guidelines and principles for developing a robust LCA framework, by outlining 4 key phases and assumptions to ensure accuracy of assessment and enable comparisons
- Evidence-based decision making: A useful tool for identifying sustainability impact hotspots and guiding decision making at business level and strategic planning towards sustainable development of the sector

There are three main types of LCA:

- Attributional: System is evaluated as "static" and sustainability performance estimated in a "slice in time". Offers more accurate estimates and can address some uncertainties, but may need to be revised / updated to account for temporal variabilities

- Comparative: An LCA framework used to compare different systems, products, services – it can be attributional or consequential. Key assumptions around the system boundaries, functional units, and allocation principles need to be satisfied to enable robust comparisons
- Consequential: More ambitious approach accounting for macroeconomic uncertainties that may affect system performance (e.g., product demand changes). Can be very vague due to large uncertainties in data for future scenarios and not meaningful for business level decisions
- The BAPL LCA has followed an attributional and comparative approach

Key phases of LCA

Goal & Scope:

- An attributional, comparative LCA was developed to evaluate the life cycle carbon footprint of two representative BAPL businesses, focusing on two specific orchards (one irrigated, one unirrigated)
- The system boundaries used were "Establishment to Distribution Centre (E to DC)" and "Establishment to Farm Gate (E to FG)"

Life Cycle Inventory:

- Historic, primary data were provided by the two businesses for the two orchards (2021 – 2023)
- The data covered all processes, inputs, outputs identified within the system boundaries

Life Cycle Inventory - key site-specific differences:

Case study characteristic	Farm A	Farm B
Soil type	Marsh	Sandy
System type	'Post and Wire'	'Post and Wire'
Irrigation strategy	Unirrigated	Irrigated
Harvest strategy	Tractors with trains & forklifts	Platforms and auxiliary tractors
Farm to <u>Coldstores</u>	On-farm using tractors and low loaders	52 miles - HGVs
<u>Coldstores to Distribution Centre</u>	180.8 (min 50.9 to max 320)	164.5 (min 13 to max 466)
Storage	Whole farm average	Dedicated Gala block
Packaging materials	Predominantly single-use cardboard	Reusable plastic crates (~400 times)

Key phases of LCA

Impact Assessment:

- The life cycle carbon footprint of both businesses was estimated for the specific orchards
- Scope 1 emissions included direct emissions from the business's operations (e.g., diesel for agronomic operations, emissions from fertilizer application)
- Scope 2 emissions included indirect emissions from the generation or purchasing of energy (e.g., electricity for storage and packing of produce)

- Scope 3 emissions included indirect emissions from upstream and downstream processes (e.g., manufacturing and supply of plant protection materials, packaging, machinery, etc.)

Interpretation:

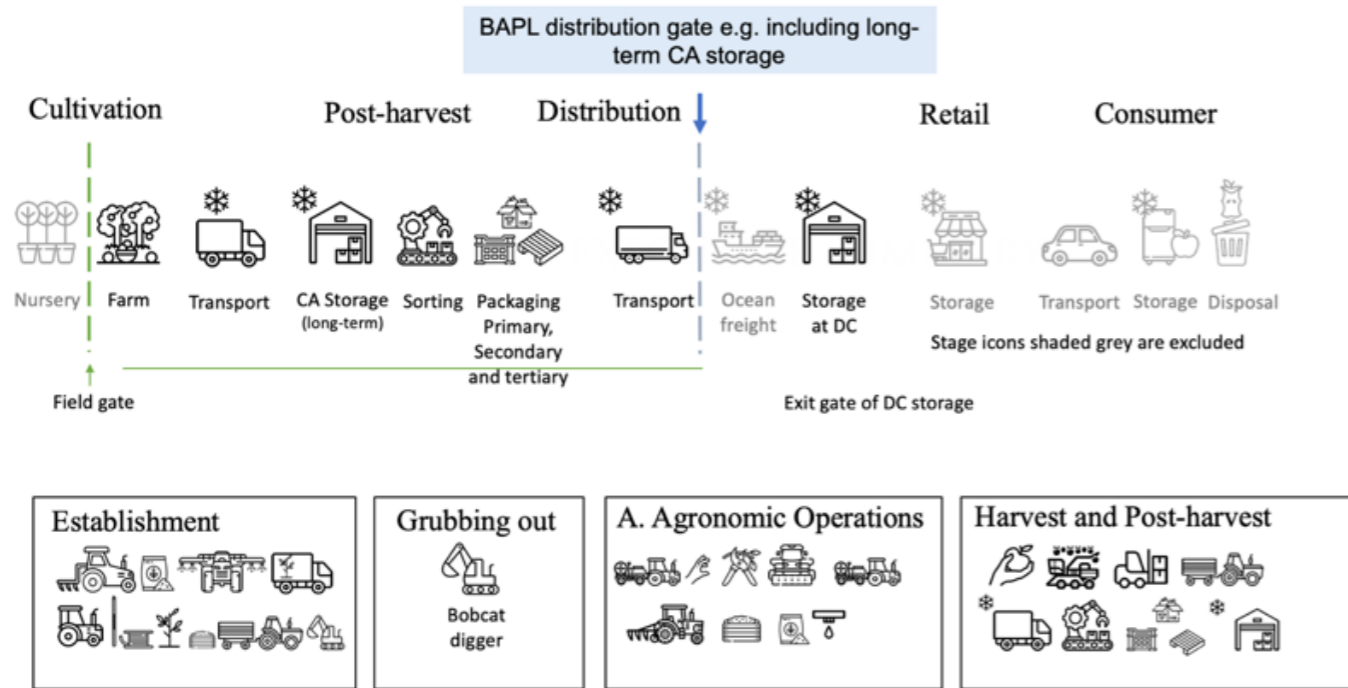
- The results were summarised in a comprehensive way considering the needs of the two businesses to enhance understanding around their Scope 1, 2 & 3 emissions and highlighting specific environmental impact hotspots

BIOCHAR

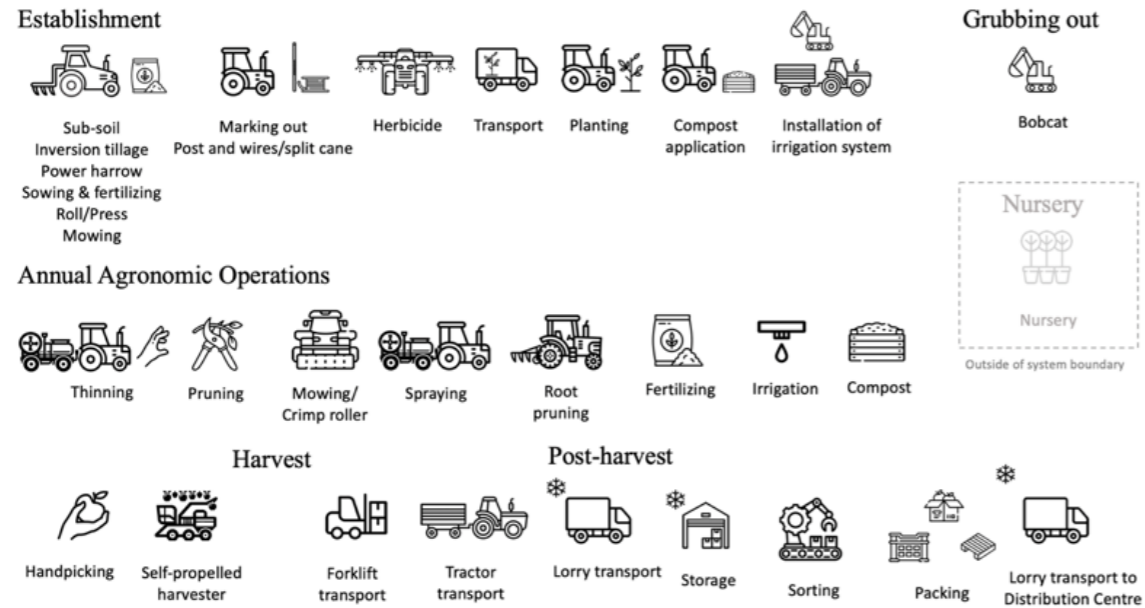
TAKING COMMERCIAL APPLE PRODUCTION TO NET ZERO



Boundaries of BAPL (2024) Life Cycle Assessment Commercial in Confidence



BAPL 2024



Parameters included in the BAPL (2024) Life Cycle Assessment (LCA) as compared with previous studies:

	BAPL (2024)	¹ Alaphilippe et al (2016)	Goossens et al (2017)	Goossens et al (2019)	Iriate et al (2021)	Vinyes et al (2018)	de Kock et al (2019)
Country/s	England	France	Belgium	NZ to Belgium	Chile to UK	Spain	South Africa
Apple Variety	Gala	Junagold	Junagold	Gala	Gala	Gala	Pome Fruit
Emission categories included	S1, S2 & S3	S1, S2 & S3	S1, S2 & S3	S1, S2 & S3	S1, S2 & S3	S1, S2 & S3	S1, S2 & S3
Machinery manufacturing	✓	✗	✗	✗	✗	✓	✓
Machinery maintenance	✗	✗	✗	✗	✗	✗	✗
Farm buildings & infrastructure	✗	✗	✗	✗	✗	✗	✗
Nursery							
Soil preparation	✗	✓	✗	✗	✗	✗	✗
Rootstock planting	✗	✓	✗	✗	✗	✗	✗
Grafting	✗	✓	✗	✗	✗	✗	✗
Mechanised pruning	✗	✓	✗	✗	✗	✗	✗
De-budding	✗	✓	✗	✗	✗	✗	✗
Uprooting	✗	✓	✗	✗	✗	✗	✗
Establishment							
Soil preparation	✓	✓	✓	✗	✗	✓	✓
Between-row management	✓	✓	✓	✗	✗	✓	✗
Planting	✓	✓	✓	✗	✗	✓	✗
Orchard Infrastructure	✓	✓	✓	✗	✗	✓	✗
Poles and wires	✓	✓	✓	✗	✗	✓	✗
Irrigation infrastructure	✓	✗	✓	✗	✗	✓	✗
Fertilization	✓	✓	✓	✗	✗	✓	✗
Compost	✓	✗	✓	✗	✗	✗	✗
Herbicide	✓	✓	✓	✗	✗	✓	✗
Transport of saplings	✗	✗	✗	✗	✗	✗	✗

	BAPL (2024)	Alaphilippe et al (2016)	Goossens et al (2017)	Goossens et al (2019)	Iriate et al (2021)	Vinyes et al (2018)	de Kock et al (2019)
Annual agronomic operations							
Thinning	✓	✓	✓	¹ ND	✗	✓	✓
Pruning (manual)	✓	✓	✓	¹ ND	✓	✓	✓
Pruning mechanical	✓	✗	✗	¹ ND	✗	✗	✓
Between-row management	✓	✓	✓	✓	✓	✓	✓
Mowing	✓	✓	✓	¹ ND	ND	✓	ND
Crimp roller	✓	✗	✗	¹ ND	ND	✗	ND
Mulching	✓	✓	✓	¹ ND	ND	✓	ND
Root pruning	✓	✗	² ND	¹ ND	ND	✗	ND
Plant protection spraying	✓	✓	✓	✓	✓	✓	✓
Compost application	✓	✓	✓	✓	✗	✓	✗
Fertilization	✓	✓	✓	✓	✓	✓	✓
Irrigation	✓	✗	✓	✓	✓	✓	✓
Orchard destruction							
Uprooting (Grubbing out)	✓	✗	✗	✗	✗	✗	✗
Harvest and post-harvest							
Manual harvest	✓	✓	² ND	✓	✓	✓	✓
Self-propelled harvester/platform	✓	✗	✓	✓	✗	✓	✓
Transport	✓	✓	✓	✓	✓	✓	✓
Forklift	✓	✓	✓	✓	✓	✓	✓
Tractor/trailer	✓	✓	✓	✓	✓	✓	✓
Lorry	✓	✓	✓	✓	✓	✗	✓
Sorting							
Packing (primary)	✓	✗	✗	✓	✓	✗	✓
Packing (secondary)	✓	✗	✗	✓	✓	✗	✓
Packing (tertiary)	✓	✗	✗	✗	✓	✗	✓
Storage (long-term CA)	✓	✗	✗	✓	✓	✗	✓

	BAPL (2024)	Alaphilippe et al (2016)	Goossens et al (2017)	Goossens et al (2019)	Iriate et al (2021)	Vinyes et al (2018)	de Kock et al (2019)
Distribution							
Lorry	✓	✗	✗	✓	✓	✗	✗
Ocean freight	✗	✗	✗	✓	✓	✗	✗
Port activities	✗	✗	✗	✓	✓	✗	✗
Storage (Distribution Centre)	✗	✗	✗	✓	✓	✗	✗
Retail							
Refrigeration	✗	✗	✗	✓	✓	✗	✗
Consumer							
Transport	✗	✗	✗	✓	✓	✗	✗
Fridge storage	✗	✗	✗	✓	✗	✗	✗
Waste Disposal	✗	✗	✗	✓	✗	✗	✗

¹ND = No detail in article authors simply state that "confidential input data was received from a farmer in Hawkes Bay". ²ND in article regarding type of harvest but fuel use associated with all on farm machinery operations included in LCA. ³ND on harvesting methods or vehicles used provided only a generic diesel usage per kg of apple harvested. ⁴Assumes a generic 6-month storage time in controlled atmosphere (CA) storage. ND = No detail provided

Summary of key findings

- Scope 3 emissions are by far the largest contributor to “Establishment to DC” carbon footprint
- More specifically, presented as percentage breakdown of total C emissions
- Scope 3: 62.4% due to manufacturing and supply of packaging, plant protection / fertiliser (15%), machinery (6.6%)
- Scope 2: 9.7% due to storage energy *, packhouse energy (3.23%) and irrigation (0.23%)
- Scope 1: 2.85% due to direct and indirect fertiliser application emissions, and on-farm fuel use (0.01%)

**the current model considers that all energy is “standard mix” and sourced from the national grid, thereby potentially overestimating relevant energy emissions for cases where this is 100% renewable.*

The full details of the LCA are not available for publication due to commercial confidentiality. However, whether one considers “establishment to farm gate” or “establishment to distribution centre”, British apples create the lowest carbon emission compared to any of the previously published studies.

SECTION 8 – CARBON CREDIT MARKET

8.1 Overview of Voluntary Carbon Credit Markets and Carbon Credit Certification

Author – Dr Leah Herrgen

Carbon markets – key concepts and stakeholders

Carbon offsetting is a trading mechanism that enables governments, companies or individuals to offset (i.e., compensate for) their greenhouse gas (GHG) emissions by financially supporting projects that reduce, avoid, or remove GHG emissions elsewhere. Offsetting is implemented through the buying and selling of carbon credits. A carbon credit represents a certain amount of GHG emissions, usually one tonne carbon dioxide-equivalent (CO₂e), whose emission has been avoided or which has been removed from the atmosphere through an offsetting project. Such projects can generate carbon credits in a variety of ways, including production of renewable energy (e.g., wind, solar, hydroelectric, biomass), implementation of energy efficiency measures, methane collection and combustion, destruction of industrial pollutants (e.g., hydrofluorocarbons, perfluorocarbons), land use-based measures (e.g., avoidance of deforestation, reforestation, improved soil management), or negative emissions technologies (e.g., biochar, carbonated building elements, geologically stored carbon).

There are two types of markets for trading carbon credits: compliance and voluntary. The compliance market enables governments, companies and other organisations to purchase carbon credits in order to comply with caps on their GHG emissions prescribed by international treaties or national legislation, such as the UK’s target to reach net zero by 2050 [1]. Conversely, the voluntary carbon market allows for the purchase of carbon credits by companies, NGOs and sometimes individuals wishing to offset emissions from their operations that are difficult or impossible to avoid. These markets make an important contribution to the mitigation of climate change by generating income for carbon reduction projects and allowing such projects to develop and grow.

Besides producers and buyers, other key players in the voluntary carbon market are standard organisations, third-party verifiers, and carbon trading platforms. All of these play distinct and important roles within the market. Standard organisations are independent entities that establish and maintain carbon accounting standards and eligibility requirements for carbon offsetting projects. There are several established standard organisations, some but not all of which offer registration of biochar-based carbon credits. Links to each organisation’s methodology for generating biochar-based carbon credits are provided in the table below (if available).

Organisation name	HQ	Established	Comments
Verra [2]	Washington	2005	Largest and best-known standard organisation. Standard covers all project classes including biochar [3].
Gold Standard [4]	Geneva	2003	Standard covers most project classes including biochar [5].
American Carbon Registry [6]	Little Rock	1996	World’s first carbon standard organisation. Standard covers US-based projects. Recently developed a biochar methodology, but this was not adopted due to methodological concerns [7].
Climate Action Reserve [8]	Los Angeles	2001	Standard covers US- and Canada-based projects. Recently established a biochar methodology [9].
Puro.Earth [10]	Helsinki	2017	Standard designed for offsets based on engineered carbon removal (e.g., biochar [11], carbonated building elements, geologically stored carbon).

Since the voluntary carbon market is largely unregulated, adherence to any of these standards is not a legal requirement for producers and sellers of carbon credits. Instead, the standards serve to give potential buyers confidence in the quality of the credits, and it is highly likely that carbon credits that have not been verified by one of the established standard organisations would be regarded as untrustworthy.

For biochar producers based in the UK, the relevant standard organisations are Verra, Gold Standard and Puro.Earth. Verra and Gold Standard are large global organisations with hundreds of live projects each. However, most of their projects are using carbon offsetting methods such as forestry-based approaches or energy efficiency measures and only a small proportion of their projects are biochar-based (5 out of >2,000 for Verra and 1 out of >2,000 for Gold Standard). In contrast, Puro.Earth is a smaller European organisation that specialises in engineered carbon removal, and a large proportion of its live projects is biochar-based (37 out of 52).

Third-party verifiers, also referred to as Validation/Verification Bodies (VVBs), work with, but independently of, standard organisations. Their role is to validate and verify the carbon removal achieved by any offsetting project wishing to gain accreditation through one of the standard organisations. During validation, the VVB determines whether a project meets all requirements of the standard in question. During verification, the VVB confirms that the carbon removal specified in the project has actually been achieved. VVBs are experts in the methodology of the technical area that they audit. To validate and verify carbon removal projects, VVBs inspect documentation submitted by the project owners and usually also conduct site visits to the production facilities. Each standard organisation has one or several VVBs that are approved to review registered projects. A list of the VVBs working with each organisation can be found on the organisations' websites.

Carbon trading platforms are online marketplaces where the buying and selling of carbon credits takes place. There are numerous such platforms available, which differ in various respects including the number and types of projects listed and whether they cater to individuals or businesses. Some but not all standard organisations have lists of recommended marketplaces available on their websites, but in principle credits from any of the standard organisations should be tradeable on any of the platforms provided they meet the platform's requirements.

Case study: Roadmap to carbon credit certification

For biochar producers wishing to generate and sell carbon credits for their product, the first step is to choose a standard organisation and to gain an understanding of the individual steps of the process that they need to go through in order to obtain accreditation. Below we will briefly outline the road to certification for biochar using Puro.Earth. This standard organisation was chosen for our case study because it is based in Europe, specialises in engineered carbon removal, and has a wealth of experience in biochar certification and accreditation. However, this should not be taken to indicate that this report endorses or seeks to promote Puro.Earth over any of the other standard organisations.

Carbon credits issued by Puro.Earth are called CO₂ Removal Certificates (CORCs), where one CORC represents one metric tonne of CO₂ that has been permanently removed from the atmosphere. The Puro Standard [12] outlines the roles and responsibilities of the different stakeholders in the accreditation process (i.e., producer, standard organisation, VVB, buyer). The Puro Biochar Methodology [11] specifies the technical requirements for biochar accreditation. Importantly, Puro.Earth regularly revises and improves its procedures and protocols to ensure maximum accountability for all its offsetting projects. Therefore, it is important for biochar producers to refer to the most recent versions of all relevant documents.

As for other standard organisations, there are several steps for biochar producers on the path to earning carbon credits for their product through Puro.Earth:

1. Biochar producer conducts Life Cycle Assessment (LCA) of their product. Since the LCA needs to conform to a high standard of quality for acceptance by Puro.Earth, this is usually done with the help of external, specialised LCA consultants.
 - a. Approximate cost: £10K (for consultancy).
 - b. Approximate time: 3-4 months.
2. Biochar producer submits LCA along with other supporting evidence (e.g. biochar analysis results) to Puro.Earth. Puro.Earth reviews LCA and requests changes if appropriate.
 - a. Approximate cost: None.
 - b. Approximate time: 3-4 weeks.
3. Once the LCA has been approved, the biochar producer signs up for an account with Puro.Earth and completes a Production Facility registration form. This is then reviewed by Puro.Earth and handed on to a VVB upon approval. A list of VVBs approved to work with Puro.Earth can be found on their website.
 - a. Approximate cost: £800 (annual Puro registry membership fee).
 - b. Approximate time: 3-4 weeks.
4. The VVB conducts a production facility audit to validate the accuracy of the carbon removal claims, and issues a Production Facility Audit Statement.
 - a. Approximate cost: None (audit cost is covered by Puro.Earth).
 - b. Approximate time: Depends on auditor availability.

5. If the facility audit is successful, CORCs are issued by Puro.Earth for the amount of carbon sequestered in the biochar. The biochar producer can then sell these CORCs on an online marketplace of their choice. A list of marketplaces that sellers of biochar carbon credits may want to consider can be found on the Puro.Earth website [13].
 - a. Approximate cost: Puro.Earth charges a Service Fee per traded CORC. This varies between 0.2 and 20% of the CORC price, depending on the volume sold and the price per CORC. Details of their fee structure can be found on their website [14].
 - b. Approximate time: Depends on speed of sale.
6. After initial accreditation, biochar producers have to produce yearly output reports, which are audited by a VVB. Upon successful completion, producers can then sell the CORCs resulting from the year's production as described above.

At the time of writing, as per the Puro.Earth website [15], the price biochar-based carbon credits ranged from €135 to €589 per CORC. Most suppliers (13/23) offered their CORCs for between €200 and €250. One tonne of biochar usually generates 2-2.5 CORCs.

Participating in the voluntary carbon market – benefits and challenges

For biochar producers wishing to gain accreditation for their product in order to be able to sell carbon credits, there are a number of things to consider.

Gaining and maintaining accreditation for biochar carbon credits requires a considerable input of time (e.g., for data collection, paperwork, communication with standard organisation and VVB) and money (e.g., consultancy and standard organisation fees). However, these upfront investments should redeem themselves fairly rapidly. For instance, a biochar producer with a yearly output of 1.000 tonnes of biochar should be able to generate about 2.000 CORCs from their product. At a price of €200/CORC, this would generate a yearly income of €360.000 (after deduction of a 10% Puro.Earth service fee), thereby easily repaying consultancy fees, Puro.Earth subscription fees and other costs (e.g. for lab analysis) within the first year of trading. Hence, upon completion of the accreditation process carbon credits could open up a considerable revenue stream for their business.

Aspiring sellers of carbon credits should be aware that the quality and validity of carbon credits, and the integrity of the voluntary carbon market, have been under intense scrutiny over the last year. For instance, scientists and journalists reported last year [16] that more than 90% of rainforest-based carbon credits issued by standard organisation Verra are worthless. Likewise, the validity of carbon credits issued by carbon finance company South Pole has been challenged [17]. Consequently, a number of large companies have moved away from buying carbon credits due to potential reputational damage, which might lead to an overall decrease in the demand for carbon credits.

Conclusions

Voluntary carbon markets have the potential to make a significant contribution to climate change mitigation by enabling buyers of carbon credits to offset difficult-to-avoid emissions, while providing finance to carbon reduction or removal projects. The biochar sector, with its product that can lock substantial amounts of carbon away in the soil and thus permanently remove it from the atmosphere, is particularly well placed for offering high-quality carbon credits to environmentally conscious buyers. A range of standard organisations such as Puro.Earth offer guidelines and step-by-step protocols for obtaining accreditation for biochar-type products.

In summary, carbon credit verification of their product opens up an additional and potentially substantial revenue stream for producers of high-quality biochar. Therefore, exploring the potential for a biochar product to obtain carbon credit certification is likely to prove a worthwhile endeavour.

References

- [1] <https://researchbriefings.files.parliament.uk/documents/CBP-9888/CBP-9888.pdf> (Accessed: 1 April 2024).
- [2] <https://verra.org/> (Accessed: 1 April 2024).
- [3] <https://verra.org/methodologies/vm0044-methodology-for-biochar-utilization-in-soil-and-non-soil-applications/> (Accessed: 1 April 2024).
- [4] <https://www.goldstandard.org/> (Accessed: 1 April 2024).
- [5] <https://www.goldstandard.org/gold-standard-for-the-global-goals> (Accessed: 1 April 2024).
- [6] <https://acrcarbon.org/> (Accessed: 1 April 2024).
- [7] <https://acrcarbon.org/methodology/inactive-biochar-projects/> (Accessed: 1 April 2024).
- [8] <https://www.climateactionreserve.org/> (Accessed: 1 April 2024).
- [9] <https://www.climateactionreserve.org/wp-content/uploads/2024/03/CAR-US-and-Canada-Biochar-Protocol-V1.0.pdf> (Accessed: 1 April 2024).
- [10] <https://puro.earth/> (Accessed: 1 April 2024).
- [11] <https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Biochar%20Methodology.pdf> (Accessed: 1 April 2024).
- [12] <https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/General%20Rules/Puro%20Standard%20General%20Rules%20v3.1.pdf> (Accessed: 1 April 2024).
- [13] <https://carbon.puro.earth/partners> (Accessed: 1 April 2024).
- [14] <https://puro.earth/fees/> (Accessed: 1 April 2024).
- [15] <https://carbon.puro.earth/CORC-co2-removal-certificate/supplier-listings> (Accessed: 1 April 2024).
- [16] <https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe> (Accessed: 1 April 2024).
- [17] <https://www.newyorker.com/magazine/2023/10/23/the-great-cash-for-carbon-hustle> (Accessed: 1 April 2024).

SECTION 9 - MARKET RESEARCH AND ECONOMIC ANALYSIS SCOPING

9.1 The Economic and Financial Assessment of Biochar Production

Biochar production can be a financially viable and economically beneficial venture, particularly when multiple revenue streams are leveraged successfully. These include the sale of biochar, carbon credits, syngas, electricity, heat, bio-oil, and wood vinegar. Despite potential financial viability, the evolutionary nature of the biochar and carbon credit market creates uncertainty for producers. Below is a comprehensive financial and economic assessment of biochar production.

9.1.1 Revenue Streams

Biochar:

Market Demand: Biochar is increasingly in demand for its potential agricultural uses, such as soil enhancement and development, carbon sequestration, and pollution control. Other agricultural uses include the inclusion into feeds and manures, although only limited trial work has been carried out on these cost to benefit ratios. Other uses include bio-concretes and brick/block additive, asphalt and tar additive and larger scale filtration units or chemical filtration units.

Pricing: The price of biochar can range from £100 to £1,000 per ton, depending on its quality, carbon content, application and regional demand.

Syngas:

Usage: Syngas, can be used as a fuel for generating electricity or heat, or it can be processed into chemicals.

Revenue from Electricity: If syngas is used to generate electricity, the revenue depends on local electricity prices. Assuming a conversion efficiency of 30% and an electricity price of £0.10 per kWh, a plant producing 1 MW of electricity could generate around £100,000 annually but extra expenditure on feed in connection with the grid is required and its granted success is heavily dependent on location.

Other Elements: Syngas can also be condensed into its individual elements including hydrogen and methane. The amounts of different elements in the syngas are dependant on the type of feedstock used. This also requires further specialist equipment that significantly adds to the capital expenditure.

Bio-oil:

Market Demand: Bio-oil can be used as a renewable fuel or a feedstock for chemicals. The quality varies widely depending on feedstock and may need refining for more precision applications. It's extremely difficult to put a value on bio oil given it's not currently widely utilised and varies considerably in quality depending on production method and feedsource.ly used and it's quality variations.

Revenue Estimation: The volume of bio oil generated can realistically be put at 2% of feedstock intake. However, due to the current reduced outlets for bio oil and for the purpose of this exercise, bio oil has been discarded as a revenue income.

Pyroligneous acid (Wood Vinegar):

Market Demand: Wood vinegar, also known as pyroligneous acid, is used in agriculture as a pest repellent, soil conditioner, and animal feed additive. It is also known to have preservative properties amongst many other qualities. Prices can range from 20p to £8 per litre depending on volume of sale, packaging and directed use. The use of wood vinegar is limited due to the lack of research, and regulatory processing and registration but given time it has the potential to be the most lucrative of all the pyrolysis outputs. Volumes generated from feedstock can be as high as 28% weight for weight so large volumes can be achieved. For the purpose of this exercise we've taken a high figure of £2.00/litre and a low figure of 20p/L.

Heat:

Usage: The heat generated during pyrolysis can be used for drying biomass, heating facilities, or sold to nearby industries or municipalities. It is by far the easiest and most obvious way to generate revenue in the first instance. Some manufacturers have aimed pyrolysis units to be a direct replacement for biomass boilers with carbon neutral heat being the main output of the unit.

Revenue Estimation: If excess heat is sold at £0.02 per kWh of thermal energy, a facility generating 1,000 MWh of thermal energy annually could generate £20,000 if not more depending on which type of previous heat source was being applied. However, the physical movement of heat from one site to another (through sand batteries or other methods) even over short distances is not shown to be economically viable.

Carbon Credits

The most recognised standard for biochar accreditation is the European Biochar Certificate (EBC). It monitors the purity of the biochar, the method used to create it and the carbon generated in the biochar production (transport, carbon used to build the unit, etc). Once accredited you are able to sell at values indicative of the biochar produced. Current carbon credit values for stable, high purity biochar (indicating that once sequestered will remain stable in that environment for 100's if not thousands of years) are £125/CC.

9.1.2 Cost Components Capital Expenditure (CapEx):

Plant Setup: The cost of setting up a biochar production facility, including the pyrolysis unit, feedstock handling equipment, and infrastructure, can range from £3,000 to £4 million depending on the scale and technology. For the purpose of this project, capital costs of £100,000 and over have been considered. Due to the range of expenditure and application each pyrolysis unit needs a detailed strategy and financial plan to avoid a negative economic outcome. For the purposes of this project, 2 generic scenarios have been outlined to illustrate to potential economic likelihood but also pitfalls of the production of biochar. The cost of pre reactor and post reactor (delivery in and exit out) equipment must not be underestimated.

Technology: Advanced technologies that enable efficient energy recovery and by-product utilization tend to increase the initial investment but by definition also increase revenues if markets are available for those outputs.

Operational Expenditure (OpEx):

Feedstock: The cost of feedstock (agricultural waste, forestry residues) depends on local availability and transportation costs. Pre processing procedures may also be required to allow for correct presentation of the feedstock into the reactor. High cost feedstocks inhibit the ability to generate profit margin and should be heavily scrutinised. Waste biomass is an ideal scenario for successfully achieving profit margin.

Energy: Operational energy costs include electricity for running the facility and any supplemental fuel required depending on how the reactor is initiated.

Labour: Skilled labour is required for operating and maintaining the facility. Labour costs vary by region but can significantly impact overall operational costs along with control systems and automation.

Maintenance: Regular maintenance of the pyrolysis unit and associated equipment is essential to ensure continuous operation.

9.1.3 Economic and Environmental Benefits

Waste Management:

Reduction in Waste Disposal Costs: Converting biomass waste into biochar reduces the need for landfilling or incineration depending on the biomass in question, cutting disposal costs and contributing to sustainability goals.

Agricultural Productivity:

Increased Yields: Farmers using biochar can see improved soil fertility and water retention, leading to higher agricultural yields and reduced fertilizer costs in not all but many scenarios.

Energy Independence:

Renewable Energy Generation: Producing electricity and heat from syngas and bio-oil reduces reliance on fossil fuels and can provide energy security for rural or industrial areas.

9.1.4 Financial Viability

Payback Period:

Revenue vs. Costs: The payback period for a biochar production facility can range from 5 to 10 years, depending on the scale of the operation, capital investment, and revenue streams but it is important that outlets for all outputs produced are found to reduce the payback period to a complete minimum.

Return on Investment (ROI):

Positive ROI: Given the multiple revenue streams and the growing demand for biochar and related products, the ROI can be attractive, especially if carbon credits are factored in but it is also possible to demonstrate a negative ROI with poor pre project planning.

Scalability:

Expansion Potential: Biochar production is scalable. As demand grows, facilities can expand capacity, making it easier to achieve economies of scale.

BIOCHAR

TAKING COMMERCIAL APPLE PRODUCTION TO NET ZERO



Example costings:

Costing a biochar facility is extremely difficult to achieve given there are so many variables involved and some units will be bespoke built to suit facilitate the site or production requirements. However, it is possible to give an example of the economic performance using basis scenarios as a baseline. Therefore, table 1 and table 2 show 2 basic scenarios – one illustrating a low volume biochar production unit with high and low performance parameters and table 2 showing a high production unit again with low and high performance parameters.

Table 1: Example cost analysis showing Low Biochar yield unit with high and low performance.

Biochar	Low volume High performance (A)	Low Volume Low Performance (B)	A	B
Biomass per hr	0.3	0.3		
Biomass per yr	2400	2400		
Biochar yield	480	480		
Biochar value range	£50-£400	£50-£400	£192,000	£24,000
Bio oil (2% feedstock)	160	60		
Bio Oil value	0	0		
Wood vinegar (28% feedstock)	672000	672000		
Wood Vinegar value per L	£0.2-£2.00	£0.2-£2.00	£1,344,000	£134,400
Heat energy (375W/t)	900,000	900,000		
Electrical energy post CHP (30%)	270,000	270,000		
Electricity value	£0.08-£0.18	£0.08-£0.18	£48,600	£21,600
Carbon credits 2.2/t biochar	1056	1056		
Carbon credit value £125/CC	132000	132000	£132,000	£132,000
Revenue generation			£1,716,600	£312,000
Costs				
Maintainence			£25,000	£15,000
Feedstock transport (£17/t)			£40,800	£40,800
Material handling (£4/t)			£9,600	£9,600
Labour £8/t feedstock			£19,200	£19,200
Misc			£40,000	£20,000
Total Costs			£134,600	£104,600
Gross P			£1,582,000	£207,400
Cap repay + int			£400,000	£400,000
Nett P			£1,182,000	-£192,600
Capital Costs				
Cost of unit	£750,000	£750,000		
Cost of CHP	£600,000	£600,000		
Dryer	£50,000	£50,000		
Grid connection	£100,000	£100,000		
Installation costs	£70,000	£70,000		
Infrastructure Sheds	£190,000	£190,000		
Concrete floors/walls	£150,000	£150,000		
Electrics	£25,000	£25,000		
Material handling pre & post unit	£65,000	£65,000		
Total	£2,000,000	£2,000,000		
Interest at 10%/annum	£200,000	£200,000		
Cap repay 10 years	£200,000	£200,000		

Table 2: Example cost analysis showing High Biochar yield unit with high and low performance.

Biochar	High volume High performance (A)	High Volume Low Performance (B)	A	B
Biomass per hr	0.3	0.3		
Biomass per yr	8000	8000		
Biochar yield	1600	1600		
Biochar value range	£50-£400	£50-£400	£640,000	£80,000
Bio oil (2% feedstock)	160	60		
Bio Oil value	0	0		
Wood vinegar (28% feedstock)	2240000	840000		
Wood Vinegar value per L	£0.2-£2.00	£0.2-£2.00	£4,480,000	£168,000
Heat energy (375W/t)	3,000,000	3,000,000		
Electrical energy post CHP (30%)	900,000	900,000		
Electricity value	£0.08-£0.18	£0.08-£0.18	£162,000	£72,000
Carbon credits 2.2/t biochar	3520	3520		
Carbon credit value £125/CC	440000	440000	£440,000	£440,000
Revenue generation			£5,722,000	£760,000
Costs				
Maintainence			£25,000	£15,000
Feedstock transport (£17/t)			£136,000	£136,000
Material handling (£4/t)			£32,000	£32,000
Labour £8/t feedstock			£64,000	£64,000
Misc			£40,000	£20,000
Total Costs			£297,000	£267,000
Gross P			£5,425,000	£493,000
Cap repay + int			£866,000	£866,000
Nett P			£4,559,000	-£373,000
Capital Costs				
Cost of unit	£2,500,000	£2,500,000		
Cost of CHP	£1,000,000	£1,000,000		
Dryer	£50,000	£50,000		
Grid connection	£250,000	£250,000		
Installation costs	£100,000	£100,000		
Infrastructure Sheds	£190,000	£190,000		
Concrete floors/walls	£150,000	£150,000		
Electrics	£25,000	£25,000		
Material handling pre & post unit	£65,000	£65,000		
Total	£4,330,000	£4,330,000		
Interest at 10%/annum	£433,000	£433,000		
Cap repay 10 years	£433,000	£433,000		

Table 3: An example 20 year cash flow for high volume biochar unit.

Combined Biochar Project - Outline DCF																							
INVESTMENT LIFETIME CASHFLOW																							
YEAR	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	TOTAL	
CAPITAL EXPENSES																							
Combined Investment (£,000 T)	4,244,000																					4,244,000	
TOTAL CAPITAL EXPENSES	4,244,000																					4,244,000	
TRADING INCOME																							
Biochar (1,000T @ £325/T)		760,000	760,000	760,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	416,000	7,852,000	
Wood Vinegar (2,34M @ 60p)		672,000	672,000	672,000	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	1,075,200	
Electricity (900,000kWh @ 13p)		58,500	58,500	58,500	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	93,600	1,566,700	
Carbon credits (1,520 @ £125)		220,000	220,000	220,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	352,000	6,644,000	
TOTAL TRADING INCOME	0	1,710,500	1,710,500	1,710,500	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	1,936,800	
TRADING EXPENSES																							
Management	60,000	61,800	63,654	65,564	67,531	69,556	71,643	73,792	76,006	78,286	80,635	83,054	85,544	88,112	90,755	93,478	96,283	99,171	102,146	105,210	108,372		
Plant site maintenance	50,000	51,500	53,043	54,636	56,279	57,964	59,703	61,494	63,339	65,239	67,196	69,212	71,288	73,427	75,629	77,898	80,235	82,642	85,122	87,675	90,319		
Site operation - staffing	64,000	65,920	67,896	69,935	72,037	74,194	76,419	78,712	81,073	83,505	86,018	88,612	91,289	94,050	96,898	99,835	102,863	105,982	109,194	112,500	115,904		
Feedstock transport	32,000	32,960	33,949	34,967	36,015	37,097	38,215	39,369	40,561	41,793	43,066	44,381	45,738	47,138	48,581	49,970	51,405	52,887	54,417	55,996	57,625		
Feedstock handling	32,000	32,960	33,949	34,967	36,015	37,097	38,215	39,369	40,561	41,793	43,066	44,381	45,738	47,138	48,581	49,970	51,405	52,887	54,417	55,996	57,625		
Administration																							
Insurance	80,000	82,400	84,872	87,418	90,041	92,741	95,520	98,380	101,321	104,344	107,451	110,643	113,921	117,287	120,742	124,287	127,923	131,651	135,472	139,388	143,401		
Bookkeeping	15,000	15,450	15,914	16,391	16,883	17,391	17,914	18,453	19,018	19,609	20,226	20,869	21,538	22,234	22,957	23,707	24,484	25,288	26,120	26,980	27,869		
Financial A/c's	6,000	6,180	6,365	6,556	6,753	6,956	7,164	7,379	7,601	7,829	8,063	8,305	8,555	8,811	9,076	9,348	9,629	9,917	10,215	10,521	10,837		
Other costs	5,000	5,150	5,305	5,464	5,628	5,796	5,970	6,149	6,334	6,524	6,720	6,921	7,129	7,343	7,565	7,796	8,034	8,280	8,534	8,796	9,067		
Bank charges	3,000	3,090	3,183	3,279	3,377	3,478	3,582	3,689	3,800	3,914	4,032	4,153	4,277	4,404	4,534	4,667	4,804	4,944	5,087	5,234	5,384		
TOTAL TRADING EXPENSES	0	451,000	464,520	478,666	493,420	507,883	523,056	538,940	554,546	570,876	587,931	604,714	622,227	639,471	656,456	673,183	690,653	707,867	724,827	741,534	757,989		
NET TRADING CASHFLOW	0	1,259,500	1,245,980	1,231,834	1,243,380	1,258,917	1,278,844	1,303,210	1,332,254	1,366,024	1,404,813	1,448,714	1,497,837	1,552,374	1,612,629	1,678,802	1,751,183	1,829,986	1,915,613	2,008,364	2,108,549	2,115,500	

Table 4: An example ROI for a high-volume biochar unit.

Combined Biochar Project - Outline DCF		OUTLINE INVESTMENT APPRAISAL					
Payback / Internal Rate of Return		Investment	Trading Cashflow	Residual Value	Tax	Annual Cashflow (before Tax)	Cumulative Cashflow (before Tax)
Client Name:	Combined Biochar Project	2024	4,244,000	0		-4,244,000	-4,244,000
Project Title:	Outline DCF	2025	0	759,500		759,500	-3,484,500
Year of Investment:	2024	2026	0	745,970		745,970	-2,738,530
Total Investment:	4,244,000.00	2027	0	732,034		732,034	-2,006,496
Investment Period:	20 years	2028	0	1,443,980		1,443,980	-562,516
		2029	0	1,429,196		1,429,196	866,680
		2030	0	1,413,967		1,413,967	2,280,647
		2031	0	1,398,282		1,398,282	3,678,930
		2032	0	1,382,127		1,382,127	5,061,056
		2033	0	1,365,487		1,365,487	6,426,543
		2034	0	1,348,347		1,348,347	7,774,890
		2035	0	1,330,694		1,330,694	9,105,584
		2036	0	1,312,511		1,312,511	10,418,095
		2037	0	1,293,782		1,293,782	11,711,877
		2038	0	1,274,491		1,274,491	12,986,368
		2039	0	1,254,622		1,254,622	14,240,990
		2040	0	1,234,157		1,234,157	15,475,147
		2041	0	1,213,077		1,213,077	16,688,224
		2042	0	1,191,366		1,191,366	17,879,590
		2043	0	1,169,003		1,169,003	19,048,592
		2044	0	1,145,969		1,145,969	20,194,561

DEFINITIONS
(N.B. All calculations are pre-Tax)
Payback - the period required to recover the cost of the initial investment from the accumulated cashflow
Internal Rate of Return - the true rate of return from the investment over its lifetime

PAYBACK In Year 5
INTERNAL RATE OF RETURN 24.94%

ANDERSONS the united business

Table 3 and 4 link together to illustrate what an example high output biochar unit may be able to achieve over a 20-year period. Output levels used are biochar at £325/t, wood vinegar at 60p/litre, 13p/kwh electricity feed in tariff and Carbon credits at £125 each. The revenues have been kept the same for the duration of the term, but the expenses have been increased by 3% annually. Other assumptions made are that the unit will only work at 50% efficiency for the first 3 years and 80% thereafter and no allowance has been made for repairs and refurbishment although the time to do this work has been taken off.

In this instance a pay back period of 5 years at an internal rate of return of 24.94% is illustrated. However, if just one of the outputs is lost or reduced to a low level, the pay back and ROI change very quickly to a loss position.

Conclusion
Biochar production can be a financially viable and economically beneficial business, particularly when multiple revenue streams are leveraged effectively. The primary product, biochar, has a strong and growing market, while by-products like syngas, bio-oil, and wood vinegar offer additional revenue opportunities. Initial capital investments are significant, but with careful management, the operation can yield a positive ROI within a reasonable timeframe, while also providing significant environmental benefits. Critical planning and execution of a biochar reactor installation with a clear vision of why it is implemented and where revenue streams will be generated from, is key to the success of any biochar business.

9.2 Overview of Key Markets for Certified Biochar Products

Author - Dr Leah Herrgen

Introduction

The beneficial effects of biochar in a wide range of applications are increasingly being recognised around the world. Consequently, the market for biochar has been expanding rapidly over the last decade, and its growth continues unabated. In this report, we provide an overview of the biochar market. We also discuss the role of certification through the European Biochar Certificate (EBC) in guaranteeing high standards of quality in biochar production and use, and how the EBC can guide end users' decisions regarding biochar deployment.

Biochar market development - present and future

There are currently no reliable up-to-date figures on the volume of global biochar production or the contribution of different regions (e.g. Europe, US, China) to overall production. However, the US Biochar Initiative (USBI) [1] collated the following estimated numbers for recent years in a 2022 booklet [2]: 85K tonnes produced globally in 2015; 45K tonnes produced in the US in 2018; 550K tonnes produced in China in 2019; and less than 1M tonnes produced globally in 2022. Estimates from Triton Market Research [3] are somewhat more conservative, putting global production at just under 400K tonnes in 2021. The European Biochar Industry Consortium (EBI) [4] estimated biochar production in Europe at 30K tonnes in 2022 in a recent market report [5]. For more detailed information on the global biochar market (e.g., US, China), the purchase of a bespoke market report is recommended. Such reports are available from a number of research companies (e.g., Triton Market Research [3], Fortune Business Insights [6], Grand View Research [7]). Within Europe, the majority of biochar is produced in a relatively small number of countries. A total of 50% of biochar comes from Germany, Austria or Switzerland and a further 25% from the Nordic countries, whereas all other countries combined produce the remaining 25%.

There is considerable divergence between estimates for biochar market revenue between different market research companies. Triton Market Research [3] estimates a market revenue of \$1.3B in 2021; Fortune Business Insights [6] gives a figure of \$185M in 2022; and Grand View Research [7] values the global biochar market at 542M in 2023. However, these companies all agree in predicting strong growth of biochar market revenues of 12-14% CAGR over the next 4-6 years.

According to a recent study [8], this growth is driven by the various agricultural and environmental benefits of biochar, and is further supported by environmental legislation. For instance, the EU recently updated [9] its Fertilising Products Regulation [10] and thereby allowed the use of biochar in fertilising products. Furthermore, commitments to reach net zero emissions by 2050, as laid down in the EU Climate Law and the UK Climate Change Act, are likely to boost biochar production due to its carbon sequestration potential. Accordingly, in a report [11] for the European Commission, biochar is included as one of the most technologically mature carbon sequestration technologies. Despite this progress, the legal framework for biochar in the EU, its individual member states, and the UK remains inadequate for the regulation of all aspects of biochar production and application. A concise regulatory regime is needed to further boost the rapid growth of the UK and European biochar markets.

The role of biochar certification

In an attempt to fill the “regulatory gap” caused by the lack of dedicated biochar legislation, several biochar quality standards have been created, including the Biochar Quality Mandate (BQM) [12] in the UK, the European Biochar Certificate (EBC) [13] in Europe, and the International Biochar Initiative (IBI) Standards [14] for international use. The aim of these standards is to give biochar producers the opportunity to demonstrate that their biochar meets a set of recognised quality standards and to provide customers with the certainty that they are buying a safe and sustainable product. For biochar production and use within Europe (including the UK), the most widely used quality

standard is the EBC. Certification of biochar products under the EBC is voluntary in all European countries except Switzerland, where it is mandatory for biochar used in agriculture. Despite being voluntary, EBC certification is widely adhered to within the industry. According to a recent EBI market report [5], nearly 70% of the production capacity within Europe in 2023 was certified under the EBC.

The EBC’s booklet “Guidelines for sustainable production of biochar” [15] is the core document for certification under the EBC. The document sets out requirements with regard to the feedstocks, sampling, pyrolysis technology, processing, labelling, quality control, health and safety, and analysis methods that are to be used in the production of biochar. These guidelines are complemented by a list of permissible feedstocks [16], which sets out the materials and additives that may be used for the production of EBC-quality biochar. Permissible feedstocks include various categories of biomass, such as wood and wood residues, agricultural products and by-products, different waste materials, digestate from biogas plants, manure and sewage sludge. The list is constantly revised and updated, and it is important to refer to the most recent version when making biochar-related production choices. In addition to prescribing permissible feedstocks and production technologies, the EBC sets out quality criteria relating to the physicochemical properties of the finished biochar. Biochar producers must demonstrate that their product adheres to a set of conditions. In particular, limit values for a number of organic and inorganic contaminants must not be exceeded.

The Guidelines also specify different application classes for certified biochar. These are named EBC-Feed/FeedPlus, EBC-Agro/Agro-Organic, EBC-Urban, EBC-ConsumerMaterials, and EBC-BasicMaterials, after their intended areas of deployment. Different classes differ with regard to requirements for the production process (e.g., permissible feedstocks) and limit values of contaminants. Of note, the assignment of a batch of biochar to a particular certification class is not a statement about its quality, but only about its admissibility for a specific set of applications.

Agricultural market for biochar

The two main uses for biochar in agriculture are for soil improvement and as a feed additive, but it can also be employed in manure and slurry management and to improve anaerobic digestion.

A substantial body of scientific literature supports the notion that biochar can increase soil quality and fertility [17] when applied directly to agricultural soils. More specifically, biochar increases soil porosity, soil water retention, organic matter and carbon content, pH, and cation exchange capacity. This amelioration of the physical and chemical properties of the soil can lead to an increase in plant nutrient availability and retention, a decrease in nutrient loss through leaching, and an increase in soil microbial activity and abundance. Consequently, biochar application can increase the yield and quality of crops grown in conditioned soils. There are, however, a number of caveats regarding biochar’s use for soil improvement in agriculture. First, biochar’s positive effects appear most pronounced in coarse-textured, sandy soils rather than in fine-textured, clayey ones, so it will likely be more appropriate for use in the former than the latter. Second, the biochar must be charged with a fertiliser before its application to the soil since it would otherwise remove plant nutrients from the soil due to its high cation exchange and nutrient binding capacity. Third, and most importantly, the majority of the evidence for biochar’s positive effects on soil quality and fertility comes from tropical agricultural systems. For temperate zones, the benefits have so far only been shown in small-scale studies under scientific conditions. Consequently, the large-scale application of biochar directly to agricultural soils in temperate zones is currently not widespread. However, a number of large-scale field trials have been or are being run to address this knowledge gap. For instance, a recent field trial [18] in northern Germany showed that a low rate of biochar application can increase plant available nutrients and crop yields in temperate, marginal soils. Similarly, the “Black goes green” [19] trial in Switzerland, which is currently ongoing, is designed to provide data on the effects of biochar on agricultural yields and soil carbon storage in European agriculture.

As in the case of soil application, the scientific literature supports a positive effect of biochar on livestock health [20] when given as a feed supplement. Biochar has been used for acute medical treatment of livestock for centuries, but has also increasingly been used as a regular feed supplement for the last decade. A large number of scientific publications have shown positive effects on a number of parameters relevant to livestock health, such as digestion, blood values, feed conversion efficiency, weight gain, and meat quality. These effects were observed in a range of species including cattle, goats, pigs, chickens and ducks. Furthermore, biochar can improve barn climate by reducing emissions of ammonia and other greenhouse gases. The use of biochar as a feed additive is one of its best-established applications. An estimate from 2014 [21] states that at the time, about 90% of biochar produced in Europe was used in livestock farming.

Relevant EBC categories for agricultural use of biochar are EBC-FeedPlus, EBC-Feed, EBC-AgroOrganic and EBC-Agro. To be allowed to sell biochar as a feed additive, the manufacturer must be approved and registered as a feed producer with the relevant authorities in accordance with applicable regional, national and/or EU regulations.

Horticultural market for biochar

The benefits of using biochar in horticulture [22] mirror those of its use in agriculture. Specifically, they include better plant growth and improved soil quality through biochar's water- and nutrient-storing effects. As in agriculture, the biochar must be charged with a fertiliser or added to substrate as part of a compost mix before use.

A particularly attractive feature of biochar in the horticultural market is its potential to replace peat in compost mixtures. Accordingly, those biochar companies in the UK that sell directly to consumers (e.g., Carbon Gold [23], SoilFixer [24]) usually offer several types of biochar-containing, peat-free compost. Of note, the biochar in this market can fetch high prices. For instance, a 10 L bag of biochar-containing compost will usually cost around £10 [25]. However, it should be borne in mind that selling biochar to gardeners as part of compost mixtures requires additional and potentially complex processing and packaging.

Relevant EBC categories for horticultural use are EBC-AgroOrganic and EBC-Agro.

Other markets for biochar

There are a number of other potential markets for biochar. These include:

- **Urban areas:** There are many uses for biochar in urban areas, including roof greening, tree planting, and stormwater management. The best-known project looking at the use of biochar in cities is the Stockholm Biochar Project [26], where garden waste from residents was collected and made into biochar, which was then used in the gardens and public spaces of the city. The project was considered a success and consequently Stockholm City has received many requests from other cities that are interested in replicating the project, which prompted them to develop a replication manual [26].
- **Construction:** Biochar has many potential uses in the construction industry, including as a component of concrete, asphalt, render and plaster, and for insulation. Academic

studies [27] have shown that the addition of biochar can increase the strength and decrease the thermal conductivity of building materials. In addition, the inclusion of biochar can reduce the otherwise large carbon footprint of many building materials.

- **Soil remediation:** Due to its ability to adsorb both organic and inorganic contaminants, biochar has been proposed for the remediation of contaminated soils (e.g., in former mining areas). In particular, scientific studies [28] have suggested the use of biochar as a less expensive and more environmentally friendly alternative to activated carbon. In fact, there already are UK-based biochar companies [29] that offer biochar-based products specifically tailored for soil remediation. As highlighted in a case study [30], their product has been used successfully for remediation of contaminated land around a former mine in Wales.

Conclusion

According to the EBRI test results of two biochar samples produced from apple and pear wood at either 450 °C or 550 °C, neither of the two samples satisfied the EBC quality criteria for EBC-FeedPlus, EBC-Feed, EBC-AgroOrganic or EBC-Agro certification classes. While EBC certification is not legally required in most European countries (except Switzerland), this will nonetheless severely limit the potential for marketing these chars for agricultural applications. Farmers must be assumed to be cautious about what materials they put on their land or feed to their livestock, and there are numerous biochar suppliers offering EBC-certified char for agricultural purposes, which the apple and pear biochar could probably not compete with.

Both biochars, however, did satisfy the quality criteria for the EBC-BasicMaterials certification class. Hence, they can be used in basic industry (e.g., building materials, road construction). A particularly interesting application in this sector is the use of biochar in concrete. Biochar can improve some of the mechanical properties of concrete, such as compressive strength and fire resistance. The incorporation of biochar into concrete can also reduce the carbon footprint

of this highly carbon-intensive material. With the global cement industry accounting for about 8 % of global emissions, new approaches for the decarbonisation of the sector are urgently needed. Hence, the use of biochar in construction has the potential to be a huge growth market over the next few years. Indeed, there are a growing number of pilot projects investigating the use of biochar in construction, both within Europe [31] and overseas [32].

In summary, it is recommended that producers of apple and pear biochar explore the use of their product in basic industry applications. Biochar as a component of concrete or other building materials holds particular promise in this sector.

References

- [1] <https://biochar-us.org/> (Accessed: 1 April 2024).
- [2] https://nfs.unl.edu/documents/ForestProducts/BIOCHAR_Roadmap_DIGITAL.pdf (Accessed: 1 April 2024).
- [3] <https://www.tritonmarketresearch.com/reports/biochar-market> (Accessed: 1 April 2024).
- [4] <https://www.biochar-industry.com/> (Accessed: 1 April 2024).
- [5] <https://www.biochar-industry.com/market-overview/> (Accessed: 1 April 2024).
- [6] <https://www.fortunebusinessinsights.com/industry-reports/biochar-market-100750> (Accessed: 1 April 2024).
- [7] <https://www.grandviewresearch.com/industry-analysis/biochar-market> (Accessed: 1 April 2024).
- [8] Jansen, D. (2023). Drivers and Barriers for Biochar Deployment in Swedish Agriculture.
- [9] <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R2088> (Accessed: 1 April 2024).
- [10] <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009> (Accessed: 1 April 2024).
- [11] McDonald, H., Bey, N., Duin, L., Frelil-Larsen, A., Maya-Drysdale, L., Stewart, R., ... & Zakkour, P. (2021). Certification of Carbon Removals.
- [12] Shackley, S., Esteinou, R. I., Hopkins, D., & Hammond, J. (2014). Biochar quality mandate (BQM) version 1.0.
- [13] <https://www.european-biochar.org/en/> (Accessed: 1 April 2024).
- [14] <https://biochar-international.org/standard-certification-training/biochar-standards/> (Accessed: 1 April 2024).
- [15] https://www.european-biochar.org/media/doc/2/version_en_10_3.pdf (Accessed: 1 April 2024).
- [16] https://www.european-biochar.org/media/doc/2/positive-list_en_v10_3.pdf (Accessed: 1 April 2024).
- [17] Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., ... & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy*, 11(5), 993.
- [18] Knoblauch, C., Priyadarshani, S. R., Haefele, S. M., Schröder, N., & Pfeiffer, E. M. (2021). Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. *European Journal of Soil Science*, 72(4), 1885-1901.
- [19] <https://www.fibl.org/en/themes/projectdatabase/projectitem/project/2134> (Accessed: 1 April 2024).
- [20] Schmidt, H. P., Hagemann, N., Draper, K., & Kammann, C. (2019). The use of biochar in animal feeding. *PeerJ*, 7, e7373.
- [21] <https://www.biochar-journal.org/en/ct/2> (Accessed: 1 April 2024).
- [22] <https://www.rhs.org.uk/soil-composts-mulches/biochar> (Accessed: 1 April 2024).
- [23] <https://www.carbongold.com/> (Accessed: 1 April 2024).
- [24] <https://www.soilfixer.co.uk/> (Accessed: 1 April 2024).
- [25] <https://www.carbongold.com/biochar/all-purpose-compost/> (Accessed: 1 April 2024).
- [26] https://nordregio.org/sustainable_cities/stockholm-biochar-project/ (Accessed: 1 April 2024).
- [27] Legan, M., Gotvajn, A. Ž., & Zupan, K. (2022). Potential of biochar use in building materials. *Journal of environmental management*, 309, 114704.
- [28] Islam, T., Li, Y., & Cheng, H. (2021). Biochars and engineered biochars for water and soil remediation: A review. *Sustainability*, 13(17), 9932.
- [29] <https://terraffix.co.uk/> (Accessed: 1 April 2024).
- [30] <https://terraffix.co.uk/case-study/frongoch-mine/> (Accessed: 1 April 2024).
- [31] <https://www.msn.com/en-gb/money/technology/new-perspectives-on-emission-free-concrete/ar-AA1mHaKd> (Accessed: 1 April 2024).
- [32] <https://www.theglobeandmail.com/investing/markets/stocks/ARLSF/pressreleases/24786592/24786592/> (Accessed: 1 April 2024).

9.3 Overview of Key Policies and Subsidies in Europe and the US that Support Biochar Production

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Introduction

Over the last two decades, the use of biochar has gained significant interest in sustainable agriculture and as a tool for long-term carbon sequestration. The interest was fuelled by the climate emergency and the global search for more productive and sustainable food production, ways to restore and increase soil health, and valorise organic wastes and residues.

Since 2019 biochar has been highlighted in the IPCC reports as a material for carbon sequestration. Biochar is used in urban applications e.g. to support growth of city trees [1] and storm drainage [2], in agriculture (e.g. as additive in animal feeding, composting, AD, slurry management and soil amendment), and in construction materials like concrete [3]. The technology used to produce biochar is highly diverse in both type and size ranging from micro plants (<100 tonnes per acre) to industrial (>5000 tonnes per acre).

At the end of 2022, more than 100 plants have been in operation across Europe with a total production capacity of 53,000 t/a. By the end of 2023, the European Biochar Industry Consortium [4] expects the capacity to grow to over 90,000t. The EBI also expects the total biochar production in Europe to exceed 50,000 t in 2023, which equals the removal of 150,000 t of CO₂. This makes Biochar by far today's most relevant industrial carbon removal technology. 60% of the total production capacity belongs to plants with a capacity of >500 tonnes per acre and 90% to plants >200 tonnes per acre [4].

Geographically, three regions are dominating the biochar market. As of 2022 Germany makes 32% of Europe's biochar production capacity, followed by Scandinavia (25%) and Austria and Switzerland (combined 18%) [4]. Other countries represent 25%. This means that more than 50% of the biochar is produced in the German-speaking D-A-CH (Germany, Austria, and Switzerland) countries and D-A-CH plus Scandinavia make approx. 75%. In Scandinavia, Sweden is the most relevant country.

The high growth rate of biochar production in Europe in the past is expected to continue at a compound annual growth rate (CAGR) of 46% until 2040 when the production capacity will exceed 30 million tons and a CO₂ removal of 100 million tons [4]. The EU Commission's current target for industrial carbon dioxide removal (CDR) in 2030 is 5 Mt CO₂ [5]. Denmark alone has committed to 2 Mt of CO₂e removal per year in 2030 with pyrolysis [6]. A survey financed by the German Federal Ministry of Education and Research shows that decarbonization of the German energy sector requires an annual CO₂ removal of 25 Mt [7]. At a CAGR of 48% biochar production in Germany could reach this target by 2038 requiring about 7000 biochar production plants [4].

The future development of the biochar industry highly depends on the shape of the regulatory and legislative framework and political and societal support in general. Along its value chain biochar crosses several highly regulated areas from using waste biomass as a feedstock and the emission-causing high-temperature production process to its use in soils and for sustainable farming practices and carbon removal biochar. The way governments and regulators address biochar in these regulations plays a critical role in the commercial development of the biochar industry. As an emerging market, the biochar industry of a country or region can benefit greatly from state incentives such as subsidies and grants that reduce costs for producers and users in agriculture and elsewhere.

European and US Policies & Regulations for Biochar Production

European Union

The EU is aiming to become carbon neutral by 2050 and has committed to investing in technological solutions to enable the transition [8]. The bloc is also leading the way in the establishment of policies to help measure and mature the carbon market. As stated by Frans Timmermans during the unveiling of the proposal, "To become carbon neutral, [...] it will be impossible to bring all of our emissions down to zero. We will need carbon removals through technology or natural carbon sinks." An additional step to dramatically accelerate the carbon removal market would be including carbon dioxide removal in the EU's Emission Trading System (ETS) or Effort Sharing Regulation (ESR). Carbon removal is not included under the EU ETS, but the Commission is set to report, by 2026, on how negative emissions could be accounted for and covered by the carbon trading [9]. The EU has set new targets for a more ambitious ESR including net carbon removals by natural sinks of 310 million tonnes of CO₂ equivalent by 2030 [10].

On November 21, 2023, the European Parliament adopted the first draft legislation for the EU Carbon Removal Certification Framework ("CRCF" or the "Framework"), which works to define and formulate methodologies for certifying carbon removals in the European Union including carbon farming. The Framework's core objective is to instil trust in the quality and reliability of certified carbon removals amongst project developers, investors, and the public. The adopted text mentions 'biochar' as a feasible CO₂ removal activity within the Amendment 10 [11].

The most relevant certification system for biochar in Europe is the European Biochar Certificate (EBC) which includes specifications on permitted feedstocks, material characteristics, limits for problematic substances and production and use requirements [12]. 70% of the total biochar capacity is expected to be EBC certified. However, EBC certification is a voluntary scheme that is not adopted by European countries into their legislation except Switzerland. However, recently biochar was adopted by EU REACH (Registration,

Authorisation and Restriction of Chemicals) within the dossiers for charcoal. This means that all biochar produced, imported and traded in the EU will soon require EU REACH registration. The EBC has reacted to this by making their requirements comply with REACH. Several biochar producers that sell to the animal feed market have registered their biochar for GMP+ (international) and QS (Germany) certification. Animal feed producing companies can display their safe, and responsible practice with GMP+ certification [13]. More information about GMP+ certification for biochar is available in the aforementioned EBC. The QS quality scheme is the leading standard for food safety in Germany and quality assurance from farm to shop including animal feed [14]. Since January 2024 the QS scheme has adopted EBC quality standards [15].

Since 2001 we have been working together to ensure that all food safety standards are reliably implemented by all partners in the QS network.

The use of waste feedstock for biochar production requires additional permits and licences from the national, state or local authorities. Because most EU countries today have only 0-10 biochar production plants, legislation on biochar is usually not specifically developed, but the local regulator has to apply existing regulations on thermal waste treatment. In Germany, biochar production plants that use waste require a permit under the Federal Emission Protection Act (FEPA). Most plants in Germany are operating under the FEPA. As for other European Countries, similar requirements are in place. Noteworthy, Denmark, Sweden and the Czech Republic are the only EU countries that allow sewage sludge waste for biochar for soil use. In Italy and Spain, the use of feedstock appears to focus on agricultural waste especially wastes from olive production while France seems to focus on wood materials. However, these three countries only operate a handful of biochar plants today, which indicates that regulations for biochar production are still in their infancy.

Looking ahead, future policies may involve further integration of carbon dioxide removal into existing regulatory frameworks like the ETS and ESR. The EU's focus on carbon removal technologies and natural carbon sinks will likely continue to shape its policy direction.

United Kingdom

In the UK, Biochar is recognised for its carbon removal potential and the technology development is supported by significant funding through the Department for Business, Energy & Industrial Strategy (BEIS) Net Zero Innovation Portfolio. The British Biochar Quality Mandate (BQM) alongside the European EBC is established as an instrument for biochar quality assurance, currently limited to non-waste feedstocks [16]. Biochar production from waste materials (other than untreated plant materials) requires an environmental permit for waste operation including the Industrial Emissions Directive (EID). Waste-derived biochar's keep their waste status unless they are granted end-of-waste status by the EA/SEPA. The European Waste Framework Directive (Directive 2008/98/EC) defines a waste as "any substance or object which the holder discards or intends or is required to discard". Non-waste biochar can be used (for example) for animal feeding and soil amendment. Some waste materials are at lower risk than others, and requirements for making an end-of-waste case will be more easily achieved. E.g. untreated waste wood is less likely to contain toxicants and will be easier to achieve an end-of-waste status. The distinction is similar to the distinction drawn by the Environment Agency's Position Statement on The Environmental Regulation of Wood between clean and treated waste wood.

Future policies in the UK may involve further refinement of regulations governing biochar production and usage, particularly concerning waste-derived biochar. Efforts to streamline the process for obtaining end-of-waste status, especially for lower-risk waste materials, could be a focus.

United States

The US government supports biochar as a renewable and low-carbon biobased strategy for soil preservation and climate change mitigation. Based on the biochar's characteristics and its potential applications in agriculture and energy sectors biochar can potentially receive funding through a variety of available programs from agencies such as the U.S. Departments of Agriculture (USDA) and Energy (DOE) as well as state governments.

Several policies and regulations support sustainable biochar production practices and encourage the use of biochar as a beneficial soil amendment. The USDA Climate Hubs provide information and resources on biochar production in the United States [17]. The Biochar Protocol developed by the Climate Action Reserve provides guidance on quantifying, monitoring, reporting, and verifying climate benefits associated with biochar projects for both countries the US and Canada [18]. A 2018 study entitled "Policy support for biochar: Review and recommendations" identified 35 US policy programs that directly or indirectly support biochar production [19]. Past and present US federal support programs include loan guarantees by the USDA 'Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program' [20], grants by the USDA and DOE 'Small Business Innovation Research Program' [21] and the 'Biofuel Infrastructure Partnership' [22], and matching payment by the USDA 'Biomass Crop Assistance Program' [23]. The USDA offers policy support by its certification scheme 'Biopreferred Program' [24], the 'National Organic Program' [25] and the 'Conservation Stewardship Program' for forest conservation [26].

Recent US laws that incentivise biochar production include the Bipartisan Infrastructure Law (BIL) [27], the Inflation Reduction Act (IRA) [28], the Farm Bill [29] and the Biochar Research Network Act [30]. The BIL was enacted in November 2021, and it includes over \$12 billion of investments directly into engineered CDR efforts and the complementary infrastructure needed to support it and an additional \$2.7 billion into land management interventions that could protect and increase

carbon sequestration on natural and working lands. These investments include \$100 million for the removal of hazardous forest vegetation for the creation of biochar and innovative wood products. The IRA, which was signed into law in August 2022, includes an additional \$2 billion for natural CDR alongside tax credits supporting carbon removal technologies expected to be worth several billions more.

There is a growing commitment in the US to invest in biochar-related initiatives. The 2023 Farm Bill, expected to be passed in 2024, holds a lot of promise for biochar carbon removal (BCR) and has enormous potential through its multipronged approach but will also create economic opportunities for farmers, ranchers, and foresters through agroforestry, BCR and other biological carbon removal methods. The Biochar Research Network Act of 2023 – which foresees an investment of \$50 million per year for five years into the intersection of biochar and agriculture [31]– looks likely to be incorporated into and passed through the Farm Bill.

Focus on Woody Biomass as Biochar Feedstock

Biomass is a limited resource. To avoid conflicts and high costs the production of biochar should target residual or waste biomass. A smart combination of biochar and thermal energy production avoids conflicts further and increases the overall energy and commercial efficiency. Woody biomass is generally well-suited for biochar production. Several research articles report also on the use of pruning residues for biochar production (e.g. [32]).

The 2021 Report 'Sustainable biomass availability in the EU, to 2050' by Imperial College [33] estimates the sustainable biomass potential for bioenergy use in the EU and UK for 2030 at 520 - 860 million dry tonnes and for 2050 at 539 - 915 million dry tonnes. Between 40% and 50% of this potential is made of woody biomasses including agricultural prunings, primary forest residues, stem wood (fuelwood), and secondary forest residues (incl. post-consumer wood). Agricultural prunings contribute the lowest volumes but still 10-13 million dry tonnes in 2030 and 12-15 million dry tonnes in 2050. Geographically, Spain possesses by far the largest amount of prunings (5m dry tonnes per year) followed by Poland (1.2m dry tonnes per year). Data for the UK was not available.

The carbon removal potential can be calculated through the biochar yield and the stable carbon concentration of the biochar. Both factors vary by feedstock type and pyrolysis conditions. A conservative approach is to use a yield of 20% and a stable carbon concentration of 70% [34]. This gives an annual CO₂ removal potential from sustainable woody biomass of 100-200 million tonnes for 2030 and 110-220 million tonnes for 2050. For pruning residues, the respective values are 5-6 million tonnes of CO₂ (2030) and 6-8 million tonnes of CO₂ (2050).

Renewable Energy Subsidies & Incentives

To better support renewable energy projects, and thereby encourage a greater uptake of renewable energy sources across the EU, the European Commission established the EU Financing Mechanism [35]. It stems from Article 33 of the Governance Regulation (EU/2018/1999) and has been in force since September 2020. Its implementation process is ongoing. However, it is unclear to what extent biochar projects will benefit in the future. Financial support schemes such as low-interest loans, grant programs, and tax rebates are available to remove barriers to investment in low-carbon heating.

EU member states have established different mechanisms to support the increase of renewable energy production and use. In Germany, the new Buildings Energy Act subsidises the investment in low-carbon heating systems [36]. This includes heating with solid biomass through grants and tax benefits. Moreover, Germany also supports the setup of new district heating systems with grants of up to 40% of the investment costs for production and distribution facilities, plus low-interest loans. For selling renewable electricity from new solid biomass installations Germany offers three options depending on size. Small units of 1-100 kW either receive a fixed feed-in tariff of ca. €0.10 per kWh or can choose to use direct marketing on the spot market plus a bonus. Larger facilities must use the spot market (101-150 kW) or bid for public tenders, which are capped at ca. €0.16 per kWh for new plants and ca. €0.18 for existing plants. Other EU countries have similar support programs in place.

However, the commercial viability of a biochar project is also affected by other factors such as the feedstock costs. Most profitable cases will use a local source of dry feedstock (like wood waste) and also supply the heat to a local user such as an energy-intensive factory. An example is the biochar production facility of Circular Carbon GmbH in Hamburg (Germany) that is connected to a chocolate factory and has an annual capacity to turn 10,000 tonnes of cocoa husks into 3,500 tonnes of biochar and 20,000 MWh of steam which supplies the chocolate processing [37]. Projects that feed head into district heating systems should also integrate

electricity production to generate more income during the summer months. An example is the biochar production plant of the German city of Darmstadt that converts 4000 tonnes of compost sieve overflow and green cuttings into 1000 tonnes of biochar per year [38]. The heat is used to dry the feedstock and to produce electricity by a gas turbine that supplies both the pyrolysis process and the composition process.

Agricultural & Environmental Support Programs

Biochar practices offer several potential benefits for farmers, landowners, and environmental conservation. Several review papers provide a comprehensive overview (e.g. [39], [40]; [41]) When made from plant biomass, biochar is highly porous and absorbent. Adding biochar to soil can enhance agricultural soil performance by improving soil hydrological properties and soil nutrients, thereby increasing crop yield. It can also lead to long-term increases in soil carbon inventory and stability, which in turn leads to increased plant-available water and a reduction in nutrient leaching to soil and water. Additionally, biochar amendment can lead to reduced fertiliser-related releases of nitrogenous gases, potentially improving regional air quality. Furthermore, biochar production can provide an additional source of income for farmers through biochar, energy and CO₂ removal certificates. These benefits contribute to improved agricultural productivity, enhanced ecosystem services, and potential economic growth for farmers.

The European Union supports the use of biochar in agriculture through various policies and regulations. The European Biochar Certificate (EBC) is a significant initiative that provides a voluntary industry standard for biochar production in Europe. It ensures transparent and traceable control, quality assurance, and compliance with EU-REACH regulations. Furthermore, the updated EU rules on fertilising products (Regulation 2019/1009) provide guidelines on materials allowed in fertilising products, including pyrolysis and gasification materials used in biochar production. See further information in the prior Section 'European (and US) Policies & Regulations for Biochar Production'

Most recently the European Parliament adopted the first draft legislation for the EU Carbon Removal Certification Framework ("CRCF" or the "Framework"), which works to define and formulate methodologies for certifying carbon removals in the European Union. The adopted text mentions 'biochar' as a feasible CO₂ removal activity within the Amendment 10 [42]. The CRCF is highly relevant for climate farming as it aims to promote carbon removal solutions, encourage carbon farming approaches, and prevent greenwashing by establishing trust through the implementation of standards and certification procedures. The framework includes certification for carbon removal, storage in products, and carbon farming sequestration. It emphasises the need for transparency, international standards, and prevention of greenwashing in carbon removal activities. The European Parliament has approved this framework to support carbon dioxide removal (CDR) efforts in the EU

The CRCF also addresses the need for clarity on what constitutes carbon removal and distinguishes between different types of activities with varying permanence levels. It sets out quality criteria and certification methodologies for carbon removal activities, with certification bodies being required to be independent and accredited by a national authority.

It is expected that the CRCF will pave the way for commercially viable biochar production and use in agriculture. It is too early to predict what financial mechanisms individual member states may put in place to further support the uptake of biochar in the farming sector.

Agricultural biochar production can benefit indirectly from the financial support that some member states offer for establishing agroforestry systems to increase biodiversity and soil health. Since 2023 Germany incentivises agroforestry for food and materials production through investment grants of up to 100% [43]. Other countries such as Spain and France have similar support schemes for agroforestry.

Carbon Pricing & Offsetting Mechanisms

As of today, the primary market for carbon removal is the voluntary carbon market (VCM). Although this market is undergoing significant growth, it is still small compared to compliance markets such as the European Emissions Trading Scheme (ETS). In the future we could see an inclusion of carbon removal in the ETS, potentially paving the way for inclusion in other compliance markets and marking a step change in the demand for CDR, including biochar carbon removal (BCR).

Prices for biochar carbon removal (BCR) credits of recent trades are mostly between €100 and €200/tCO₂. The CORC Carbon Removal Price Index published by Puro.earth shows prices of around €120/tCO₂ between July and December 2023.

The biggest challenge in including CDR and BCR in compliance with climate policy today is that there is no clear definition of what high-quality carbon removal actually means, and how to certify it. This is precisely what the European Carbon Removal Certification Framework (CRCF) is addressing. The direction of the CRCF is likely going to have immediate impacts on the Voluntary Carbon Market (VCM), seen by many as an early indication of where CDR is heading and followed closely by companies that are currently opting to voluntarily procure CDR, but which might soon be legally obliged to do so. It can be expected that the CRCF will encourage food companies as well as fertiliser producers to reward farmers for higher carbon removals to offset their carbon emissions.

Conclusion

The evidence supporting the environmental and agricultural benefits of incorporating biochar into the soil is substantial, yet its adoption remains slow. Well-designed policy can play an important role in establishing pathways to achieving a wide range of biochar's benefits and lead to increased utilization. The EU Carbon Removal Certification Framework ("CRCF") represents a promising avenue for establishing biochar production and use as an attractive and widely used method of carbon farming.

Until a dedicated biochar initiative is established, the optimal avenues for securing funding for biochar production require leveraging existing programs. This can be achieved through channels such as initiatives supporting the production and utilisation of renewable heat and energy, as well as those fostering higher biodiversity, such as agroforestry support programs. Both EU and national-level efforts are needed to create incentives for biochar production and application, alongside increased investment in research to drive technological advancements.

Advancing our understanding of biochar properties is crucial for developing standardised products, ensuring consistency among biochar producers, and aligning with future laws and regulations. Further exploration of biochar's ecosystem benefits and refinement of environmental and economic models for accurate assessment and monetisation can provide valuable insights to shape biochar policies effectively.

References

- [1] Embrén, B. (2016) 'Planting Urban Trees with Biochar', the Biochar Journal. Available at: <https://www.biochar-journal.org/en/ct/77-Planting-Urban-Trees-with-Biochar> (Accessed: 17 February 2024).
- [2] Mohanty, S.K. et al. (2018) 'Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment', *Science of The Total Environment*, 625, pp. 1644-1658.
- [3] Schmidt, H.-P. and Wilson, K. (2013) 'The 55 uses of biochar', the Biochar Journal. Available at: <https://www.biochar-journal.org/en/ct/2-The-55-uses-of-biochar> (Accessed: 17 February 2024).
- [4] EBI - European Biochar Industry Consortium (2023) 'European Biochar Market Report 2022 & 2023'. Available at: <https://www.biochar-industry.com/market-overview/> (Accessed: 17 February 2024).
- [5] Jensen, L. (2022) 'Sustainable carbon cycles - Promoting removal, storage and recycling'. European Parliamentary Research Service. Briefing - Towards climate neutrality. PE 733.679 - October 2022. Available at: [https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733679/EPRS_BRI\(2022\)733679_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733679/EPRS_BRI(2022)733679_EN.pdf) (Accessed: 17 February 2024).
- [6] KEFM - Klima-, Energi- og Forsyningsministeriet (2023) 'Klimaprogram 2023'. Available at: <https://kefm.dk/Media/638315764817167867/Klimaprogram%202023.pdf> (Accessed: 17 February 2024).
- [7] Merfort, A., Stevanović, M., Strefler, J. (2023): 'Energiewende auf Netto-Null: Passen Angebot und Nachfrage nach CO₂-Entnahme aus der Atmosphäre zusammen?' Kopernikus-Projekt Ariadne, Potsdam. Available at: <https://ariadneprojekt.de/publikation/energiewende-auf-netto-null-passen-angebot-und-nachfrage-nach-co2-entnahme-aus-der-atmosphaere-zusammen/> (Accessed: 17 February 2024).
- [8] EC - European Commission (2023a) 'European Climate Law' Available at: https://climate.ec.europa.eu/eu-action/european-climate-law_en (Accessed: 17 February 2024).
- [9] EP - European Parliament (2022) 'Report - A9-0162/2022'. Available at: https://www.europarl.europa.eu/doceo/document/A-9-2022-0162_EN.html (Accessed: 17 February 2024).
- [10] EC - European Commission (2023b) 'Questions and Answers - Increasing the ambition of the EU's Effort Sharing Regulation and boosting natural carbon sinks' Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_4757 (Accessed: 17 February 2024).
- [11] https://www.europarl.europa.eu/doceo/document/TA-9-2023-0402_EN.pdf (Accessed: 17 February 2024).
- [12] <https://www.european-biochar.org/de> (Accessed: 17 February 2024).
- [13] <https://www.gmpplus.org/en> (Accessed: 17 February 2024).
- [14] <https://www.q-s.de/en/> (Accessed: 17 February 2024).
- [15] QS - Qualität und Sicherheit GmbH (2023) , QS und CSI treffen Vereinbarung zum Futtermittelmonitoring', 17 October 2023. Available at: <https://www.q-s.de/news-pool-de/qs-und-csi-treffen-vereinbarung-zum-futtermittelmo.html> (Accessed: 17 February 2024).
- [16] <https://www.research.ed.ac.uk/en/publications/biochar-quality-mandate-bqm-version-10> (Accessed: 17 February 2024).
- [17] <http://www.climatehubs.usda.gov/hubs/northwest/topic/biochar> (Accessed: 17 February 2024).
- [18] <https://www.climateactionreserve.org/how/protocols/ncs/biochar/dev/> (Accessed: 17 February 2024).
- [19] <https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12582> (Accessed: 17 February 2024).
- [20] <https://www.rd.usda.gov/programs-services/energy-programs/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance-program> (Accessed: 17 February 2024).
- [21] <https://www.sbir.gov/> (Accessed: 17 February 2024).
- [22] <https://sandbox.fsa.usda.gov/programs-and-services/energy-programs/bip/index> (Accessed: 17 February 2024).
- [23] <https://sandbox.fsa.usda.gov/programs-and-services/energy-programs/BCAP/index> (Accessed: 17 February 2024).
- [24] <https://www.biopreferred.gov/BioPreferred/> (Accessed: 17 February 2024).
- [25] <https://www.ams.usda.gov/about-ams/programs-offices/national-organic-program> (Accessed: 17 February 2024).
- [26] <https://www.nrcs.usda.gov/programs-initiatives/csp-conservation-stewardship-program> (Accessed: 17 February 2024).
- [27] <https://www.fs.usda.gov/research/projects/bil> (Accessed: 17 February 2024).
- [28] <https://www.wri.org/update/carbon-removal-BIL-IRA> (Accessed: 17 February 2024).
- [29] <https://usbiocharcoalition.org/policy-priorities> (Accessed: 17 February 2024).
- [30] <https://www.congress.gov/bill/118th-congress/senate-bill/732/text?s=1&r=16> (Accessed: 17 February 2024).
- [31] <https://extension.colostate.edu/wp-content/uploads/2023/05/AFT-Recommendations-to-Scale-Up-Biochar-Research-and-Commercialization.pdf> (Accessed: 17 February 2024).
- [32] Kazimierski, P. et al. (2021) 'Pyrolysis of Pruning Residues from Various Types of Orchards and Pretreatment for Energetic Use of Biochar', *Materials*, 14(11), 2969. Article available at <https://www.mdpi.com/1996-1944/14/11/2969> (Accessed: 17 February 2024).
- [33] <https://www.concawe.eu/publication/sustainable-biomass-availability-in-the-eu-to-2050> (Accessed: 17 February 2024).
- [34] Masek O. et al. (2013) 'Influence of production conditions on the yield and environmental stability of biochar', *Fuel*, 103, pp. 151-155.
- [35] https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-renewable-energy-financing-mechanism_en. (Accessed: 17 February 2024).
- [36] <https://www.bmi.bund.de/EN/topics/buildinghousing/building/energy-efficient-construction-renovation/buildings-energy-act/buildings-energy-act-node.html> (Accessed: 17 February 2024).
- [37] Kemper S. and Ertl, F. (2022) 'Dekarbonisierung mit Pflanzenkohle aus Reststoffen'. Mühle und Mischfutter. 11 November 2022. Available (in German) at: <https://www.muehle-mischfutter.de/artikel/dekarbonisierung-mit-pflanzenkohle-aus-reststoffen> (Accessed: 17 February 2024).
- [38] Bauer, S. (2023) 'Darmstadt beschreitet neue Wege der Grünabfallverwertung', *B_I MEDIEN*, 2 February 2023. Available (in German) at: <https://bi-medien.de/fachzeitschriften/galabau/stadtgruen/klimaschutz-durch-kreislaufwirtschaft-darmstadt-beschreitet-neue-wege-der-gruenabfallverwertung-g15470>. (Accessed: 17 February 2024).
- [39] Bhattacharyya P.N. et al. (2024) 'Biochar as Soil Amendment in Climate-Smart Agriculture: Opportunities, Future Prospects, and Challenges', *Journal of Soil Science and Plant Nutrition*, 2024. <https://doi.org/10.1007/s42729-024-01629-9> (Accessed: 17 February 2024).
- [40] Kavitha, B. et al. (2018) 'Benefits and limitations of biochar amendment in agricultural soils: A review', *Journal of the Environmental Management*, 227, pp. 164-154.
- [41] Campion et al. (2023) 'The costs and benefits of biochar production and use: A systematic review', *Journal of Cleaner Production*, 408, 137138. <https://doi.org/10.1016/j.jclepro.2023.137138> (Accessed: 17 February 2024).
- [42] https://www.europarl.europa.eu/doceo/document/TA-9-2023-0402_EN.pdf (Accessed: 17 February 2024).
- [43] <https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/gap-2023.html> (Accessed: 17 February 2024).

9.4 Overview of Key UK Environmental Regulations Relevant to Biochar Production in the UK

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Introduction

Adhering to environmental regulations is critical for sustainable and responsible biochar production in the UK. The aim of this document is to give an overview of the environmental regulatory framework for biochar production in the UK ranging from emissions and waste management to soil management.

Environmental Regulatory Framework in the UK

The 2023 'Biomass Strategy' of the Department of Energy Security and Net Zero contains an introduction of the status and regulatory of biochar activities in the UK [1]. The key environmental regulatory bodies in the UK include the Environment Agency (EA) in England, Natural Resources Wales (NRW), the Scottish Environment Protection Agency (SEPA), and the Northern Ireland Environment Agency (NIEA). These agencies enforce much of the key environmental legislation in the UK and play a crucial role in regulating and protecting the environment. Adhering to environmental regulations is critical for sustainable and responsible biochar production in the UK. The key regulations include the areas waste treatment, air quality standards and land spreading. By adhering to these regulations, biochar producers can demonstrate environmentally responsible practices, prevent pollution, and build public trust. Strict compliance also helps the industry make the case for more government incentives and subsidies to support wider adoption of biochar for carbon removal. Responsible biochar production is vital for the technology to realise its potential environmental benefits.

Air Quality Regulations

The key air quality regulation relevant to biochar production in the UK is the Medium Combustion Plant Directive (MCPD) [2]. It aims to improve air quality by controlling emissions of nitrogen oxides (NOx), sulphur dioxide (SO₂), and dust. MCPD controls apply to biochar production units with a rated thermal input between 1 MWth and 50 MWth regardless of the type of feedstock used. Biochar producers must comply with these regulations to ensure that their operations do not exceed the specified emission limits [3].

Standard emission limit values (ELVs) for new biochar/combustion plants are: SO₂ - 200 mg/Nm³, NOx - 300 mg/Nm³, dust - 20 mg/Nm³ [4]. The ELV for SO₂ does not apply in case the plant is only using woody solid biomass. The ELV for NOx increases to 500 mg/Nm³ in the case of plants with a total rated thermal input of 1-5 MW. The ELV for dust increases to 50 mg/Nm³ for plants of 1-5 MW and 30 mg/Nm³ for plants of 5-20 MW.

MCP plans are regulated by the Environment Agency for England, NRW for Wales, Department of Agriculture, Environment and Rural Affairs (DAERA) for Northern Ireland, and Scottish Environment Protection Agency (SEPA) for Scotland.

Plants under 1 MWth do not need a MCPD permit. Small biochar plants under 1 MWth might fall under emission controls of the Ecodesign for Energy-Related Products and Energy Information Regulations 2021 [5].

For clarification on the regulations for a biochar production plant and the emission limits interested parties should contact the local authorities early in the project. Additionally, adherence to environmental permitting regulations is crucial for biochar production from waste.

Waste Management Regulations

Biochar production from waste requires an environmental permit for a waste operation, usually for a waste incineration activity (see next chapter).

There is an exemption for small-scale biochar production in the low risk waste position LRWP 60 by the Environmental Agency on storing and treating waste to make biochar [6]. Essentially, it allows the use of untreated plant tissue waste and wood waste in a biochar unit with a maximum throughput of 50kg/h without an environmental permit for a waste operation.

In addition, the Environmental Agency published a low risk waste position (LRWP 61) on storing and spreading biochar to benefit land [7]. Producers and users of waste-derived biochar produced in accordance with LRWP 60 can store up to 10 tonnes of biochar and spread up to 1 tonne per hectare and year.

Biochar projects outside the scope of LRWP 60 and 61 can apply to register a waste exemption at their environmental regulator. The application needs to demonstrate that the waste activity is not harmful to human health and the environment. Depending on the type and scale of the project acquisition of the required information can be lengthy and costly. Interested parties should contact their regulator early in the project.

Waste Incineration Regulations

In England and Wales operators and regulators must follow the Environmental Permitting Regulation 2010, as amended. These set out how the adopted EU directive 2010/75/EU (the Industrial Emissions Directive, IED) applies to England and Wales [8].

Scotland and Northern Ireland have implemented the controls of the IED by their respective Pollution Prevention and Control Regulations (PPC Regulations) [9,10].

In general, Chapter 4 of the IED applies to all waste incineration and waste co-incineration plants that thermally treat solid or liquid waste, unless an exclusion applies. This includes pyrolysis and gasification processes that yield biochar as the main or by-product. Wastes that are excluded from Chapter 4 are (among others) vegetable waste from agriculture and forestry and untreated sawdust, wood shavings or wood offcuts. Pyrolysis and gasification plants can be excluded if they meet certain criteria including end-of-waste status for both the biochar and the gases produced by the process. Providing the required evidence to pass an end-of-waste test can be costly and time consuming. It is important to engage early with the relevant regulator.

Large-scale biochar units that process more than 3 tonnes of waste feedstock per hour (including wastes that are excluded from Chapter 4) may also be subject to Chapter 2 controls. Unless excluded, a small waste incineration plant (below 3 tonnes per hour) needs an environmental permit issued by the local authority. The permit must be issued in line with schedule 13A of the Environmental Permitting Regulations and must reflect the requirements of article 44 of the Industrial Emissions Directive.

Soil Management & Contaminated Land Regulations

The key regulations concerning soil management in the UK relate to protecting soil quality and preventing pollution during construction, waste disposal, and agricultural activities. Overall, the focus of UK soil regulations is on preventing contamination and overuse while promoting sustainable practices. Permits and waste exemptions also play a key role.

For waste disposal activities, regulations like the waste exemption allow the spreading of certain wastes on agricultural land to improve soil quality, within specified limits and conditions [11].

The Rules for Farmers and Land Managers aim to prevent water pollution from agricultural sources through soil management practices like appropriate use of manure, fertilizers and minimizing soil erosion [12].

There are also general guidelines like the Code of Good Agricultural Practice which covers protecting soil resources during farming operations [13].

Additional regulations apply to contaminated soil as defined in the Contaminated Land Regulations of all UK states. The regulations place a duty on local authorities to identify any contaminated land in their areas, and bring about its remediation. Example for England [14].

Applying biochar to soil offers several potential benefits for farmers, landowners, and environmental conservation. Biochar can enhance agricultural soil performance by improving soil hydrological properties and soil nutrients, thereby increasing crop yield. It also leads to long-term increases in soil carbon inventory and stability, reducing nutrient leaching to soil and water. Additionally, biochar amendment can reduce fertilizer-related releases of nitrogenous gases, potentially improving regional air quality.

Assessing and remediating contaminated land in relation to biochar application need to follow all relevant regulations including the Contaminated Land Regulations. A biochar remediation project should start with site assessment and developing a remediation plan. The appropriate biochar type and application rate should be selected based on site conditions and remediation goals and biochar application should be integrated into the overall remediation strategy and timeline. Biochar should be applied by using effective techniques to maximise contact with contaminants. Monitoring of contaminant levels and soil function over time is required to evaluate the remediation efficacy. It is important to keep records of the biochar application and post-remediation monitoring.

Compliance & Reporting Obligations

Regulatory compliance is essential for any biochar project. The compliance obligations and reporting requirements are very specific to the type, size and location of the activity. In general the level of requirements will increase for large biochar units and the use of waste feedstocks. In certain regions additional restrictions may apply e.g. in terms of noise emissions and emissions of air pollutants. Non-compliance might lead to financial penalties, disruptions in operations, loss of permits and can also have serious consequences in terms of civil and criminal law.

Conclusion

Adhering to environmental regulations is critical for sustainable and responsible biochar production in the UK. The key regulations include waste treatment, air emissions and land spreading. The key air quality regulation relevant to biochar production in the UK is the Medium Combustion Plant Directive (MCPD). Biochar production from waste requires an environmental permit for a waste operation, usually a waste incineration activity. There is an exemption for small-scale biochar production and land spreading in the low-risk waste positions LRWP 60 and 61 of the Environmental Agency. Other projects that use wastes must follow the controls of the Industrial Emissions Directive (IED). Pyrolysis and gasification plants that use virgin wood waste or can demonstrate end-of-waste status for the biochar and gases might be excluded from Chapter 4 of the IED. Biochar application to soil in general and contaminated land in particular offers several benefits, but must be carried out in accordance with regulatory requirements. Overall, proactive engagement with regulatory bodies and compliance with environmental obligations is essential for successful biochar projects in the UK.

References

- [1] <https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf> (Accessed: 18 February 2024)
- [2] <https://www.gov.uk/guidance/medium-combustion-plant-mcp-comply-with-emission-limit-values> (Accessed: 18 February 2024)
- [3] <https://www.gov.uk/guidance/part-b-activities-combustion-and-incineration-permits> (Accessed: 18 February 2024)
- [4] <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32015L2193#d1e32-15-1> (Accessed: 18 February 2024)
- [5] <https://www.legislation.gov.uk/uksi/2021/745/> (Accessed: 18 February 2024)
- [6] www.gov.uk/government/publications/low-risk-waste-positions-miscellaneous/storing-and-treating-waste-to-make-biochar-lrwp-60 (Accessed: 18 February 2024)
- [7] www.gov.uk/government/publications/low-risk-waste-positions-landspreading/storing-and-spreading-biochar-to-benefit-land-lrwp-61 (Accessed: 18 February 2024)
- [8] www.gov.uk/government/publications/environmental-permitting-guidance-the-waste-incineration-directive/environmental-permitting-guidance-waste-incineration (Accessed: 18 February 2024)
- [9] www.legislation.gov.uk/ssi/2012/360/ (Accessed: 18 February 2024)
- [10] www.legislation.gov.uk/nisr/2013/160 (Accessed: 18 February 2024)
- [11] www.gov.uk/guidance/waste-exemption-u10-spreading-waste-to-benefit-agricultural-land (Accessed: 18 February 2024)
- [12] www.gov.uk/guidance/rules-for-farmers-and-land-managers-to-prevent-water-pollution (Accessed: 18 February 2024)
- [13] www.gov.uk/government/publications/protecting-our-water-soil-and-air (Accessed: 18 February 2024)
- [14] www.legislation.gov.uk/uksi/2006/1380/ (Accessed: 18 February 2024)

BIOCHAR

TAKING COMMERCIAL APPLE PRODUCTION TO NET ZERO



9.5 Presentation of relevant Case Studies that demonstrate implementation of biochar in the same or similar context

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Case Studies Review

Studies of biochar application to land are limited due to expense and the biochar industry being in its early stages. Biochar has only been allowed to be used on crops in Europe since 2020.

This document explores existing case studies where the solution has been implemented in the same or similar context, particularly within the agricultural industry. The proposed solution suggests utilising the variety of woody residues arising from the activities of apple and pear orchards for sustainable production of biochar for use as a soil enhancer, during the replanting of new orchards, and potential other markets.

The introduction of biochar solutions in apple and pear orchards presents an innovative strategy within the agricultural sector. The focus on wood biochar application in various field trials provides valuable insights into the potential benefits of biochar in sustainable farming practices.



Challenges in Apple and Pear Orchards:

Soil Management Issues: Orchards often face compaction issues due to the nature of agricultural machinery regularly travelling through the orchards to protect the crop from pests and disease. Biochar is a potential solution that may have the potential to increase and maintain soil health going forward.

Waste Management Challenges: Orchards generate significant organic waste at the end of orchard life. It is unlikely that biochar is a solution for orchard prunings or fruit waste due to the cost of removal. Efficient disposal of trees at the end of orchard life poses environmental concerns and resource inefficiency. By turning orchard waste into biochar, this waste will be recycled into a product that can be used as a fertiliser for future soil health, and create a circular, sustainable cycle of use either in orchard soils or other poorer quality soils, eliminating waste and capturing carbon.

Carbon Emissions from Agricultural Activities: Farming activities contribute to carbon emissions through organic matter decomposition and energy-intensive practices, necessitating mitigation strategies for sustainable farming. Turning waste into biochar has the potential to prevent carbon emissions from organic matter during decomposition, by trapping the carbon in the biochar product, which can sequester carbon in the soil for hundreds of years.

Case Study 1: Impact of biochar amendment on the growth, physiology and fruit of a young commercial apple orchard (Eyles et al. 2015)

This study assessed the effects of biochar on crop yields, tree growth and tree physiology of a high-input perennial horticultural system.

The trial started in November 2009 during replanting of an existing apple orchard in the Huon Valley of Tasmania. The soil at the site was classified as a Bleached Mottled Grey Kurosol. The A1 horizon (0–38 cm depth) into which the biochar was applied consisted of a dark brown-black sandy loam.

The site was levelled and re-mounded 1 week after the removal of old trees. The trial design was a randomised complete block with four treatments and five replicates, giving a total of 20 plots. Individual plots consisted of 3 trees. Treatments consisting of biochar, compost, biochar + compost and an untreated control were applied to the plots 1 week after grubbing of old trees. Manure was applied at 10 Mg ha⁻¹ (fresh weight) as a top dressing 1 week after planting.

The biochar consisted of Acacia whole tree green waste which had undergone pyrolysis in a continuous flow kiln at up to 550 °C for between 30 and 40 min. Each plot received 15 kg biochar, equivalent to 5 kg/tree or 47 Mg/ha. The biochar was incorporated into the surface 10-cm soil layer prior to replanting. The orchard was replanted with 1-year-old nursery stock consisting of 'Fuji (Nagu-Fu 2)' on M26 rootstock with a 'Royal Gala' inter-stem.

Trees were irrigated during the growing season at a rate of 48 L/h for 3 h/week. The plots received approximately 42.5, 5.98, 131.1 and 12 kg/ha year of N, P, K and Ca fertiliser input, respectively.

Tree growth, crop yield efficiency and fruit quality were assessed to investigate the effects of biochar, compost and combined biochar + compost treatments on the orchard's productivity over a four-year period. In the fourth year, stem girth was 15% and 9% higher than control in the biochar + compost and biochar groups, respectively. Compost alone had no effect on trunk growth.

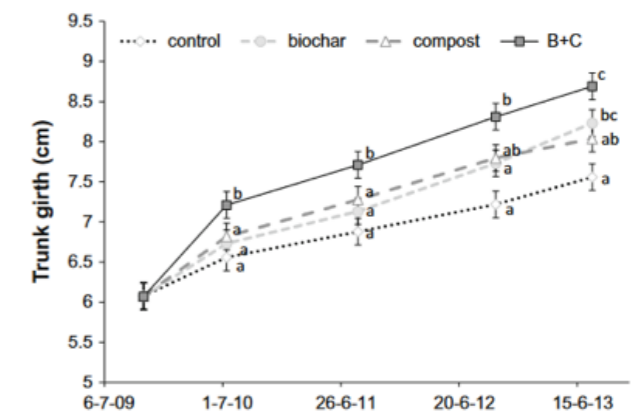


Figure 1 from Eyles et al. 2015: Effect of soil treatments on trunk girth of apple trees.

None of the soil treatments affected total leaf area, yield efficiency, average fruit weight, total soluble solids, fruit firmness, background colour, red blush intensity, percentage blush coverage, starch pattern index, percentage dry matter content or fruit L/D ratio. Similarly, tree water use, photosynthetic capacity and leaf micro-nutrient content were unaffected by the treatments.

	No. of fruit cm ⁻² TCSA		Yield efficiency (kg cm ⁻² TCSA)		Average fruit weight (g)	
	2012	2013	2012	2013	2012	2013
Control	8.69 (1.05)	7.10 (0.53)	1.46 (0.19)	1.11 (0.10)	168.0 (2.4)	196.1 (2.4)
Biochar	9.88 (1.47)	8.13 (1.01)	1.82 (0.22)	1.06 (0.04)	189.9 (3.7)	202.0 (3.0)
Compost	8.45 (0.94)	6.89 (0.78)	1.54 (0.23)	1.05 (0.10)	178.6 (2.5)	211.1 (2.8)
B + C	7.37 (0.73)	6.72 (0.49)	1.35 (0.10)	1.04 (0.10)	186.1 (3.0)	211.4 (2.9)
2-way ANOVA						
Biochar						
<i>F</i> _{1,12}	0.00	0.31	0.20	0.16	2.0	0.20
<i>P</i>	0.96	0.59	0.66	0.70	0.18	0.67
Compost						
<i>F</i> _{1,12}	1.54	1.08	1.04	0.19	0.00	3.04
<i>P</i>	0.23	0.32	0.33	0.67	0.74	0.11
B × C						
<i>F</i> _{1,12}	1.04	0.59	1.93	0.06	0.48	0.16
<i>P</i>	0.33	0.46	0.19	0.81	0.50	0.70

Significance of treatment effects for biochar, compost and their interaction (B × C) are shown by the *F* and *P* values. Standard errors are shown in parentheses. *n* = 5
TCSA trunk cross-sectional area

Table 1 from Eyles et al. 2015: Effect soil treatments on crop load, yield efficiency and fruit weight of apple trees.

This study showed that biochar soil amendments in combination with compost in replant orchards may be beneficial in terms of maximising early growth to optimise light interception. However, the increase in trunk girth of trees in the biochar treatment could not be explained by changes in leaf area, leaf-level photosynthetic capacity nor were they related to foliar nutrients. The positive effect of biochar alone on trunk girth was only evident in the last year of the trial suggesting that the impact of carbon-based soil amendments may require a longer timescale for study.

Overall, biochar had a limited influence on tree physiological processes. The general lack of differences between treatments highlights the challenges of elucidating the possible mechanisms underlying biochar-induced plant responses, particularly in intensive high-input production systems.

The key message from this research is therefore that the potential benefits of biochar as a soil amendment may not be realised in high-input perennial horticultural systems such as apple orchards.



Case Study 2: Influence of Biochar on Soil Nutrients and Associated Rhizobacterial Communities of Mountainous Apple Trees in Northern Loess Plateau China (Ahmad et al. 2022)

The article investigated the effects of biochar on soil health, especially soil nutrients and microorganisms, in soil taken from mountainous apple orchards in China.

Loess soil was taken from an apple orchard located in the northern section of the Loess plateau in Shaanxi Province, China. The soil was classified as silt loam.

For the experiment, the collected soil was transferred to plastic pots with top and bottom diameters of 30 cm and 20 cm, respectively, with a height of 30 cm. Each pot received 15 kg of soil. A basal dose of 650 kg hm⁻² urea, 120 kg hm⁻² calcium superphosphate and 310 kg hm⁻² potassium sulfate were applied to all treatments. Two-year-old dwarf apple trees of similar height were planted in the pots. The pots were kept outdoors and were watered with tap water as required.

Biochar was produced from clipped apple branches at a pyrolysis temperature of 550 °C. For the experiment, the biochar was ground and then sieved through a 2 mm sieve. The experiment consisted of six treatment groups with different application rates of biochar: Control (0), T1 (2), T2 (4), T3 (6), T4 (8), and T5 (10) Mg hm⁻². There were three replicates for each treatment group. All chemical fertilisers and biochar were thoroughly mixed in 0–20 cm of soil depth. Soil samples for chemical and microbiological analyses were collected from the plant rhizosphere after 3, 6, 9, and 12 months.

Biochar application altered the physiochemical properties and enzymatic activities of the soil at all experimental timepoints. Compared to the control, the highest biochar application rate (T5) increased soil pH, organic matter and total nitrogen as well as the enzymatic activity of urease, alkaline phosphatase, catalase and sucrase. These variables were also changed in the T3 and T4 experimental groups with intermediate biochar application rates, albeit to a lesser extent than in T5. In contrast, there were no changes in the T1 and T2 groups with the lowest biochar application rates.

The presence of biochar in soil was also associated with changes in the soil microbiome. However, there was no uniform trend across treatment groups, with T1 and T2 displaying greater changes compared to control than T4 and T5.

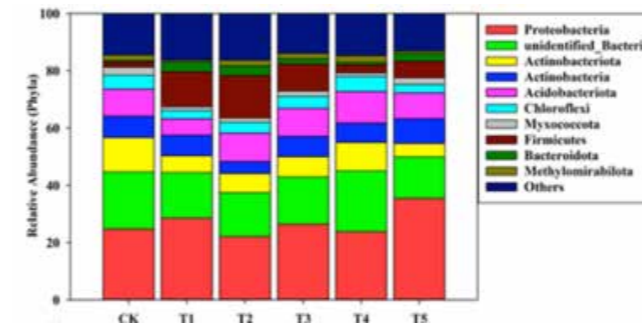


Figure 2B from Ahmad et al. 2022: Effect of biochar treatment on relative abundance of major bacterial phyla.

Bacterial diversity as measured by the Shannon index was reduced in all biochar treatment groups when compared to control. Again, there was no systematic variation in the effect size across treatment groups with increasing application rates of biochar.

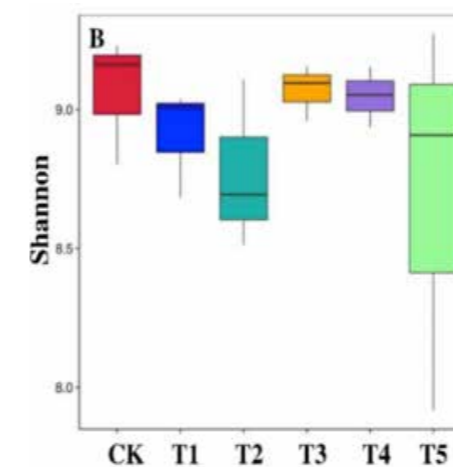


Figure 4B from Ahmad et al. 2022: Effect of biochar treatment on bacterial alpha diversity as measured by Shannon index.

Overall, the results of this study show that applying biochar at 10 Mg hm⁻² (T5) along with chemical fertilisers increases soil nutrients and alters the soil microbiome. The authors conclude that biochar may be beneficial to soil health. The study did not attempt to assess the effect of biochar on the physiology, growth or productivity of the apple trees.

Case Study 3: Biochar promotes soil organic carbon sequestration and reduces net global warming potential in apple orchard: A two-year study in the Loess Plateau of China (Han et al.)

The final case study we are looking at focuses on the Loess Plateau area in China - their primary apple-growing area. The orchard is a significant source of greenhouse gas emissions due to high nitrogen fertiliser input. Thus, a two-year field study was carried out to investigate the effects of apple wood-derived biochar on greenhouse gas emissions during apple orchard production, including soil organic carbon sequestration and net global warming potential assessments.

The field experiment was conducted in Wangdonggou Catchment, Changwu Country, Shaanxi Province, China, at the Changwu State Key Agri-Ecological Station, Loess Plateau (1200 m above sea level). According to the Chinese Soil Classification System, the soil type was dark loessial, which is porous and uniform. The parent material of the soil is Loess of Malan and the soil texture is silt loam (11.8% clay, 72.2% silt, 16.0% sand). At Yixin Bio-energy Technology Company in Shaanxi, China, biochar was made from apple branches at a pyrolysis temperature of 550 °C.

The experiment was conducted in an apple orchard with uniform planting density and similar tree growth. Fuji (*Malus pumila* Mill) apple trees were planted at a rate of 1500 trees per hectare in 2002. The experiment was replicated three times and included four treatments: (1) chemical fertiliser with 20 t ha⁻¹ biochar (FB), (2) only 20 t ha⁻¹ biochar (B), (3) only chemical fertiliser (F), and (4) no fertiliser and biochar as a control (CK). Every treatment included 3 trees and the single plot area was about 6.6 m².

Throughout the experiment, no irrigation was used, and water was replenished solely through rainfall. In the apple orchard, fertiliser was applied by digging ditches (20 cm deep and 20 cm wide) at a distance of 1 m from the tree row, then backfilling the soil into the ditch. The FB and F treatments had sampling chambers on one side of the fertilised ditch, while B and CK treatments had sampling chambers in the centre of the two fertilised ditches, 1 m away from the two fruit trees. Weeds were killed by using locally produced herbicides, and pesticides and fungicides were used as needed to keep pests and diseases at bay.

The CH₄, CO₂ and N₂O emissions were measured between 9:00–11:00 a.m. every other week using static chamber-gas chromatographic techniques. GHGs emission was measured every other day for 7–10 days starting on the first day after fertilisation. The gas sampling equipment consists of an insulated opaque box (25 cm × 25 cm × 50 cm) with a small electric fan and a stainless-steel base (25 cm × 25 cm × 10 cm) with a groove of 3 cm wide and 3 cm high.

The cumulative CH₄ emissions for the first year were shown to be positive, however, the trend was just the opposite in the second year, with the cumulative emission of CH₄ being characterised by absorption. The average annual cumulative CH₄ emissions for the FB and B were shown to be positive, while those of F and CK were negative. However there was no significant difference between the four treatments. Moreover, there was no significant correlation between CH₄ flux and environmental factors during the observation period.

When biochar was added alone, there was no significant change in cumulative emissions relative to CK for two years. However, when biochar and fertiliser were used together, annual cumulative CO₂ emissions increased by 5.9%–38.6% compared to CK. Biochar and fertiliser all significantly affect CO₂ emissions, but it was not affected by the interaction between fertiliser and biochar.

During this study, CO₂ emissions increased significantly when biochar was applied in combination with nitrogen fertiliser. In this study, biochar did not reduce N₂O emissions. In

this study, the soil organic carbon sequestration increased significantly after biochar was applied at a rate of 20 t ha⁻¹ to the apple orchard while there was no significant difference between B and FB treatments.

The result of the experiment was that apple wood-derived biochar increased cumulative emissions of CO₂ emissions when used with chemical fertiliser for a short period, as expected in line with the added carbon from the Biochar. This CO₂ amounted to only a tiny portion of the carbon from the Biochar. The biochar reduced net global warming potential through a strong carbon sequestration effect. Therefore, it is concluded that in the local apple orchard, using apple wood-biochar helped to sequester carbon in the soil, mitigate climate change and maintain the soil nutrient level of the apple orchard.

Comparative Analysis

The three case studies presented here investigated different aspects of the effect of biochar on perennial horticultural systems, more specifically apple orchards. Case study 1 assessed the impact of biochar on tree growth, physiology and productivity, and detected increased tree girth but no change in any of the other variables. Case study 2 showed that biochar can increase soil nutrients and enzymatic activity, and provided evidence for changes in the composition of the soil microbiome in the presence of biochar. Case study 3 discussed the potential of reducing net-global warming potential through the use of biochar.

Overall biochar seemed to have a positive effect on some of the variables investigated across the studies, but many others seemed to be unaffected. No significant negative impacts were detected in any of the studies, nor were any specific risks of biochar use discussed. In many of the systems in which biochar's impact is applied in and measured from, there are many complex factors involved, which may make it difficult to accurately measure the levels of beneficial impact, perhaps until further large-scale testing is available.

Case study strengths and weaknesses

Case study 1 was well written and presented, with a clear scientific rationale and sound methods for data collection and analysis. The study took place in a commercial apple orchard, making it relevant to real-world agricultural businesses. Data were collected over a timespan of four years, thereby giving biochar an appropriate amount of time to exert its effects. All in all this appeared to be a high-quality study whose key message – that the potential benefits of biochar soil amendment may not be realised in high-input perennial horticultural systems such as apple orchards – should be of interest to anyone in the fruit growing business.

Unfortunately, there was a number of concerns with regard to case study 2. This included the use of language that was obtuse in places as well as glaring errors in data reporting (e.g., giving percent values for changes in pH) and poorly documented statistical methods. Furthermore, the study assessed potted apples trees rather than an actual orchard, and only collected data for one year. Taken together these concerns were sufficient to call into question the validity of the data and conclusions presented as well as the relevance of the article to real-world situations even if all data reported were correct. While assessing the effect of biochar on soil nutrients and microbes is useful in principle, the experiments in this study should be repeated using sound scientific methods and in a real orchard in order to make them valid and relevant to fruit growers.

Case study 3 set out to better understand the increase in CO₂ release after the addition of biochar to soils. This study followed up on other studies, which had reported that CO₂ release results from the breakdown of biochar microorganisms and chemically, and only accounts for a small proportion of the carbon introduced into the soil by the biochar. This study was able to confirm that the long-term storage of carbon is sufficient to outweigh the increase in short-term release of carbon dioxide, thus leading to a long-term reduction in the net global warming potential.

Conclusion

Across the three case studies, evidence was presented for an effect of biochar on soil nutrients, soil microorganisms and global warming potential in apple orchards. However, in terms of tree growth, physiology and productivity, only trunk girth was affected, with other physiological parameters and productivity of the trees the same as in control.

Previous studies of biochar effects in cereal and annual crops have yielded contrary results. There are many factors that influence the impact of biochar on agricultural systems, including depth and method of biochar incorporation, difference in biochar properties, whether biochar is used alone or with a fertiliser, soil type and quality, crop type, and local climate. It remains difficult to predict how biochar-induced improvements in soil nutrient status affect the productivity of agricultural or horticultural systems.

The most relevant conclusion from the different case studies is probably that the message from case study 1 that the potential benefits of biochar as a soil amendment may not be realised in high-input perennial horticultural systems such as apple orchards. Nevertheless, as suggested by case studies 2 and 3, biochar might have beneficial effects on soil properties and global warming potential of such systems. Biochar can also sequester carbon and support waste management through recycling of end-of-life orchard waste.

Further research will be required to determine the effect of biochar on different variables of interest in apple orchards in various geographical locations, local climates, and soil types.

References

- [1] Ahmad, R., Gao, J., Gao, Z., Khan, A., Ali, I., & Fahad, S. (2022). Influence of biochar on soil nutrients and associated Rhizobacterial communities of mountainous apple trees in northern loess plateau China. *Microorganisms*, 10(10), 2078.
- [2] Eyles, A., Bound, S. A., Oliver, G., Corkrey, R., Hardie, M., Green, S., & Close, D. C. (2015). Impact of biochar amendment on the growth, physiology and fruit of a young commercial apple orchard. *Trees*, 29, 1817–1826.
- [3] Han, J., Zhang, A., Kang, Y., Han, J., Yang, B., Hussain, Q., Wang, X., Zhang, M. & Khan, M.A. (2022). Biochar promotes soil organic carbon sequestration and reduces net global warming potential in apple orchard: A two-year study in the Loess Plateau of China. *Science of The Total Environment*, 803, 150035.

9.6 Literature Review on Biochar Production from Woody Biomass

Author – Dr David Vaughan - Carbogenics

Methodology

Carbogenics conducted a search of the scientific literature as well as any other relevant online sources. This was then collated into specific subject areas. Including:

Biochar production from woody materials Includes:

- Sources of feedstock
- Advantages and disadvantages of woody feedstocks
- Physical and chemical properties of biochar

Environmental impacts of biochar application include:

- Effects on soil structure
- Effects on soil microbiome
- Effects on water absorption in soils
- Effects on nutrient availability
- Effects on pests and diseases

Practical parameters for application:

- Dosage
- Application methods
- Influence on crop growth parameters



Introduction

Biochar as an industry is relatively new but charcoal and charcoal-like materials have been used for thousands of years in many different capacities. The current interest in biochar is derived from its ability to lock up carbon and, when applied to the soil, become an effective carbon sink. This is vital in the context of global warming and the drive towards net zero emissions. The desire for the agricultural sector to look at the by-products and waste materials from their activities, with a view to decarbonisation, is a key element in achieving these goals.

Currently, the dessert fruit industry occupies 5400 hectares of farmland of which 5% is grubbed out annually. This generates approximately 3500 tonnes of dry feedstock per annum, which is predominantly woody waste and can be disposed of via composting or burning. As well as generating greenhouse gas emissions it is also wasting a valuable resource.

One outlet for this waste would be the production of biochar. The European production capacity for biochar was 53,000 tonnes in 2022 and is expected to be 90,000 tonnes by the end of 2023 [1] and the industry will be increasing over the coming years. Of this capacity, the bulk of the biochar is derived from woody materials. This means that wastes from orchards would be ideal for biochar production. The markets for biochar are expanding but currently, the major use for biochar is land application for reclamation and soil improvement.

This review will look at the feasibility of producing biochar from woody materials as well as the benefits that could be accrued by adding biochar to the orchard soil. We will look at the characteristics of the biochar that would be derived from this material as well as potential effects on the soil and crop growth. Where possible the review will include apple and pear-derived chars but will look at other woody materials when this example is not available.

Biochar Production from Woody Materials

Sources of Feedstock

The pyrolysis process is amenable to many feedstocks, the limiting factors will be moisture content and availability of sufficient quantities to maintain a continuous process. For the pyrolysis process to be efficient the feedstock should not be too wet more than 70% dry matter is best to sustain efficient combustion. The quantity of biochar produced from any given feedstock will be much reduced compared to the input volume, for example from straw feedstocks we can expect to get one tonne of biochar for every 4-5 tonnes of feedstock. This means that a 400-tonne/annum site will require roughly 2000 tonnes of feedstock [2] (Carbogenics). In addition, a feedstock that can be maintained at a consistent particle size will produce a much more consistent char.

The most popular source of feedstock has traditionally been woody materials; however, manures and sewage sludges, municipal wastes and plastics are also amenable to the process.

Some examples of different feedstocks and the resultant biochar are shown below.



Images taken from the UK Biochar Research Centre [3]

Advantages of Woody Material

The cellulose, hemicellulose and lignin content of the feedstock, coupled with the production parameters can have an effect on the physiochemical properties of the resultant biochar. Woody materials make excellent sources of biomass due to their relative simplicity and abundance of these components. Non-lignocellulosic materials including sewage sludge and animal wastes can be problematic due to high levels of heavy metals and other contaminants and could be more harmful to soils than lignocellulosic materials. Pyrolysis of woody materials such as olive husks and date pits results in a coarse biochar with a carbon content of 80%. Biochar from woody materials with a high lignin content can have a higher carbon amount than herbaceous materials but reduced nitrogen. High yields have been reported for switchgrass, poultry litter and sewage sludge whereas sorghum oil palm and peanut waste produce comparatively lower yields but with a higher carbon and nitrogen content and greater porosity further indicating the variability in biochar obtained from different feedstocks [4].

Physical and Chemical Properties of Biochar from Woody Wastes

Various different parameters of the biochar can affect the way in which they behave in the soil. These fall into physical and chemical properties [5].

Physical Properties:

Porosity varies depending on the material used and production method and is either micropores or macropores. The distribution of these pores may determine the ability of the biochar to adsorb materials,

Specific surface area gives an active area for reacting with species targeted or colonisation by microbes. Some of the chemical properties such as cation exchange capacity and water holding capacity will be related to the surface area.

The bulk density of the biochar is generally lower than that of soil due to the pores formed in the material this means that when mixed with soils biochar generally lowers the bulk density of the mix.

Water holding capacity of the biochar is a function of the pores and the hydrophobicity of the surface. The hydrophobicity of the surface is increased with increased pyrolysis temperature up to a point and then drops off again [2]. A balance of the hydrophobicity and pore structure will determine the water-holding capacity.

Grindability of biochar is due to its mechanical stability which is generally more delicate than the starting material. The ability to break down under mechanical stress could have implications in soils if the particles are too fine and fill soil voids.

Chemical properties:

These parameters are expressed in terms of such things as elemental analysis, pH and cation exchange capacity.

The **elemental analysis** will show a higher carbon content than the raw biomass with high-temperature biochars having carbon contents of up to 95% and those produced at around 600OC having carbon contents of over 70%. Heavy metal composition is an important factor for biochar production, but these are not an issue for biochar generated from woody materials. The ratios of hydrogen to carbon and oxygen to carbon are also altered by temperature and drop as the temperature increases.

pH is increased with increased pyrolysis temperature and pH is a property which could be of interest in agricultural applications. Functional groups on the surface of the biochar allow the char to adsorb potentially harmful materials. These functional groups are reduced with increased pyrolysis temperature. Similarly with increased pH the acidic functional groups are decreased.

Cation exchange capacity is the measure of a biochar's ability to interact with positively charged ions such as calcium, magnesium, sodium and potassium and can have an influence on soil structure, nutrient availability and pH [6]. Biochar's produced at lower temperatures have a higher cation exchange capacity [7].

Environmental Impacts of Biochar

Effect on Microbiology

Soil microbiology is an important factor for plant health and growth as well as being important for soils health. While biochar has been considered a good material for soil application, land remediation investigations into the effect on soil microbiology have been limited, especially at field scale.

These studies are hampered by the long-term nature of the biochar and soil interaction and also by the complexity of the soil microbiome which will itself be a function of the soil type and land management. The soil contains organisms such as bacteria, fungi, nematodes, algae, archaea, actinomycetes, bacteriophages and protozoa [8]. These are involved in nutrient recycling, organic matter decomposition, soil structure formation and degradation of organic contaminants.

The aspects of biochar which affect the soil microbiota are the physical parameters such as pore size and surface. The pores could simply be a mechanism of providing a growth habitat for bacteria and fungi as well as providing protection from predators such as mites and nematodes. In addition, the potential for increased water-holding capacity in some soil types may have an improved effect on some microbial activity.

If enough biochar is added to the soil this will increase the pH. Xu et al [9] noted that the addition of corn straw biochar increased the soil pH and electrical conductivity as well as decreased nitrogen leaching, as a result, changes were observed in the bacterial community composition. However, Luo et al [10] noted that the addition of maize straw biochar did not increase soil pH but this may be due to the addition rate being too low.

The activity of some enzymes, both extracellular and intracellular has been observed to change. Biochar increased the levels of beta-glucosidase, B-D-cellobiase, B-xylosidase, a-glucosidase and sulfatase, involved in soil Carbon and Sulphur cycling [11]. There is some inconsistency which is dependent on the rate of biochar addition.

For example, a low rate (0.5% w/w) of maize biochar application elevated the enzyme activity whereas applications above 1% w/w decreased enzyme activity [11]. In addition, some enzymes may only be altered by specific biochar's, Demisie et al [12] found that dehydrogenase activity in red soil was elevated with both oak and bamboo biochar whereas b-glucosidase activity was only increased by the application of bamboo biochar.

Biochar production temperature can influence the microbial community with Luo et al [13] noting that Gram-positive bacteria used the biochar carbon when produced at 350OC but not when produced at 700OC. Wang et al [11] showed a reduction in the relative abundances of bacteria and fungi with increasing quantities of biochar added, this is likely due to the increased pH of the soil which may inhibit soil microbiology.

Further work is needed on this aspect and given that much of the current research is laboratory-based, long-term field studies are required. However, this further goes to highlight the variability in response of adding biochar to soils.

Water Retention

The ability of biochar to enhance water retention within a soil is a matter of debate and in fact, it may be that reduced water retention is a desired characteristic. The latter would have more to do with the ability of water to affect the soils physical properties by providing a more aggregated and aerated structure, but this would only be relevant in certain soil types.

A number of studies have been conducted on soil water content in the presence of biochar. Gaining a consensus is difficult due to the different soil types used, different biochar feedstocks, production parameters and application rates.

Table 1 Pyrolysis of different types of feedstocks and physicochemical properties of biochar samples from manufacturers.

Biomass	Temp °C	Total Carbon %	Yield %	Ash %	CEC (cmol kg-1)	Surface area m2g-1	pH
Wheat straw	500	62.9	29.8	18	95.5	33.2	10.2
Grass	500	62.1	27.8	20.8	84.0	3.33	10.2
Sawdust	500	75.8	28.3	9.94	41.4	203	10.5
Peanut shell	500	73.7	32	10.6	44.5	43.5	10.5
Wastewater sludge	500	26.6	45.9	61.9	168	71.6	8.82
Waterweeds	500	25.6	58.4	63.5	509	3.78	10.3
Cow manure	500	43.7	57.2	67.5	149	21.9	10.2

Cation exchange capacity (CEC). The tabular data were adapted from Ghodake et al [6]

A systematic review was conducted by Razzaghi et al [14] looking at several different parameters including the field capacity of the soil, the wilting point and the plant's available water content. In addition, soil types were grouped into coarse textured (loamy sand and sandy soil), medium textures (loam, sandy loam, silt loam, sandy clay and sandy clay loam) and fine textured (clay, clay loam and silty clay, silt and silty clay loam) Fig 1 shows the number of experiments conducted on each soil type. This shows that the bulk of the trials, 47%, were on the medium-textured group with 32% on the coarse-textured group and 21% on the fine-textured soils. The results of this analysis show that field capacity and wilting point increased significantly (51% and 47% respectively) for coarse textured soils, in medium soils the increased for field capacity and wilting point increased marginally (13% and 9% respectively) and for fine soils the field capacity was unchanged, and the wilting point decreased by 5%. **Available water was reported to have increased in all soils with values of 45%, 21% and 14% for coarse, medium and fine soils. This suggests that biochar would have a greater benefit on course soils.**

While having an overview of the available literature is useful prevailing conditions will always determine the benefits of biochar additions and care needs to be taken with generalisations. Phillips et al [15] looked at agricultural soils in Oregon with the specific aim of looking at the effect of biochar on drought tolerance. **The results showed that there was no benefit for drought adaptation through biochar as the large pores which develop between the biochar and soil particles resulted in an increased saturated water content but observed no increase in water content at field capacity.** Decreases in volumetric water content of 0.09 to 0.8% were observed at wilting point which translates to small increases in plant-available water capacity. The study also observed that water loss after irrigation could be quicker in biochar-amended soils. In this situation, the type of biochar used, wheat straw and conifer wood made no difference to the outcome suggesting it is the physical characteristics that are most prevalent in the interaction.

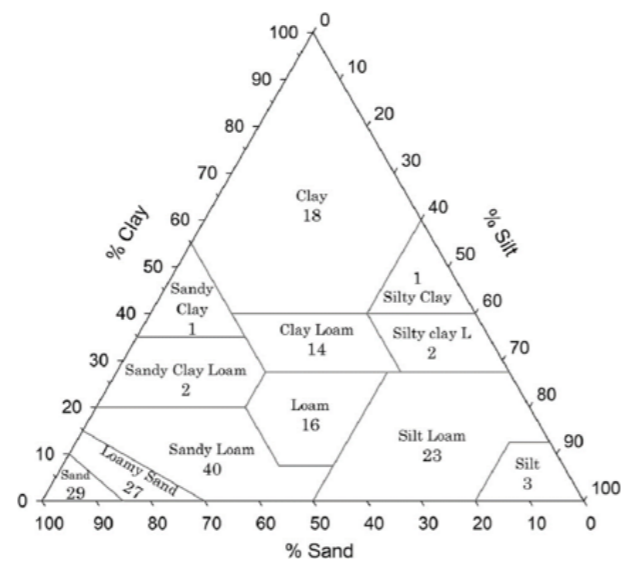


Figure 1. Breakdown of the different soil types analysed and the number of trials conducted on each. Razzaghi et al [14]

Soil Structure

Biochar additions are generally considered to be a mechanism of soil carbon sequestration but there are additional benefits that can be accrued from the application of biochar to the soil. One of these additional benefits is that of soil structure. Soil structure is of vital importance for crop production and plant health, it helps regulate soil water content, temperature and aeration, in addition, it can have positive effects on plant root growth and soils microbiology.

As with all aspects of biochar addition to the soils the level of the benefit attained will be dependent on a number of factors. These factors will include the current soils condition for example moisture, composition of sand, silt and clay as well as any other additions such as manure or chemical fertilizer.

The starting material for the biochar will also have an effect on how it performs in the soils as well as the production parameters. Woody feedstocks will inherently produce a biochar with a larger surface area than biochar's from manures or digestates and will, therefore provide a better material for colonisation by microbes and retention of nutrients as well as increasing overall soil organic carbon.

Various studies have shown differences in the ability of biochar to affect soil structure and it is these differences depending on the feedstock of the biochar, the production parameters for the biochar and the environment that the biochar is being added to which need careful consideration when applying biochar to the soil. For example, one study [16] found that wheat straw biochar significantly increased water-stable aggregate formation in Chinese soil whereas Peng et al [17] showed that rice straw did not have any effect on subtropical red clay. Wang et al [18] conducted experiments on fine and coarse Californian soils and found that aggregation of the soil particles was significantly increased by biochar additions in the fine soil but showed no effect in course soils.

Nutrient Retention

The story for nutrient retention in soils is similar for many aspects of the process of adding biochar to soils in that it depends on a number of factors. These include the biochar feedstock, temperature of production, application quantity soil texture, pH, nutrient species being studied also the biochar water repellence and age.

For example, laboratory studies have shown that different biochar's are able to adsorb ammonia [19], nitrate [20] and phosphate from aqueous solutions [21]. In field studies biochar's from corn were shown not to adsorb nitrates whereas biochar from oak was able to absorb nitrates for a short period [22]. Uzoma et al [23] reported that biochar's produced at 300OC and 400OC retained significantly more nitrate than biochar's produced at 500OC. Angst et al [24] reported that hardwood biochar significantly reduced nitrogen leaching from soils but significantly increased the leaching of phosphate.

Hardie et al [25] conducted a study on the effect of biochar on nutrient leaching in a young apple orchard. This work was conducted using biochar derived from Acacia wood before replanting of *Malus domestica* orchard. This study noted that the volume of leachate collected was higher in the biochar-treated soils. The concentration of nitrate and potassium in the leachate was not affected, however there was a significant increase in phosphorous concentration.

This study also noted that the trees were fertilized with a mix of an N-P-K (7-3-22) fertilizer and chicken manure and that the nutrient application and irrigation were in excess of the tree requirements and storage capacity of the soils. This study highlights the variable nature of the results obtained from biochar applications. **In addition, it would point towards a careful assessment of management practices when applying materials such as biochar to the soils as increased leaching of nutrients is not only wasteful it could have subsequent environmental impacts.**

Effect on Pests and Diseases

Given the potential positive effects biochar can have on soils some studies have been conducted into the effect it may have on plant pests and diseases. While many studies have found positive effects there can still be some negative effects too which may be as a function of the biochar feedstock material and the dosing. For example, biochar from poultry manure has a high phosphorous content and can have a negative effect on the root colonization of mycorrhizal fungi [26] although in this study crop productivity was not affected. Biochar from rice straw showed a damaging effect on a model organism *Caenorhabditis* (nematode) due to a neurotoxic effect [27].

Of particular interest to this review is a potential effect on apple replant disease. Wang et al [28] conducted experiments on apple seedlings using soil taken from an established Chinese orchard and looked at microbial communities. Soils with biochar showed a reduced prevalence of pathogenic fungi *fusarium* spp which led to increased seedling growth and resistance to replant disease in these soils.

Conversely, a study by Eyles et al [29] looked at the ability to improve soil fertility and subsequently affect the ability of the trees to overcome replant disease with the addition of a biochar-compost mix. They found that they did not see any reduction in the appearance of the apple replant disease symptoms. The rationale was that as biochar is thought to improve soil fertility on already fertile soils the benefits of biochar are not seen. However, in this study, there was no direct measurement of potentially pathogenic fungal species.

Lacomino et al [30] conducted a review of trials on the use of biochar and its effect on above-ground and below-ground plant pathogens. The review concluded that the most common biochars in successful studies were from woody wastes. The pathogen species studied were far from exhaustive with *Fusarium oxysporum* f. sp. *radices lycopersici* being the most studied fungi and *Ralstonia solanacearum* for bacteria. Suppression efficiencies were 86% for fungi and 96% for bacteria.

Practical parameters for application

Dosage

This aspect of biochar usage has been highly variable throughout the studies conducted and a consensus is difficult to reach. This is then further compounded by whether the application is at a field scale or planting pits as in the case of orchards. On top of this soils type may play a role and as we have seen some studies have shown that the excess application can hamper some of the benefits of biochar applications.

Some efforts have been made to determine optimum application rates, for example, Yi Li et al [31] recommends an optimum application rate of 10 tonnes/hectare for sugar beet. For fruit trees, an application rate of 20% (v/v) for peach trees [32] showed improvement and applications of 2.3-3.6 kg per plant have had beneficial effects on Chinese mandarin plants [33].

Pacific Biochar [34] offers an attempt at a biochar calculator and Soilfixer.co.uk [35] advises on application rates for some applications. However, some specificity will need to be taken into account for each application and this is likely to be trial and error.

<https://pacificbiochar.com/biochar-application-rate-calculator>

Application Methods

There are no specific guidelines for application methods. Biochar is a granular material which will not be readily amenable to be applied in liquid applications. However, due to the dusty nature of the biochar, any method which can reduce clouds of dust will be useful. Mixing with other materials such as manures and composts prior to application will aid in this, however maintaining even application may be difficult. The biochar needs to be worked into the soil rather than being left on the surface. With planting pits for trees, the char can be applied directly to the area around the roots. Interrow applications will again require some method of incorporation.



Effects on Orchard Growth

Several studies have been conducted on fruit trees to look at growth and improvement in crops following the application of biochar with variable results.

Applications of biochars made from orchard wastes in China [33] showed an improvement in fruit yield and quality in mandarins. The study also showed an increase in leaf nutrient concentration and a change in soil microbial profile. Similarly work on peach trees [32] in Colorado showed an increase in above and below-ground biomass production with biochar application compared to controls, an increase in root carbon and soil nitrate levels and improved foliar magnesium concentrations were also observed this work was specifically looking at resistance to peach replant disease and crop yield was not measured.

Work on apple orchards with the application of 5kg per tree in Australian newly planted apple orchard [29] showed no improvement in crop yield but did see an increase in trunk girth with biochar and 'biochar+compost' additions. Other aspects such as water use, and leaf nutrient concentration were also unaffected.

A four-year field study of a replanted apple orchard in Iran [36] concluded that the addition (application rate of 10 t/ha) of biochar showed an improvement in soil quality and an increase in the trunk diameter and shoot number by the end of the first year. **However, the overall fruit yield and quality was unaffected.**

These studies show the variability in result depending on the species and soil type. In areas where the soil is of poor quality the benefits of biochar can be observed. **However, in orchards characterised by high nutrient and water inputs the benefits of biochar may be minimal.**

These are just a few trials conducted on different soils with different biochar's and parameters and further study may be necessary to get a true impact of biochar application and accumulation on UK soils.

Conclusions

The conclusion from this literature review is that biochar, although a relatively new industry, has the potential to have a large impact on soil health. However, there are a number of caveats to the potential benefits.

Firstly, the scale of the benefits will be determined by the effect that is required, for example if the aim is to increase crop production the benefit will be limited however crop quality can be improved.

Secondly, the benefit will be determined by the prevailing conditions. On a good soil with adequate nutrient content, it is likely that the benefits will be marginal if observed at all. If, on the other hand, the soils are nutrient poor the improvements gained for adding biochar may be significant.

Finally, other aspects such as soil water retention and pest and disease control have been shown to be variable depending on the soil type and pest and diseases targeted as well as the crop being studied. This all goes to show that the benefits of using biochar in soils can have many factors affecting the outcomes these also include the type of feedstock the char is derived from, and the parameters used in its production.

In addition, because this is a young industry and the benefits are likely to accrue over time rather than be instant, there is a lack of long-term trials to draw relevant information from. This all points towards further research needed into specific crops and situations such as apple and pear orchards.

References

- [1] European Biochar Industry Consortium (2023). European biochar market report 2022-2023. <https://www.biochar-industry.com>
- [2] Gajanan Sampatrao Ghodake, Surendra Krushna Shinde, Avinash Ashok Kadam, Rijuta Ganesh Saratale, Ganesh Dattatraya Saratale, Manu Kumar, Ramasubba Reddy Palem, Hind A. AL-Shwaiman, Abdallah M. Elgorban, Asad Syed, Dae-Young Kim (2021). Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. *Journal of Cleaner Production*, 297.
- [3] UK Biochar Research Centre. <https://www.biochar.ac.uk/index.php>
- [4] Aisha Al-Rumaihi, Muhammad Shahbaz, Gordon McKay, Hamish Mackey, Tareq Al-Ansari (2022). A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. *Renewable and Sustainable Energy Reviews* 167
- [5] Shubh Pravat Singh Yadav, Sujan Bhandari, Dibya Bhatta, Anju Poudel, Susmita Bhattarai, Puja Yadav, Netra Ghimire, Prava Paudel, Pragya Paudel, Jiban Shrestha, Biplov Oli. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, 11
- [6] Hazelton, P. and Murphy, B (2007). *Interpreting Soil Test Results: What do all the numbers mean?* 2nd ed. CSIRO Publishing.
- [7] Yu H, Zou W, Chen J et al (2019) Biochar amendment improves crop production in problem soils: a review. *J Environ Manag* 232:8–21.
- [8] Paul EA (2014) *Soil microbiology, ecology and biochemistry*. Academic Press, New York
- [9] Xu N, Tan G, Wang H, Gai X (2016) Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *Eur J Soil Biol* 74:1–8
- [10] Luo S, Wang S, Tian L, Li S, Li X, Shen Y, Tian C (2017) Long term biochar application influences soil microbial community and its potential roles in semiarid farmland. *Appl Soil Ecol* 117:10–15
- [11] Wang X, Song D, Liang G, Zhang Q, Ai C, Zhou W (2015) Maize biochar addition rate influences soil enzyme activity and microbial community composition in a fluvo-aquic soil. *Appl Soil Ecol* 96:265–272
- [12] Demisie W, Liu Z, Zhang M (2014) Effect of biochar on carbon fractions and enzyme activity of red soil. *CATENA* 121:214–221
- [13] Luo Y, Dungait JA, Zhao X, Brookes PC, Durenkamp M, Li G, Lin Q (2018) Pyrolysis temperature during biochar production alters its subsequent utilization by microorganisms in an acid arable soil. *Land Degrad Dev* 29:2183–2188
- [14] Fatemeh Razzaghia, Peter Bilson Obourb, Emmanuel Arthur (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* 361
- [15] Claire L. Phillips, Sarah E. Light, Hero T. Gollany, Stephanie Chiu, Thomas Wanzek, Kylie Meyer, Kristin M. Trippe, (2020) Can biochar conserve water in Oregon agricultural soils? *Soil and Tillage Research* 198
- [16] Liu, Z., Chen, X., Jing, Y., Li, Q., Zhang, J., Huang, Q., (2014). Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. *Catena* 123, 45–51.
- [17] Peng, X., Ye, L.L., Wang, C.H., Zhou, H., Sun, B., (2011). Temperature- and duration-dependent rice straw-derived biochar: characteristics and its effects on soil properties of an ultisol in southern China. *Soil Tillage Res.* 112 (2), 159–166.
- [18] Daoyuan Wang, Steven J. Fonte, Sanjai J. Parikh, Johan Six, Kate M. Scow (2017) Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma* 303
- [19] Yao, Y., B. Gao, M. Zhang, M. Inyang, and A.R. Zimmerman. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* 89: 1467–1471.
- [20] Kameyama, K., T. Miyamoto, T. Shiono, and Y. Shinogi. 2012. Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcareous dark red soil. *J. Environ. Qual.* 41:1131–1137.
- [21] Hale, S.E., V. Alling, V. Martinsen, J. Mulder, G.D. Breedveld, and G. Cornelissen. 2013. The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. *Chemosphere* 91:1612–1619.
- [22] Hollister, C.C., J.J. Bisogni, and J. Lehmann. 2013. Ammonium, nitrate, and phosphate sorption to and solute leaching from biochars prepared from corn stover (*Zea mays* L.) and oak wood (*Quercus* spp.). *J. Environ. Qual.* 42:137–144.
- [23] Uzoma, K.C., M. Inoue, H. Andry, A. Zahoor, and E. Nishihara. 2011. Influence of biochar application on sandy soil hydraulic properties and nutrient retention. *J. Food Agric. Environ.* 9:1137–1143.
- [24] Angst, T.E., C.J. Patterson, D.S. Reay, P. Anderson, T.A. Peshkurand, and S.P. Sohi. 2013. Biochar diminishes nitrous oxide and nitrate leaching from diverse nutrient sources. *J. Environ. Qual.* 42:672–682.
- [25] Marcus A. Hardie, Garth Oliver, Brent E. Clothier, Sally A. Bound, Steve A. Green, and Dugald C. Close. (2015) Effect of Biochar on Nutrient Leaching in a Young Apple Orchard. *J. Environ. Qual.* 44: 1273–1282
- [26] Solaiman ZM, Yang H, Archdeacon D, Tippett O, Tibi M, Whiteley AS. 2019. Humus-rich compost increases lettuce growth, nutrient uptake, mycorrhizal colonisation, and soil fertility. *Pedosphere*. 29(2):170–179. doi:10.1016/S1002-0160(19)60794-0.
- [27] Lieke, T., Zhang, X., Steinberg, C. E., & Pan, B. (2018). Overlooked risks of biochars: persistent free radicals trigger neurotoxicity in *Caenorhabditis elegans*. *Environmental science & technology*, 52(14), 7981–7987.
- [28] Yanfang Wang, Zhiting Ma, Xiaowei Wang, Qiran Sun, Haiqiang Dong, Gongshuai Wang, Xuesen Chen, Chengmiao Yin, Zhenhai Han, Zhiquan Mao. (2019) Effects of biochar on the growth of apple seedlings, soil enzyme activities and fungal communities in replant disease soil. *Scientia Horticulturae* 256
- [29] Alieta Eyles, Sally A. Bound, Garth Oliver, Ross Corkrey, Marcus Hardie, Steve Green, Dugald C. Close. (2015) Impact of biochar amendment on the growth, physiology and fruit of a young commercial apple orchard. *Trees*, 29, 1817–1826
- [30] Giuseppina Iacomino, Mohamed Idbella, Stefania Laudonia, Francesco Vinale and Giuliano Bonanomi. (2022) The Suppressing Effects of Biochar on Above- and Belowground Plant Pathogens and Pests: A Review. *Plants*, 11, 3144
- [31] Yi Li, Ning Yao, Jiaping Liang, Xiaofang Wang, Yonglin Jia, Fuchang Jiang, De Li Liu, Wei Hu, Hailong He, Tehseen Javed (2022) Optimum biochar application rate for peak economic benefit of sugar beet in Xinjiang, China. *Agricultural Water Management* 272
- [32] Amaya Atucha and Greg Litus (2015). Effect of Biochar Amendments on Peach Replant Disease. *HortScience* 50(6) 863–868
- [33] Guo YJ, Qiu BL, Khan Z, Jiang H, Ji QH, Fan QZ and Khan MM (2022) The potential for biochar application in “Shatangju” (*Citrus reticulata* cv.) orchard on acid red soil: biochar prepared from its organic waste in an orchard. *Front. Plant Sci.* 13
- [34] <https://pacificbiochar.com> (Accessed: 5 April 2024).
- [35] <https://soilfixer.co.uk> (Accessed: 5 April 2024).
- [36] Mahdi Safaei Khorram, Gan Zhang, Akram Fatemi, Rudolf Kiefer, Kamalodin Maddah, Mujtaba Baqar, Mohamad Pauzi Zakariaf and Gang Lig. (2019) Impact of biochar and compost amendment on soil quality, growth and yield of a replanted apple orchard in a 4-year field study *J Sci Food Agric* 2019; 99: 1862–1869

SECTION 10 - CONCLUSIONS AND RECOMMENDATIONS TO INDUSTRY

British Apples and Pears Ltd believe that the project has been extremely important to explore the possible end of life scenarios for commercial orchard production. Apple and pear orchards are a low emission crop – trees are in the ground for c.20 years, the soil is not turned over every year, just at orchard planting and grubbing. And orchard trees and grass alleyways sequester carbon during their lifetime. The burning of wood at the end of orchard life is the one farm practice that needs to be addressed.

This project, funded by Innovate UK, demonstrates that it is possible to grub the trees, chip and season/dry the wood, shred the rootball, and process this orchard biomass into a biochar product that can significantly lock up and store carbon in our soils for a significant period. It has provided us with the knowledge of what is already being achieved in other areas of Europe and the USA in carbon sequestration and removal. The project has demonstrated that there are already biochar pyrolysis systems available in the marketplace that can be utilised, at costs that are within reason.

This comprehensive report provides a full analysis of pyrolysis kilns, the production and lifecycle carbon assessment of biochar from orchard wood, the economic and financial assessment of biochar production, an overview of the carbon voluntary credits market, the policy landscape for biochar, a lifecycle carbon analysis of British grown Gala apples and a literature review of biochar production from woody biomass.

Exactly how we should utilise biochar on productive fertile soils will be further researched. There is excellent academic evidence that biochar can hugely improve poor unfertile soils (improving water holding capacity and soil condition), however, there is also evidence that biochar can lock up nutrients in fertile soils and the addition of biochar may be counter-productive for commercial orchard growers.

In the future businesses that can make use of the biproduct of heat from pyrolysis kilns in either packhouse heating, cold storage or glasshouses will be able to collaborate to create a centralised regional facility for the creation of biochar from wood chip.

The Life Cycle analysis undertaken by Cranfield University is essential for industry to understand its carbon production. Their work in producing carbon production figures will be essential for our industry going forward. It will be a surprise to some that the highest carbon emission from orchard establishment to supermarket distribution centre, is the packaging that the apples are contained within. This packaging is defined by the retail customer and is currently the focus of much work and effort to find alternatives to the recyclable film.

We recommend:

- When grubbing orchards growers should chip the orchard wood for biochar production. The wood chip can be seasoned/dried in-field under covers and anchor bags which are water repellent and breathable
- The root system from old orchards can be shredded and left in the orchard to compost naturally
- Businesses should collaborate regionally to establish biochar production with pyrolysis units sited where the heat can be utilised – cold store, glasshouse, etc
- Continue the assessment of existing biochar in orchard trials and undertake further field scale trials to assess the efficacy of biochar added to the planting hole and to the orchard alleyways. These trials should test different methods to “charge” the biochar – be that with compost, green waste or fluids
- The Lifecycle Carbon Analysis of British grown apples will be disseminated to growers in order that they understand the key levers to reduce carbon in their low emission crop.



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