# Biochar - evidence on potential environmental impacts and social implications

## Chief Scientist’s Group report

September 2025

SC230003/R5

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If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Dr Robert Bradburne
**Chief Scientist**

## Contents

# Introduction

This research is part of a series of reports which aim to collate and review current evidence on the potential environmental impacts and social implications of five greenhouse gas (GHG) removal technologies: ocean alkalinity enhancement, enhanced rock weathering (ERW), biochar, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). This report synthesises the evidence relating to biochar and highlights evidence gaps. The carbon removal efficacy of each GHG removal technology, and the economic impacts of their implementation, are not explored in this research.

The structure of the report is as follows:

- A description of how biochar delivers greenhouse gas removal and key considerations for the application of biochar
- Synthesised evidence on potential environmental impacts of application of biochar
- Synthesised evidence on potential social impacts of application of biochar
- A summary of the evidence and identification of evidence gaps

The findings in this report are based on a review of the published and grey literature. The approach to identifying, collating, and synthesising the available information is described in detail in the Appendix.

A non-technical summary of this research is also provided as a separate document.

# Overview of biochar

This section provides an overview of how the formation and application of biochar delivers carbon dioxide ($CO_2$) removal from the atmosphere and details of the various forms of the technology, spatial constraints on their implementation, and their current commercial maturity in the UK and globally. Later sections discuss the potential environmental and social implications from use and scale up of this technology.

## Description

Biochar is a porous, carbon-rich material similar to charcoal, produced by heating biomass in the absence of oxygen or under a limited oxygen atmosphere (Amalina et al. 2022). It has a high degree of chemical stability, which is assumed to originate from its characteristic aromatic carbon molecular structure as conjugated carbon atoms bonded in a stable ring shape[1] (Wang et al. 2016; Wiedemeier et al. 2015). This chemistry makes biochar a potential greenhouse gas removal (GGR) technology. This is because the formation from biomass extends the time window over which the carbon would be returned to the atmosphere if it was not converted to biochar. This assumes the biomass would have otherwise naturally decomposed or been combusted completely (Woolf et al. 2010). When created from renewable materials that have removed $CO_2$ from the atmosphere, generally plant matter, biochar could be used to achieve a net reduction of carbon emissions and contribute to greenhouse gas removal. Biochar can be created using other materials.

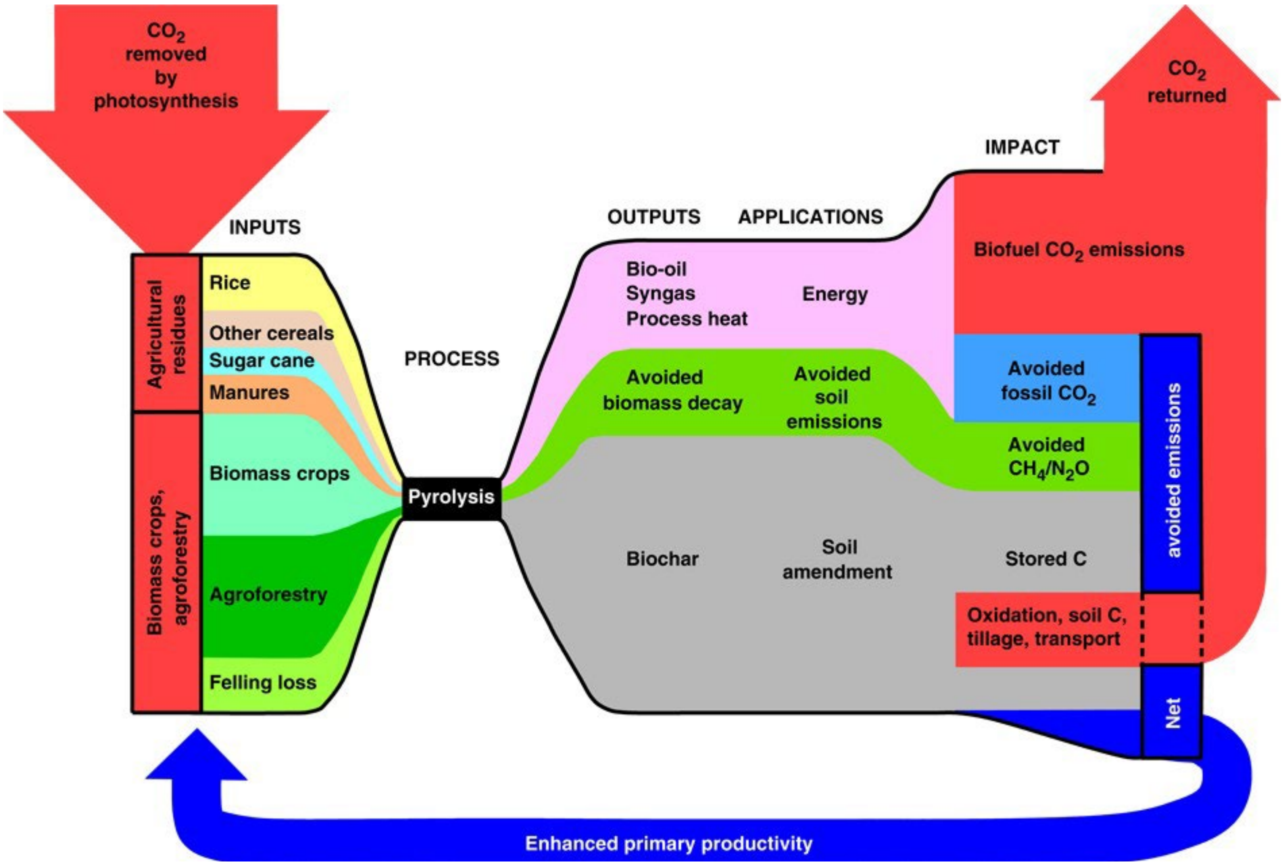


**Figure 1: A schematic of the inputs, process, outputs, applications, and impact of biochar production on global climate. Adapted from the work of Woolf *et al.* 2010.**

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[1] The aromatic compounds that give biochar its stability are different to the polycyclic aromatic hydrocarbons (PAH) that are harmful to human health e.g. as defined by the US EPA (2008). The harmful PAHs are individual molecules typically with 2-6 fused aromatic rings, while stable aromatic carbons in biochar are part of a larger, crystalline carbon matrix of condensed polyaromatic sheets (Wiedemeier et al. 2015).

Producing biochar requires an input of biogenic feedstock that results from the removal of $CO_2$ from the atmosphere, to be considered a GGR technology, realistically this is exclusively via photosynthesis. This can include plant matter and its derivatives (e.g. paper and cardboard), food waste, and sewage sludge. It differs from industrial decarbonisation as it results in a net reduction in atmospheric carbon, while industrial decarbonisation prevents additional carbon being added to the atmosphere (e.g. carbon capture and storage of emissions from fossil fuel combustion).

The biomass undergoes a thermochemical conversion process, which involves heating it in an oxygen-limited environment. The most widely used of these processes, which are discussed further in the *Technological development* section below, are pyrolysis, gasification and hydrothermal carbonisation (Yaashikaa, 2020). As a result of these processes, roughly half of the organic carbon is retained as a solid material called biochar, while the other half is released as vapours and gases containing organic compounds referred to as bio-oil and syngas (Chiquier et al.  2022). Bio-oil is produced by condensation of the vapours (Kumar, 2009), syngas is a shortened name for synthesis gas (generally a mix of hydrogen and carbon monoxide).

The production of biochar and its application to land can yield several potential co-benefits. Firstly, pyrolysis offers a renewable energy source, as it also produces biofuel (bio-oil and syngas) and heat. Biofuel offers an alternative to fossil fuel consumption (though is not low-carbon), either by being burned directly or processed into other fuels. The heat generated during pyrolysis can also be used directly or converted to electrical energy. Woolf et al. (2016) noted that while biochar production with bioenergy offered benefits such as facilitating earlier deployment of carbon reduction strategies at lower carbon prices and providing soil amendment advantages, it generally produced less energy compared to complete combustion of biomass for energy, as in Bioenergy with Carbon Capture and Storage (BECCS).

Secondly, biochar soil amendment has received much attention because various beneficial effects on soil biology, soil water retention, plant physiology, and biomass yield have been observed across a range of crop types, soil types, and study durations (Schmidt et al. 2021; Bolan et al.  2024; Figure 1). The yield enhancement benefit can further augment the carbon sequestration benefit of biochar, if the greater biomass yield is used to produce more biochar in a circular system. The applicability of these potential impacts in the context of the UK is discussed in the *Environmental Impacts* section below.

While biochar is highly stable, it will gradually return retained carbon to the atmosphere though decomposition over the long term, with decay rate estimates ranging from a few decades to several centuries (Chiquier et al.  2022). A meta-analysis by Wang et al. (2016) fitted a double first-order exponential decay model to experimental data (116 observations from 21 studies) of the percent of biochar remaining in soil over time, using data primarily from slow pyrolysis (heating biomass at relatively low temperatures in an oxygen-limited environment). This showed a decomposition rate of the recalcitrant biochar pool of 0.0018% per year, translating into an average persistence in soil of around 556 years, although this number varied significantly across different studies (+/- 483 years). The wide range in stability is related to the biochar composition, such as the ratio of hydrogen content to carbon content, and the soil characteristics, such as soil temperature. This wide range in soil persistence may compromise the global warming benefit of biochar over multiple decades and complicate its use as a verified carbon dioxide removal (CDR) technology. This highlights the need to control for the factors that result in higher soil stability. The choice of conversion process, and conversion conditions, leads to different biochar properties, and therefore different biochar decay rates (Chiquier et al. 2022). Woolf et al. (2021) calculated that over 100 years, between 54-84% of the carbon content of biochar is stable, falling to 6–35% over 1,000 years. Therefore, using the average rates, in the UK, where the average soil temperature is around 11°C, the permanence of biochar is approximately 70% over 100 years, and 12% over 1,000 years (Chiquier et al. 2022).

# Technological development

Three main technologies can be employed in the production of biochar: pyrolysis, gasification, and hydrothermal carbonization (HTC) (Yaashikaa, 2020). These methods differ in their technological maturity and the characteristics of the biochar they produce (Lin et al. 2016). Pyrolysis is the most extensively researched, hence there is a wealth of data on the variables influencing the process (Sharma, 2015, Yaashikaa, 2020), while information on gasification and HTC is comparatively sparse (Lin et al. 2016). The subsequent sections provide a comprehensive overview of each technology including their process constraints, how they affect the quality of biochar produced and in turn its potential applications, and an estimation of the technology readiness level (TRL) of each of the processes. The TRL scale ranges from 1 (basic principles observed) to 9 (actual system proven in operational environment).

## Pyrolysis

**Produces:** energy, biochar and bio-oil. Produces syngas as a byproduct.

Pyrolysis is the most common method employed to produce biochar (Yaashikaa, 2020), producing both biochar and heat. It involves the thermal decomposition of organic material at high temperatures, typically between 350°C to 900°C, depending on the feedstock material (Al-Rumaihi, 2022), and in the limited presence or absence of oxygen. This results in the decomposition of polymer chains within the biomass molecules, producing bio-oil and biochar, with syngas as a byproduct (Zhang et al. 2013). The pyrolysis process can be optimised to focus on the desired output, with slow pyrolysis producing biochar as the primary product and fast pyrolysis, reaching higher temperatures over a shorter timeframe, producing more bio-oil (Wang et al. 2020). The bio-oil obtained can be further processed to produce advanced biofuels, however, this current product is considered to be unstable with poor ignition and combustion properties, limiting its market and usage as a fuel (Zhang et al. 2013).

Pyrolysis systems can range from simple kilns to more sophisticated equipment like paddle kilns, bubbling fluidised beds, and rotating kilns, making it adaptable from small-scale use on farms to industrial applications capable of processing thousands of kilograms of biomass per hour (Rizwan et al. 2023, Gabhane et al. 2020). According to the EBI 2023 biochar report, pyrolysis technology is considered mature for biochar production (EBI, 2023), with several operational facilities worldwide (Al-Rumaihi, 2022), indicating it is likely at a high TRL, potentially between 6 (demonstrated at scale) to 9 (commercial full-scale).

## Gasification

**Produces:** energy, syngas. Produces biochar as a byproduct.

**Gasification** is primarily used to extract syngas, by converting carbon-rich materials into syngas, a mixture of carbon monoxide, hydrogen, and $CO_2$, and producing biochar as a byproduct. This process, described by Gabhane et al. (2020), occurs at high temperatures without combustion, using controlled amounts of oxygen and/or steam. The temperature range for gasification is usually 700°C to 1,100°C, depending on the specific technology and the material being processed. Since gasification uses a controlled amount of oxygen, it facilitates higher fine-tuning and standardisation of production of syngas components compared to pyrolysis. Gasification systems are typically more complex and are designed to produce smaller quantities of biochar compared to pyrolysis, but with the advantage of producing a more controlled syngas output. Like pyrolysis, gasification units can be mobile or stationary and can cater to a variety of scales, from local or regional operations to small industries, with the capability of processing significant amounts of biomass (Gabhane, 2020).

Pyrolysis and gasification offer greater flexibility, compared to Hydrothermal Carbonization (HTC), in terms of feedstock variety and operational scale, catering to a broad spectrum of potential users (Gabhane, 2020). Like pyrolysis, gasification is a well-established technology for energy production, and is emerging as a technology for producing biochar (EBI, 2023). While specific TRL values are not cited in the literature, its broad implementation also suggests a high TRL, likely between 6 to 9 (Masoumi et al. 2021), although this may be more related to its use for syngas, not biochar for land spreading, which is likely at a lower TRL as it is not widely implemented.

## Hydrothermal Carbonization (HTC)

**Produces:** biochar

Hydrothermal Carbonization (HTC) is a process that converts biomass into biochar material at lower temperatures, simulating the natural coal formation process. HTC typically operates at temperatures between 180°C to 250°C, under high pressure (2-6MPa) (Czerwińska, 2022) to keep water in a liquid state, which acts as a medium for the reaction. This process is particularly suited for wet biomass, such as aquatic biomass, municipal and agricultural wastes (Pandey, 2019), as it does not require the feedstock to be dried prior to processing (Czerwińska, 2022). This suggests its potential for use in settings where wet biomass is more readily available, possibly including wastewater treatment facilities or in industries generating high-moisture organic waste. However, this also means the biochar produced assists industrial decarbonisation, not GHG removal via photosynthesis.

The application of HTC is niche, as it is best suited to scenarios where wet biomass (such as aquatic and municipal waste) is readily available, thereby potentially restricting its use to specific industries or processes. However, HTC is likely to be important in the UK context, where the availability of sewage sludge is high (UK Government, 2022a). Given the more recent development and ongoing research into optimising the process (Masoumi et al. 2021), HTC is generally considered to be at a slightly lower TRL compared to pyrolysis and gasification, potentially in the range of 4 (laboratory validation) to 7 (pilot demonstrations at full-scale).

### Biochar physicochemical properties

Biochar can be produced to different physicochemical specifications through the selection of feedstocks and production temperatures. Table 1 outlines findings from a review of 5,400 studies investigating these parameters (Ippolito et al. 2020). Feedstock type and production temperatures are thus important variables influencing the suitability of biochar for different uses.

**Table 1. Effect of feedstock and pyrolysis temperature on physicochemical properties of biochar. Adapted from Ippolito et al. (2020).**

| Feedstock/conditions | Biochar properties |
| --- | --- |
| **Wood-based feedstock** | Highest surface area |
| **Straw-based feedstock** | Highest cation exchange capacity |
| **Manure feedstock** | Highest N and P content |
| **Highest treatment temperature >500°C** | Higher persistence in soil; higher ash content; higher pH |

## Logistical considerations

The main sources of biomass feedstock for biochar production are agricultural residues, forestry waste and energy crop (Shackley et al. 2011; DESNZ, 2023). The following sub-sections give an overview of the availability of each of these feedstocks, as well as a summary of advantages and logistical challenges for each.

## Feedstock sourcing and availability

Sourcing biomass for biochar presents logistical advantages and challenges. Data for biochar feedstock sourcing within the UK is summarised in the Government's Biomass Strategy (DESNZ, 2023), however, the wider EU has a more established market, which can be used for longer term comparisons. The availability of biochar feedstock, derived from agricultural, forestry, and biowaste origins within the EU, can be assessed through the lens of biomass availability as projected by the following three studies (Prussi, 2022):

- Directorate General for Research and Innovation (DG RTD). 2017. Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe.

- European Commission Joint Research Centre (JRC). ENSPRESO—an open data, EU-28 wide, transparent, and coherent database of wind, solar and biomass energy potentials.

- CONCAWE Sustainable Biomass Availability (2021) [22]—focus on selected feedstocks.

Each of these studies presents varying estimates and assumptions regarding biomass potential by 2030, influenced by factors such as the inclusion or exclusion of first-generation biofuel crops, forestry management practices, and the treatment of biowastes.

The tables below (Table 2, Table 3, Table 4) show that within the EU there could be a surplus of feedstock for biochar that could be imported as a sustainable source as the UK market for biochar, and other applications such as BECCS, grows. Feedstock availability within the UK is discussed below, where data is available.

**Table 2: Estimated availability of agricultural feedstocks by 2030. Note that tonnages have been provided using an estimated average biomass energy content of 18.0 MJ/ kg.** [2]

| Agricultural Feedstocks | DG RTD | JRC ENSPRESSO | Concawe |
|---|---|---|---|
| **Mtonnes** | 140 – 160 | 221 – 444 | 254 – 381 |

**Table 3: Estimated availability of forestry feedstocks by 2030. Note that tonnages have been provided using an estimated average biomass energy content of 18.0 MJ/ kg.**

| Forestry Feedstocks | DG RTD | JRC ENSPRESSO | Concawe |
|---|---|---|---|
| **Mtonnes** | 251 – 358 | 209 – 505 | 188 – 344 |

**Table 4: Estimated availability of biowaste feedstocks by 2030. Note that tonnages have been provided using an estimated average biomass energy content of 18.0 MJ/ kg.**

| Biowaste feedstocks | DG RTD | JRC ENSPRESSO | Concawe |
|---|---|---|---|
| **Mtonnes** | 53 – 95 | 30 – 58 | 42 – 74 |

## Agricultural Residues

Agricultural residues comprising of straw, husks, and pruning waste, represent a potential source of biomass for biochar production. Along with forestry byproducts, these residues could hold substantial potential for carbon sequestration when converted into biochar. A

[2] Given that the studies above explore the potential of biomass to fulfil European demand for alternative fuels, biomass availabilities are expressed in terms of the potential million or mega tonnes of oil equivalent (Mtoe). Since the energy content of biomass can vary significantly depending on the type of biomass, its moisture content, and other factors, an average energy content of 18.0 MJ/kg has been used to provide crude approximations of tonnages in Table 2, Table 3 and Table 4 (Government of Ontario, 2021).

report by the European Biochar Industry (EBI, 2023) estimated that only between 1% and 19% of sustainable agricultural and forestry waste across Europe would be needed for 6 Mt of $CO_2$ removal by 2030 and 100 Mt by 2040 respectively. However, with competition for the feedstock from other sources, such as BECCS, and alternative options such as to replough the residues into the soil, this figure may not be attainable without knock-on impacts.

**Availability:** The CONCAWE (2021) report estimated that, in a low mobilisation scenario, the UK will have 5.7 million dry tonnes of agricultural waste for biomass by 2030 and a further 2.8 million dry tonnes per year by 2030 from secondary agricultural residues from industrial crop processing e.g. almond shells. It is estimated that half of the agricultural waste biomass in the UK is typically available for the energy sector (Welfle, 2014), leaving a substantial amount that could be used to produce biochar. Hence, assuming only secondary agricultural waste is available for biochar and no competition with the energy sector, there would be ~1.4 million dry tonnes per year available to produce biochar. This would translate into ~1.26Mt $CO_2$ removal across the biochar life cycle[3] and ~1Mt $CO_2$ sequestered in the biochar alone[4].

**Advantages:** Lehmann et al. (2021) highlighted the dual benefits of using agricultural residues for biochar in terms of reducing waste and enhancing soil quality. In addition, it is currently considered that there is an untapped resource of agricultural waste in the UK that could be allocated for biochar.

**Challenges:** The availability and accessibility of these residues, and their markets, vary significantly across regions in the UK. For example, Tang et al. (2024) explored the utilisation of available wheat straw for biochar production in the UK and the potential yield for biochar. They found variation between two neighbouring counties in the UK, East of England and East Midlands, with potential yields of 350,000 and 210,000 respectively. It is also recognised that while agricultural residues can be viewed as a product to make biochar, these residues may have other uses, such as straw used for animal bedding. Should there be an increased demand for straw it is likely that prices could increase for animal bedding, having a knock-on effect on other industries. A study by Townsend et al. (2018) showed that farmers in the UK were reluctant to sell straw as biomass due to these other uses and the finite supply, suggesting that the available agricultural waste for biochar production may not be as high as estimated by some authors.

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[3] Assuming a median estimate of ~0.9t $CO_2$ removed per tonne of feedstock across the life cycle, taken from Tisserant & Cherubini (2019) figure 3.

[4] Assuming a feedstock:biochar mass ratio of 1:0.25 and a carbon content in biochar of 78% assuming typical values reported for modern biochar production units in Sormo et al. (2020) and Cornelissen et al. (2023).

## Forestry Waste

Forestry waste, including felled trees, branches, leaves, and sawdust, is another viable feedstock for biochar. This biomass source is particularly appealing due to its potentially large quantities and widespread availability.

**Availability:** According to BEIS (2021), the majority of biomass supplied in the UK comes from forestry waste. National Statistics compiled by Forest Research (2023) showed that in March 2023 the UK had 3.25M hectares of woodland across the four regions, representing approximately 13.4% of total land area, with the majority located in Scotland. Approximately 10M tonnes of wood was produced in 2022, with an estimated 2.3M tonnes used as ‘wood fuel’, which included wood used for biomass fuel. The Wood Recyclers’ Association (WRA, 2023) found that 4.5M tonnes of wood waste was produced in the UK in 2022, consistent with previous years, but that 4.31M tonnes was processed (chipped), the highest volume to date. The biggest user of wood waste, and the only sector seeing a growth in waste use, was as biomass for energy (63%) followed by panel board manufacture (24%) and animal bedding (8%). Only 5% of wood waste (0.23M tonnes) was exported or landfilled, suggesting that only a small proportion of the feedstock might be available for biochar. Nonetheless, this amount of material used for biochar production could still yield carbon removal at the kt scale[5],[6].

**Advantages:** According to the Food and Agriculture Organization (FAO), sustainable management of forestry waste not only provides a steady feedstock for biochar but also contributes to forest health management by reducing fire hazards (FAO, 2023).

**Challenges:** The transportation of forestry waste can be challenging and costly, given its bulkiness and the remote locations of many forests. Small-scale, portable systems located at the origin site of the forestry waste could help to mitigate some transport implications and costs somewhat, by allowing processing of some feedstock at source, reducing transport impacts from source to processing (Sahoo et al.  2020). However, transport from processing to application site would still be a challenging factor, and competition for feedstock with energy producers could prohibit availability (WRA, 2023).

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[5] Assuming a median estimate of ~0.9t $CO_2$ removed per tonne of feedstock across the life cycle, taken from Tisserant & Cherubini (2019) figure 3.

[6] Assuming a feedstock:biochar mass ratio of 1:0.25 and a carbon content in biochar of 78% assuming typical values reported for modern biochar production units in Sormo et al. (2020) and Cornelissen et al. (2023).

## Dedicated Energy Crops

Dedicated energy crops, such as switchgrass, miscanthus, and bamboo, are grown specifically for energy production and can produce biochar as a byproduct. This integrated approach means that the biomass from dedicated energy crops is not only utilised for generating bioenergy but also for producing bio-oil and biochar (Oginni, 2017). However, this also means that there are competing uses for dedicated biomass crops, predominantly BECCS, potentially impacting the ability to scale up biochar application.

**Availability:** Agricultural land use statistics from DEFRA (2023) showed that of the 8.8 million hectares of utilised agricultural area in the UK, 4.9 million hectares (55%) were considered suitable for growing crops. Of this, 121,000 hectares was used to grow energy crops, representing around 2.5% of crop land, and 1.4% of total agricultural land. The availability of marginal land is difficult to quantify due to conflicting definitions and the potential of many kinds of unused land for energy crops (Csikós and Tóth, 2023). Given the range of energy crops that can be grown on marginal land, it is highly likely that there is land availability in the UK to increase feedstock supply. However, as with other feedstock sources, there is likely to be competition from other GGR technologies, such as BECCS, for feedstock.

**Advantages:** Dedicated energy crops offer high biomass yields and can be grown on marginal lands, reducing competition with land for food production.

**Challenges:** Land is a finite resource, and any use of productive agricultural land as opposed to marginal land should therefore be carefully considered to avoid unintended consequences, especially for food security. As the demand for biomass grows, so would the land requirement. Encroaching on land currently used for food sources could lead to the requirement to import more food, shifting carbon issues rather than mitigating them, and potentially impacting on carbon sequestration efforts, such as afforestation, in the exporting countries (FAO, 2023). Conversely, an increase in demand for biomass feedstock could mean that the UK could end up importing biomass feedstock from developing countries to meet demand. Both scenarios could have wider reaching implications, such as land degradation, loss of biodiversity, food scarcity and increased food price in these supplying countries (Smith et al. 2019).

## Other organic wastes

These include waste from municipal sources comprising of food waste, waste wood and sewage sludge and manure from agriculture.

**Availability:** In the UK in 2022, 26.5 million tonnes of municipal solid waste (MSW) was generated (DEFRA, 2022). Of this, it is estimated that 6.8 million tonnes were sent to landfill. This includes waste that could potentially be used as biomass, such as food waste, green waste, wood and paper products, which could be as much as 65% of the total composition (WRAP, 2020). Government policy updates and plans, such as the Resources and Waste Strategy, seek to reduce the amount of recyclable and biodegradable wastes that are landfilled meaning that there may be an increased availability of MSW for biomass in the coming years. However, municipal waste has seen a general decline in tonnages over previous years (DEFRA, 2024). This factor, combined with the impact of other competing uses of MSW (e.g., for AD, district-scale heat and power, or in creating sustainable available fuels), could mean that MSW is not readily available for biochar production.

As of 2011 it was estimated that about 90 million tonnes of sewage sludge and manure is generated in the UK each year (DEFRA, 2011). Of this, another 2011 estimate indicated that 18.3 million tonnes are used for AD (Ofgem, 2011; POST, 2011 a), with the rest primarily used for fertiliser, offering vast potential availability for biochar production. According to EA guidance, sewage sludge (known as biosolids) must be treated before it is spread on land. However, under the EA's waste exemption U10, manure is not treated as waste if it is used as a fertiliser, potentially limiting the actual feedstock availability. Further, public concern about the wider use of biosolids could mean that thermal treatment of them will be become a necessity. Assuming only 5% (4.5 million tonnes per annum) was used for biochar production, this could yield ~4Mt $CO_2$ removal over the biochar life cycle, and ~3.2Mt sequestered in the biochar alone.[7,8]

Aquatic biomass, comprising of aquatic weeds, algae and other aquatic plants is another potential feedstock source for biochar (Biller, 2018). Currently at an early research stage, the availability and adaptability of these wastes to biochar is yet to be determined. However, aquatic biomass from algae shows potential efficiencies as a soil amendment in some initial studies (Singh, 2024; Dhinesh, 2024).

**Advantages:** Converting municipal solid waste (MSW) into biochar can reduce landfill waste and greenhouse gas emissions. As a waste product of livestock, converting waste animal products, such as bones and carcasses (Um-e-Laila 2021), to biochar offers the potential for a positive environmental impact, utilising an otherwise discarded feedstock. Other biowastes such as food waste, garden waste, and paper products also represent an underutilised feedstock for biochar production (Welfle, 2014). Rathnayake (2023) explored the concerns about pathogen content and potential toxicity of manure, especially in intensive livestock farming, driving an argument for processing with heat via pyrolysis into biochar to use as fertiliser, eliminating pathogenic microorganisms.

**Challenges:** The heterogeneous nature of MSW requires it to be sorted and processed to remove non-organic materials, which can add to the complexity and cost of biochar

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[7] Assuming a median estimate of ~0.9t $CO_2$ removed per tonne of feedstock across the life cycle, taken from Tisserant & Cherubini (2019) figure 3

[8] Assuming a feedstock:biochar mass ratio of 1:0.25 and a carbon content in biochar of 78% assuming typical values reported for modern biochar production units in Sormo et al. (2020) and Cornelissen et al. (2023).

production (Lin et al. 2023). Further, biowaste often constitutes a wet waste and is required to undergo a drying process before it is suitable for pyrolysis or gasification to produce biochar (Rathnayake, 2023). Processing wastes containing animal by-products (including food waste) require additional approvals and permissions (Animal and Plant Health Agency, 2014), potentially limiting their appeal as a feedstock for biochar over other, less controlled feedstocks. Further, the nutrient content and availability of manure processed into biochar, versus using in its natural or composted state is not fully understood (Rathnayake, 2023).

Although HTC presents some technological opportunities, such as the suitability for treating wet waste, the sorting and/or drying burden could be prohibitive in some operations (Lin et al. 2023). In the case of wastes such as manure, producer preference may also be a factor, as farmers may wish to remain applying manure directly at source as a fertiliser rather than sell it be processed into alternative fertilisers. This is due to the potential cost and risk implications, including those related to the potential reclassification of the manure as a waste product and its movement from the source site.

# Environmental impacts

Life cycle assessments of the environmental impacts of biochar indicate that it can have a range of positive and negative impacts on the environment depending on the feedstock used, the production conditions employed, and its effect on different soils (Tisserant & Cherubini, 2019). Biochar’s efficacy as an environmental remediation tool therefore depends on various context-specific impact trade-offs that must be carefully considered on a case-by-case basis to realise the maximal desired benefit.

The following sections outline the environmental impact considerations and trade-offs associated with biochar from the perspective of its life cycle stages from cradle to grave. These include;

- **Feedstock impacts**: the environmental implications of sourcing, transporting and processing feedstocks, as well as how feedstock choice influences the positive and negative characteristics of biochar.
- **Production impacts**: the environmental impacts associated with the pyrolysis process such as air pollution.
- **Handling and application impacts**: the environmental impacts of transporting, storing, and applying biochar to land.

# Feedstock impacts

## Sourcing

### Growing dedicated crops for biochar production

In the UK context, growing dedicated crops for biochar would present a challenge, given the varied competing land uses such as the UK government policy goals to maintain domestic food production at current levels (UK Government Food Strategy, 2022) while increasing land allocated for nature restoration (Carbon Budget Delivery Plan, 2023). Furthermore, purpose-grown energy crops have a range of environmental impacts and resource consumption considerations.

Assuming a 50% lower $CO_2$ removal compared to BECCS, depending on the biomass crop, the land and water requirements for biochar could range from 0.06 to 0.12 ha and 120 $m^3$ per $tCO_2$ removed (RS & RAE, 2018). Other estimates of land use requirements translate to 2 to 3.4 ha per tonne $CO_2e$ per annum for forest residues, 1.2 ha per tonne $CO_2e$ per annum for agricultural residues, and between 0.2 to 0.8 ha per tonne $CO_2e$ per annum for bioenergy crops (Smith et al. 2015). Using commentary from Babin et al. (2021) for BECCS, to achieve a $CO_2$ removal target of 5 Mt of $CO_2$ per year using switchgrass or miscanthus for biochar production would require between 1.14 and ~10 Mha of land, depending on yield, and ~600 million $m^3$ of water. This is equivalent to up to ~60% of the utilised agricultural area in the UK in 2023 (UK Government, 2023), and yearly water consumption of ~11.3 million people in England and Wales (Salas, 2024). From the above, it is apparent that growing primary crops for climate-relevant biochar production in the UK is infeasible without impacting other environmental aims.

### Deterioration in soil health from crop change

Arising from changing soil carbon levels and depending on the types of crops, soil health can deteriorate when switching from land use to bioenergy crops. Crops with positive impacts included miscanthus, willow, or poplar, and negative impacts involved conversion of grassland and woodland to bioenergy crop (Richards et al. 2017). For example, the conversion of land from arable to miscanthus would sequester carbon at rates ranging from 0.4 to 3.8 Mg C $ha^{-1}$ $yr^{-1}$, whereas converted grassland reported losses (McCalmont et al. 2017; Dimitriou and Bolte, 2012; Langeveld et al. 2012). Targeted use of low carbon soils for perennial bioenergy crop cultivation was found to reduce carbon losses in the short-term and promote sequestration in the long-term (Whittaker et al. 2017). Van der Hilst et al. (2012), noted that erosion risks from land-use change were relatively small and confined to sandier soil types.

### Effects on biodiversity

Studies in the UK have suggested that miscanthus fields were richer in biodiversity compared to cereal crops (AFBIBI, 2021). However, much of this increased diversity was attributed to non-crop weeds (McCalmont et al. 2017). Donnelly et al. (2010) found that conversion of pasture land to miscanthus was likely to result in greater losses in biodiversity, particularly bird diversity of birds that prefer open landscapes.

Soil fauna are influenced by the type of plants, soil pH and calcium content (McKay et al. 2011). Dimitriou and Bolte (2012) explored the environmental impacts of crops grown for biomass on biodiversity and found that it compared favourably to arable crops.

**Repurposing wastes or residues as biochar feedstock**

Repurposing crop or forest residues or waste streams like manure (discussed in Logistical considerations section) need not require expansion of existing land allocated to these industries. It also has the advantage of displacing alternative residue or waste management practices that can be more environmentally harmful than biochar production and application. Owsianak et al. (2021) conducted a life cycle assessment (LCA) comparing composting to biochar production as two alternative biowaste management systems, finding that biochar production consistently performed better in terms of damage to ecosystems, human health, and resources across six different countries. This occurred even in China where the yield increase from biochar was relatively low at 14%, which may be in the ballpark expected in a UK context (Ye et al.  2020). Furthermore, in the case of gasifier use, the ability to replace electricity from the grid further reduced biochar’s life cycle environmental impacts. However, it is important to note that the use of residues can impact nutrient cycling and soil carbon over consecutive years of residue removal (Tisserant & Cherubini, 2019). Hence, care must be taken to ensure that nutrient and carbon stocks are preserved in soils. This may be achievable by amending the soils with biochar produced from residues removed from the same system (Tisserant & Cherubini, 2019) as biochar may provide the soil nutrient and carbon benefits achieved from the residues themselves (see Plant, soil, livestock, and water impacts section).

The use of sludge produced from paper and pulp mills for biochar production is another alternative feedstock (Mohammadi et al.  2019a; b). It has been reported that its use for biochar production and land application reduces risks associated with its incineration, landfilling or land application of its ashes such as from aquatic toxicity, carcinogenic and terrestrial toxicity, and acidification (Tisserant & Cherubini, 2019, Mohammadi et al. 2019a; b).

Paper mill sludge biochar is a rich source of calcium and thus can be used as a phosphorous removal adsorbent (Wang et al.  2021), which can have application in remediation of eutrophic water. However, one study analysed the leaching potential of six heavy metals in biochar produced from paper mill effluent sludge, finding that leaching was above the bounds set by the UK government for acceptable effluent loads to water or sewers (UK Government, 2022b) for cadmium, lead, zinc, nickel, copper and chromium

**Summary:** Growing dedicated crops for climate-relevant biochar production is likely to be infeasible in the UK with current technologies due to the excessive land, water, and environmental footprint this would entail, while repurposing industrial and agricultural wastes can have a net positive environmental impact.

(Cd, Pb, Zn, Ni, Cu, Cr) (Devi & Saroha, 2014). Nonetheless, it was also found that lead and zinc leaching were under the limits when pyrolysis temperatures were 700°C, and that the bioavailability and leaching potential of all metals reduced with increasing pyrolysis temperature (Devi & Saroha, 2014). Another incubation experiment also found that biochar made from deinking sewage sludge from a paper recycling plant amended to lead-contaminated soils reduced the mobility of zinc in the soils (Ferreiro et al. 2014). One glasshouse study of papermill sludge biochar showed typical soil effects expected from biochars in agronomy (see section: Plant, soil, livestock, and water impacts), namely increased pH, exchangeable calcium, total carbon, and reduced exchangeable aluminium in an acidic soil (van Zwieten et al. 2010). In light of these results, biochar from paper mill sludge may have applicability in contaminant remediation in heavily contaminated soils, since the metal toxicity it may add to the soil may be insignificant relative to the remediation benefit it could provide. It may also be viable as a soil amendment for improved agronomic performance if safe ecotoxicity thresholds can be ensured through appropriate production conditions.

## Transportation

The location of each feedstock, processing facilities, and intended sites of biochar application all influence the required supply chain complexity and size, and hence the environmental impacts of biochar logistics. However, modular and portable biochar production technologies are currently commercially available, such as the Pyreg production plant (Sormo et al. 2020; Cornelissen et al. 2023) that facilitate small-scale biochar production at the feedstock source (up to 3,600 tonnes per year; PYREG, 2023). Coupling this to a circular biochar model would effectively nullify the requirement for a transport and distribution network external to the feedstock source and could reach 1 Mt of production with ~280 units in operation.

Nonetheless, in systems where this configuration is not possible or desirable, the literature indicates that transport of feedstock and biochar makes a relatively small contribution (usually <10%) to the overall supply chain climate impact, even when feedstocks are transported across oceans (e.g. from Canada to the UK; Hammond et al. 2011; Tisserant & Cherubini, 2019). Furthermore, the UK has the benefit of a well-connected rail network that could be used to transport feedstocks and biochar, reducing or avoiding the need for fossil-powered heavy goods vehicle transport. However, typical bulk densities of biochar are between 80-320kg per $m^3$ (Brewer & Levine, 2015), and the volume of a large tipper truck (used to deliver sand to a building site) is ~20$m^3$, meaning that 1.6-6.4 tonnes of biochar can be shipped in one truck movement. Applying biochar at 10t per ha, which is considered a relatively modest rate of application in industry guidelines and the academic literature (Schmidt et al. 2021) means that ~0.16-0.64 ha can be amended with biochar in one vehicle movement. Amendment of biochar to fields is therefore likely to require many vehicle movements that could create an important environmental impact hotspot in the biochar life cycle, including through affecting local air quality. No detailed literature on environmental impacts of besides climate impacts for biochar supply chains was found as part of our review. However, it can logically be assumed that wider impacts typical of fossil-fuel intense transportation (like fossil fuel depletion and air quality impacts) are likely to increase with transportation distances.

**Summary:** Biochar production is flexible in siting due to the existence of modular, portable production technologies, avoiding the need for resource-intensive supply chains. Nonetheless, even in the case of long-distance transport, biochar can still be a net positive GGR technology, with mitigations possibly needed for transport options (e.g. electric vehicles).

## Storage

Biomass can pose a fire risk (Jørgensen et al. 2011), and is a potential source of emissions (Alakoski et al. 2016). As woody materials degrade, they generate gases, including CO, $CO_2$, methane, and volatile organic compounds (VOC). Storage in confined containers may therefore result in serious injury and death. Ensuring an efficient biochar supply chain, where feedstocks are converted to biochar shortly after harvesting and before they have time to decompose, can mitigate this potential issue.

## Processing

One environmental consideration is the inputs required to process feedstocks for pyrolysis. The use of wet feedstocks like manures, or even woodchips with too high moisture content, can impose a high energy demand on the production process due to the need for drying prior to pyrolysis (Tisserant & Cherubini, 2019). This can contribute 25% - 83% of the supply chain GHG emissions due to fossil fuel consumption and can be a human health and ecosystem degradation impact hotspot in the biochar life cycle (Rajabi et al. 2019; Cao & Pawlowski, 2013; Lu & Hanandeh, 2019; Tisserant & Cherubini, 2019). However, these impacts are likely to be mitigated if using waste heat - one advantage of biochar systems is the ability to repurpose the heat production from the pyrolysis process or co-products to dry feedstocks, reducing the demand for grid energy (Tisserant & Cherubini, 2019).

Drying of feedstocks can also emit volatile organic compounds (VOC), which can form ground-level ozone in the presence of nitrogen oxides (Vidlund, 2004), condensable compounds, and particulate matter (Fagernas et al. 2010). In commonly used dryers, namely directly heated atmospheric flue gas dryers, conventional gas cleaning techniques can be used to mitigate these effects e.g. flue gas condensation can mitigate organic compound emissions, and particulate matter can be filtered using bag filters, however, sub-micron aerosols are very difficult to avoid emitting (Fagernas et al. 2010). It has been noted that drying of wood fuel at temperatures below 100°C can avoid emitting harmful amounts of organic compounds (Fagernas et al. 2010). In steam dryers, which facilitate heat recovery through condensing the waste steam, organic compounds emitted from the drying process end up in the condenser as inert gases, dissolved in the condensed water as tar (Fagernas et al. 2010).

Another processing consideration is the need to comminute feedstocks to appropriate dimensions which requires grinding or crushing machinery. However, some biochar from waste systems will receive already comminute waste e.g. sawdust from wood processing facilities like paper mills (Haile et al. 2021). Feedstock particle size selection for biochar production will depend on the intended biochar use, since feedstock particle size correlates with biochar particle size (Leng & Huang, 2018), which in turn influences the physicochemical properties and soil effects of biochar (Leng & Huang, 2018).

## Biochar quality

The choice of feedstock for biochar production affects the chemical composition of the produced biochar, that can in turn affect its potential impacts on the environment (Xiang et al. 2021). A review by Xiang et al. (2021) outlined the findings from across the biochar literature, on the contaminants that can occur in biochars produced from various feedstocks and associated risk management. They reported that wood biochar can contain heavy metal pollutants like zinc and manganese, and that as a precaution, biomass with a low heavy metal content should be used. This was supported by Sormo et al. (2020) who compared the contaminants in biochar produced from waste timber (a lightly contaminated mix of wood products from various businesses like housing demolition and public recycling stations, consisting of both pure wood, wood fibre and traces of painted wood, hard board and soft board with various binding agents, and wood with some remains of scrap metal pieces having had most metal removed by a magnet and manual sorting) to those of a mixture of clean wood and leaves from gardening waste. They found that the garden waste biochar had contaminant levels that fell well within the ranges required to be classified as premium quality by the European Biochar Certificate. Meanwhile, the waste timber biochar had variable levels of lead, copper, zinc and polycyclic aromatic hydrocarbons (PAH) that varied above the threshold for basic quality. These findings imply that the use of forestry residues rather than timber residues will produce biochar with acceptable levels of contaminants for soil application in the UK.

One study investigating production conditions on PAH content in biochar found that the most important influence on the levels of toxic PAHs in biochar was the design of the pyrolysis unit itself (Buss et al. 2022). They investigated the content of 16 of the priority US EPA PAHs for a suite of 73 biochars produced from different feedstocks and production conditions, specifically focusing on 15 of the 16 most harmful PAHs (excluding naphthalene). They found that post-pyrolysis contact (condensation and deposition) of the pyrolysis vapours with the produced biochar was the most important factor affecting the content of non-naphthalene PAHs in the biochar, which was far more important than the effect of feedstock type or pyrolysis temperature. The average non-naphthalene PAH content in biochar was found to be 9 mg per kg (median 0.9 mg per kg) in biochars where conditions in the post-pyrolysis area favoured PAH condensation and deposition on the biochar, while the biochars that were not affected by this process, the average non-naphthalene PAH content was 2mg per kg (median 0.5 mg per kg). Approaches to mitigate PAH deposition and condensation on char are suggested by the authors, namely ensuring temperatures and heat distribution in the chamber where pyrolysis vapours are discharged is sufficiently heated to minimize condensation and ensuring vapours can escape freely (Buss et al. 2022).

It is also noteworthy that the lowest European Biochar Certificate threshold allowance for PAH content is 4 mg per kg (European Biochar Foundation. (2012), indicating that the majority of biochars produced under both conditions meet safety standards for PAH contamination. However this certificate only considers the 15 most toxic US EPA priority PAHs.

The findings by Xiang et al. (2021) for other feedstocks and production conditions are reported in Table 5. These findings suggest that the use of clean wood is favourable for minimising the pollutant load in the resultant biochar. However, the use of other feedstocks is still viable if the chemical content can be appropriately managed. For example, despite food waste having a risk of producing dioxins, investigation of bioavailability of these in food-derived biochar has shown to be below detection limits and well within safe limits set by the EBC, and the selection of food waste with a low salt content is one recommendation for preventing formation of detectable levels of dioxins (Xiang et al. 2021; Table 5). Additionally, dioxins are destroyed at production temperatures greater than 1000°C (Xiang et al. 2021), providing another option to avoid their formation in biochar (although only gasification reaches appropriate temperatures, which is not optimised for biochar production). Nonetheless, more generally the wide range of toxins that biochar may contain is an important environmental consideration that necessitates a wider range of unified industrial standards as well as predictive knowledge around feedstock selection for acceptable contaminant load across different applications (Xiang et al. 2021).

**Table 5: Contaminants associated with different feedstocks and production conditions and recommended avoidance measures reported in Xiang et al. (2021).**

| Feedstock / production condition | Dominant contaminant | Recommended avoidance measures |
|---|---|---|
| **Sewage sludge** | Heavy metals, PAHs, PFCs, dioxins | None |
| **Food waste with high salt content** | Dioxins | Select feedstock with low chlorine content |
| **Softwood (Douglas Fir)** | Environmentally persistent free radicals (EPFR) | Use hardwood |

| Feedstock / production condition | Dominant contaminant | Recommended avoidance measures |
|---|---|---|
| **Herbaceous plant** | Micro and nano biochar[9] | Woody plant biochar is less prone to physical ageing |
| **Increasing temperature** | Higher heavy metal and EPFR concentrations | Reasonable selection of pyrolysis temperature |
| **Low temperature** | PAHs are dominant pollutant | Reasonable selection of pyrolysis temperature;<br><br>Even heat distribution, no vapour trapping during pyrolysis, no cool zones in post-pyrolysis area (Buss et al. 2022) |

**Summary:** There are various pollutants that may be present in biochar, influenced by feedstock choice and production temperature. Some methods to mitigate formation of toxic levels of these exist, but more research is needed to identify safe thresholds and mitigation methods during application.

## Production impacts

A primary concern with the thermochemical conversion of biomass to biochar is air pollution. Producing biochar releases $CO_2$, CO, VOC, methane, particulate matter (PM) and nitrogen dioxide ($NO_2$) (Cornelissen et al. 2023) that can have various environmental impacts on human health and climate change. A comparison between Pyreg emissions and acceptable EU emissions standards for municipal waste incineration shows that biochar PM potential emissions are ~40 times higher than the acceptable waste

[9] Micro and nano biochar are biochar particles mainly smaller than 1 um and 100nm respectively, which can promote the release and mobility of heavy metal ions (Xiang et al. 2021). It can be produced through the physical degradation and ageing of biochar in the soil environment (Xiang et al. 2021).

incineration limit, while CO and nitrous oxides (NOx) potential emissions fall well within the acceptable limits (Cornelissen et al.  2023). Previous research studying emissions from Pyreg systems has suggested the need for studying the effect of better filtering technology on particle emissions (Sormo et al.  2020).

Production conditions also have implications for the environmental impacts associated with feedstocks. As production temperature increases, the biochar yield (i.e. the quantity of biochar produced per quantity of feedstock) decreases, but the carbon content and aromaticity increases, which implies a trade-off between higher persistence of biochar as a carbon sink, and biochar yield (Tisserant & Cherubini, 2019). This suggests that the environmental impacts associated with the sourcing of feedstock (see above) will increase with a longer durability of stored carbon in biochar. Yields can range from 15-80% depending on the pyrolysis method (James et al.  2022), implying that sourcing impacts could vary considerably depending on the pyrolysis method. Therefore, biochar applications for climate change mitigation should take care to consider the time window over which mitigation is preferrable, and which local and upstream environmental impacts are worth incurring for the desired climate benefit.

Additionally, pyrolysis conditions like temperature can affect the pollutant content in the produced biochar including heavy metal load and bioavailability, PAH, and dioxin content. As a general rule, PAH content decreases as pyrolysis time and temperature increases, and dioxins are destroyed at pyrolysis temperatures greater than 1,000°C, however, increased temperatures are associated with increases in EPFRs in biochar (Xiang et al. 2021; Table 5). With regards to metal concentrations, it has been found that heavy metal content increases as pyrolysis temperatures increase, however the bioavailability of these metals may decrease (Xiang et al.  2021). These factors highlight the importance of having rigorous industrial standards enforcing acceptable pollutant thresholds for biochars so that production conditions can be optimised (Xiang et al.  2021).

**Summary:** Biochar production releases emissions into the atmosphere, with particulate matter being a particular concern. More technological innovations and research are needed to try different ways of curtailing these emissions to safe levels. On another note, the temperature at which biochar is produced influences the pollutant content of the biochar, and more work is needed to set appropriate industrial standards for biochar production to mitigate toxic levels of pollutants.

## Handling, storage and post-application impacts

### Self-heating during storage

Storing biochar presents a few potential environmental risks, including spontaneous combustion which can be caused by exothermic oxidation between the char and oxygen in surrounding air, which can cause thermal runaway and release of $CO_2$, even at low temperatures (12°C) (Phounglamcheik et al. 2022). The factors affecting this are initial char temperature, the size of the storage container (larger storage containers can lower the heat loss rate), ambient temperature, and amount of available oxygen (which increases with lower bulk density of biochar in the container). Permeable storage containers like woven plastic bags stored on a pallet are more susceptible to thermal runaway as they lower the bulk density in the storage container which corresponds to higher surface reaction rates (Phounglamcheik et al. 2022). Some methods that are used in the storage of coal to prevent self-heating can be applied to mass biochar storage, include cooling by water and oxygen purging with inert gases (Phounglamcheik et al. 2022).

It has been hypothesised that higher pyrolysis temperatures result in less thermally reactive biochar, because it reduces the number of defects in its aromatic molecular structure, increasing its chemical stability (Phounglamcheik et al. 2022). This agrees with Riva et al.  (2020) whose statistical investigation of the effect of pyrolysis temperature on biochar pellet self-heating found that self-heating was lower when the prior heat treatment was carried out at higher temperatures.

**Summary:** A key concern with biochar handling and application is the release of particulate matter from the surface of biochar to the atmosphere. There are various management strategies that can curtail these emissions like wetting, pelletising, sieving, or feedstock selection, although these can have their own additional environmental impacts. More research is needed to establish the optimal management strategies that would provide adequate curtailment of PM emissions from biochar.

## Particulate matter emissions

Biochar can have various beneficial effects on a range of emissions from agricultural practices (Luyima et al. 2021; Schmidt et al. 2019). Luyima et al. (2021) discuss that tillage operations in agriculture are a prominent source of PM emissions, where the emission load depends on the soil texture and water content. The addition of biochar to soil could help alleviate these emissions through improving soil aggregation and water content. However, a major environmental concern with biochar is that during handling, storage, transport and application, biochar can emit PM into the atmosphere that may negatively affect air quality, so it may exacerbate the PM problem rather than solve it (Luyima et al. 2021).

It has also been noted that PM emissions from biochar, namely black carbon aerosols, may directly distort the earth's radiative balance through absorbing shortwave radiation and re-emitting energy as longwave radiation (Genesio et al. 2016), and indirectly through modification of surface albedo when deposited on ice and snow (Genesio et al. 2016). Genesio et al. (2016) calculate the potential direct radiative forcing effect of biochar assuming 101.5Gt of carbon are applied to 4.03Gha of cropland and pastures in the next

100 years and under the unlikely assumption that all black carbon aerosol contained in biochar is released to the atmosphere. They estimate that this would add between 0.77-1.44 W $m^{-2}$ to the background black carbon aerosol radiative forcing currently (the average being between 0.17-0.31 W $m^{-2}$: Wang et al. 2014), thus increasing it by more than a factor of 2 and potentially completely reversing the negative radiative forcing achieved by biochar due to carbon sequestration as calculated by Genesio et al. (2016). It is unclear what effect UK-specific biochar application would have on radiative forcing because these effects are unlikely to scale linearly or be uniformly geographically distributed (Genesio et al. 2016; Wang et al. 2014).

Biochar PM emissions have also been observed from physical shaking, and PM emissions have been observed to increase from sandy soils amended with biochar (Maienza et al. 2017; Ravi et al. 2016). Nonetheless, these effects have been shown to be significantly reduced through various management strategies. For example, one experiment testing the effect of pelletising the biochar before deliberate shaking of fixed duration, that was shown to substantially reduce the amount of PM emitted by it, although pelletised biochar was also shown to have poorer agronomic performance (Maienza et al. 2017). Similarly, amending sandy soil with biochar strained through a 2mm sieve showed lower particulate emissions than biochar amendment without sieving (Ravi et al. 2016). It has also been suggested that burying the biochar in the subsurface of sandy soils would curtail the PM emissions, however there is currently no evidence for this, and tillage operations in agricultural contexts would likely bring the biochar back to the surface (Genesio et al. 2016; Luyima et al. 2021). Another suggested PM curtailment strategy is to avoid applying biochar to fields on windy days (Genesio et al. 2016). The efficacy of these strategies in terms of facilitating an environmentally permissible PM load from biochar, or indeed to what extent or in which context such strategies are needed to maintain environmentally permissible PM emissions, is lacking.

Another suggested method to curtail PM emissions is tailoring the feedstock and pyrolysis conditions to produce biochar with the least tendency to release PM (Luyima et al. 2021). It has been found that feedstocks with high lignin content (e.g. wood) fragmented more easily than biochar produced from high cellulose feedstocks like maize stalks (Spokas et al. 2014). This complicates the notion that clean wood waste is a more favourable feedstock due to it producing comparatively low-toxicity biochar (see feedstock impacts section). Another finding is that lower pyrolysis temperatures produced biochar with a lower chance of comminution into fine particles (Spokas et al. 2014), which adds a further consideration to the trade-off described above between biochar yield and recalcitrance (higher temperatures may increase the potential PM emissions, as well as sacrificing yield, though it increases the carbon sink durability). These are further considerations that provide limits on the ability to maximise biochar’s full potential across multiple environmental impacts.

A further plausible management strategy to check biochar PM emissions is to keep the biochar wet during storage, handling and application (Luyima et al. 2021). This has been corroborated by research showing that biochar kept at moisture levels of 15% was the optimal method for avoiding dust emissions from wood-derived biochar (Silva et al. 2015), and another study showed that wetting biochar to a moisture level of 50% reduced dust emissions by up to 93% and 84% in pelletised and non-pelletised biochar respectively (Maienza et al. 2017). However, besides adding additional water use impacts, wetting the material is likely to increase the bulk density, because of the capacity of biochars to hold water in inter- and intrapore spaces (Adhikari et al. 2023). The increased weight creates a higher energy demand for transport and handling that could increase the transportation-related emissions. More broadly, any further management intervention to account for PM emissions, like pelletising or sieving, will have an associated additional resource use impact.

Overall, there is a lack of detailed literature investigating the wider environmental impacts that these PM emission considerations can have on biochars life cycle environmental performance. An important next step would be to establish the optimal quantities (water, pellet sizes, sieving sizes) needed to provide the required suppression of PM emissions.

## $NH_3$ emissions changes

Besides PM emissions, a large body of literature has also generally corroborated that biochar can diminish gaseous $NH_3$ volatilisations from composting piles when amended with biochar (Luyima et al. 2021). The adsorptive ability of biochar is also understood to be the mechanism by which it can check $NH_3$ emissions when amended to excrement, with a handful of studies finding significant reductions in $NH_3$ volatilisation from biochar-amended excrement of ~13-77% (Luyima et al. 2021). This effect can also have positive effects on animal welfare and vitality by reducing inhalation of $NH_3$ and dampness of animal beddings, which may in turn translate into improved agricultural performance (Luyima et al. 2021). More research however is needed to further elucidate the magnitude of this effect and its mechanisms.

## Plant, soil, livestock, and water impacts

### Soil impacts

Besides acting as a climate mitigation technology, a key positive application of biochar is as a soil amendment (Schmidt et al. 2021). Schmidt et al. (2021) conducted a systematic review of 26 meta-analyses investigating biochar effects in agricultural soils, specifically excluding studies focused on a single geographic area or specific agro-ecosystem not representative of agriculture in general. They found that biochar soil amendment had significant positive effects on plant productivity and crop yield, plant available soil water, plant photosynthetic rate, plant water use efficiency, root biomass, length, and number of root nodules (Figure 2). In terms of soil effects, they also found significant positive effects on soil microbial biomass nitrogen and carbon, soil-available phosphorous, and plant nitrogen uptake. Additionally, they found significant reductions in heavy metal content in plants (Cd, Pb, Cu, Zn and Ni). Furthermore, it was observed that $N_2O$ emissions from soil were significantly reduced, as well as nitrate leaching from soil.

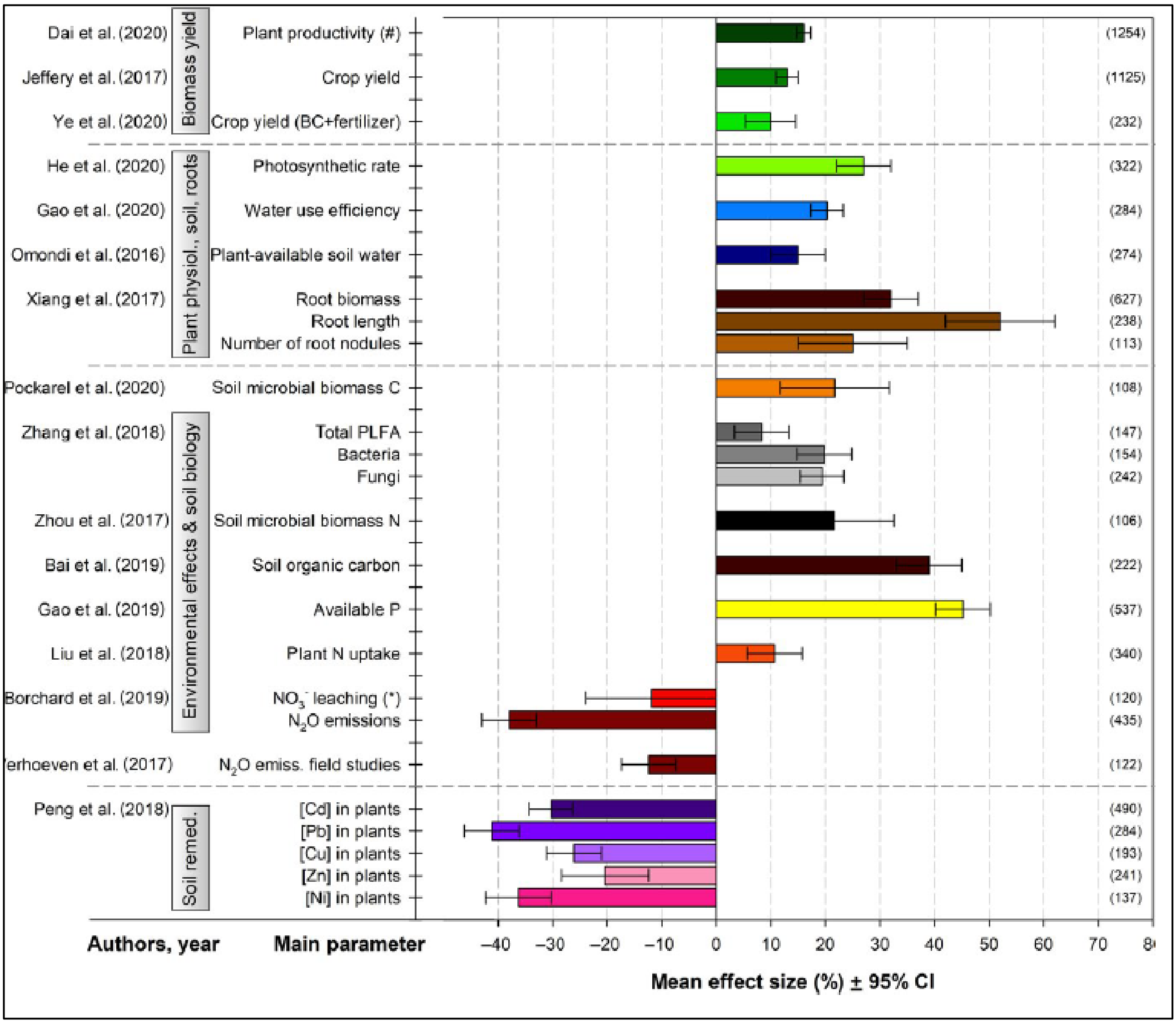


**Figure 2: A compilation of selected agronomic parameters that were analysed across 26 meta-analyses. It focuses on the mean overall effect size, which is expressed as the percentage change, along with the 95% confidence intervals as reported in the original studies. Each parameter listed also includes the number of pairwise comparisons used to assess that specific parameter, which is denoted in parentheses. This visualization effectively highlights the key findings from the meta-analyses, emphasizing how biochar influences various agronomic factors. Reproduced from the work of Schmidt et al. (2021).**

## Yield impact in temperate regions

While the previously mentioned results are promising, it has been noted that the yield benefits of biochar are not consistently observed in temperate latitudes, thus not directly relevant to regions like the UK (Jeffery et al. 2017). However, increased soil pH, enhanced cation-exchange capacity (CEC), improved soil microbial biomass, enhanced nutrient availability, and soil water retention have been observed in temperate soils (Kloss et al. 2014; Lévesque et al. 2021). Enhanced soil water holding could prove particularly beneficial in water-stressed environments which will become increasingly common due to climate change.  Furthermore, the lack of a consistently observed yield boost in temperate systems is attributed to the absence of severe soil acidity, nutrient deficiencies, or water scarcity, which are conditions where biochar's effects are most pronounced (Joseph et al. 2021), implying that agriculture in temperate soils with these properties can achieve significant yield increases with biochar amendment. One meta-analysis found that biochar yields in temperate latitudes were increased by 15% on average when applied in combination with fertiliser (compared to fertilisation with the same amount of nutrients without biochar), when using application rates well below 10 tonnes per hectare and lignin-poor, mineral-rich biomass feedstocks (Ye et al. 2020). It was found that no impact on yields only occurred in regions with mean annual temperatures below 10°C (Ye et al. 2020) i.e. in the case of the UK.

**Soil microbiome and nutrient cycling**

Given that biochar changes the physicochemical properties of soils, it has great potential to influence soil microbial communities and soil nutrient cycling, and the specific effects can vary depending on the biochar pyrolysis temperatures, feedstock type, and soil type (Dai et al. 2021). Some effects can be negative, for example, one study found that the labile carbon fraction of biochar acted as a source of carbon to soil microbes which increased saprotroph abundance (organisms that feed on dead and decaying organic matter), enhancing their competitive capacity and ultimately decreasing fungal diversity (Dai et al. 2018). Increased saprotroph abundance has implications for soil biogeochemical cycling because it can accelerate the decomposition of soil organic carbon. It can logically be expected that this effect would subside once the labile carbon in the biochar is consumed, however one study reported that saprotrophic fungi can consume recalcitrant carbon in biochar (de la Rosa et al. 2018).

Dai et al. (2021) recommended that the selection and application of biochar to alter microbial communities and mediate nutrient cycling should be tailored to the specific requirements of the agricultural context in which it is applied. However, there are still key aspects in the science of biochar effects on the soil microbiome that are poorly understood, like its effects on viruses and protists that affect soil bacteria and fungi, key microbial food web interactions, how the effect of biochar on the abundance of different microbial genes in the soil in turn affects coupling of nutrient transformation processes and the microbes that benefit plant growth and health, and their interactions with plant roots (Dai et al. 2021). More research is needed to develop a comprehensive predictive understanding of effects of biochar on soil microbiology and nutrient cycling.

**Dosage-related soil impacts**

There is potential that excessive quantities of biochar additions to soils can cause various negative environmental impacts (Luyima et al. 2021; Xiang et al. 2021). Luyima et al. (2021) for instance discussed that biochar contains hydrophobic C-H functional groups on its surface, which has the potential to reduce the soil water holding capacity at high application rates, undoing the water retention benefit provided by water-adsorbing functional groups on the biochar surface. Furthermore, while biochar has been shown to have a high affinity for pesticides which can reduce the pesticide volatilisations and leaching into the environment (Luyima et al. 2021), the adsorption of pesticides by biochar may lower the efficacy of pesticide application, which would incentivise farmers to apply higher quantities and therefore negate the environmental benefit while imposing a higher input cost on the farmer (Luyima et al. 2021). The pesticide adsorption function of biochar is thus best used in the context of remediating soil contamination. Additionally, the ability of biochar to absorb various plant nutrients can impose a competitive cost on plants, potentially inhibiting plant growth at excessive application rates (Xiang et al. 2021). These dosage-related effects require further research to establish optimal application rates and biochar chemistries for different soil types (Luyima et al. 2021), as well as avoiding unintended negative consequences to the soils.

### Pollutant release

Potential environmental impacts related to the pollutants that biochar may release are also discussed by Xiang et al. (2021). The release of various chemicals that may be present in biochar like PAHs, heavy metals, environmentally persistent free radicals (EPFR), VOCs, and micro and nano biochar could inhibit crop growth, rooting, and germination, with these effects being demonstrated across a range of studies (Xiang et al. 2021). The key considerations concerning these effects are the biomass type, pyrolysis temperature and the physicochemical properties of the receiving soils (Xiang et al. 2021). Additionally, the release of potentially biotoxic pollutants may inhibit microbial activity in the soil (Xiang et al. 2021). More research is needed to establish the safe thresholds of all variables involved in biochar production and application where pollutants can be controlled at safe levels.

**Summary:** There is an extensive body of literature evidencing biochar's ability to significantly improve various indicators of soil health and plant growth and vitality. However, there is also a large body of literature showing potential harmful effects on plants depending on the pollutant load in the biochar and the application rates. A greater understanding of plant and soil tolerances for different pollutants and biochar application rates is needed. This will facilitate establishing needed industrial standards for biochar pollutants and soil application levels.

### Livestock impacts

Biochar has been shown to have various beneficial effects on livestock health and the environment when used as a feed supplement (Schmidt et al. 2019). These include increases in feed efficiency and weight gain in aquaculture, poultry, pig, and cattle husbandry, as well as evidence of improved immunity and vitality in cattle and pig husbandry (Schmidt et al. 2019). This is thought to be related to its selective ability to adsorb toxins in the digestive tract, although there is considerable uncertainty regarding the electrochemical mechanisms by which biochar may do this (Schmidt et al. 2019). The Schmidt et al. (2019) review of 112 studies on biochar feed supplementation concluded: "in most studies and for all farm animal species, positive effects on different parameters such as growth, digestion, feed efficiency, toxin adsorption, blood levels, meat quality and/or emissions could be found. However, a relevant part of the studies obtained results that were not statistically significant. Most importantly, no significant negative effects on animal health were found in any of the reviewed publications.” This implies that biochar may have the potential to significantly improve the efficiency of animal agriculture and thereby lead to multiple positive environmental impacts like freeing up land for nature restoration.

A further positive impact of biochar when used as a feed supplement is reduced enteric methane emissions from ruminants (Schmidt et al. 2019). Methanogenesis is caused by the digestion products of microbes ($H_2$, $CO_2$ or methanoic acid) being converted to methane by archaea in the bovine rumen. This includes $H_2$ donating electrons to $CO_2$ to form methane. Biochar is thought to act as an electron acceptor that reduces methane production, with one in-vitro study observing significant reductions in methanogenesis (~10-22% depending on dosage and nitrogen supplementation; Leng et al. 2012; Schmidt et al. 2019).

**Summary:** Biochar can be used as a feed supplement in animal agriculture, where it could improve feed efficiency and weight gain, and can check methane emissions in ruminants. However, the evidence for these effects is based on a handful of studies, and some are not consistently observed. More research is needed into these effects.

### Water impacts

Biochar and its pollutants can migrate into surface and ground waters through runoff, irrigation, and infiltration, and can pose environmental risks and toxicity to aquatic life (Xiang et al. 2021). Additionally, when biochar is added to water rich in ions, its pollutant adsorption ability is reduced, and the release of inorganic N and P adsorbed onto the biochar is promoted, which can cause eutrophication (Xiang et al. 2021). Means of mitigating such effects discussed by Xiang et al. (2021) include using biochars with lower content of N and P (dependent on the type of biomass used to produce it) and producing biochar as macroscopic structures like sheets or foam to inhibit migration to water bodies.

# Social impacts

This section explores the actual and potential social impacts of biochar identified within the existing evidence and identifies where research currently falls short of exploring these impacts. This section is split according to the life cycle of the biochar from sourcing, through transport to application.

The following social impacts identified within the available evidence are explored:

- **Social acceptance and acceptability** – explores public opinions of biochar and the factors that can influence this both positively and negatively.

- **Impacts on local communities** – explores the impacts of biochar on those who work or reside within the immediate vicinity of biochar transport routes and production facilities, including potential health impacts.
- **Other impacts** – brief exploration into the wider social impacts of biochar, including the potential impacts of policy and governance.

## Feedstock sourcing and production

### Social acceptability

The social acceptability of sourcing feedstock and producing biochar is a multifaceted issue that depends on various factors, including the origin and type of feedstock, the sustainability of sourcing and production practices, and public perceptions and awareness of biochar's environmental impact (Sutradhar, 2021). Generally, public awareness of biochar is low and so the way that the technology is presented in the media and by public bodies is important in shaping the level of social acceptability moving forwards (Nerlich et al. 2023).

As discussed previously, biochar can be sourced from a wide range of feedstocks, from dedicated energy crops, to waste products from agriculture and forestry for example. Across the literature, it is clear that the source of feedstock plays a significant role in social acceptability (Thomas et al. 2018; Latawiec 2017, Sutradhar, 2021, Beuchelt, 2017). Biomass from waste products or residues is perceived as more sustainable than energy crop feedstocks as it eliminates the emissions from additional production, avoids conflicts over land-use and diverts waste from landfills (Morone, 2020; NatCen, 2022). To mitigate concerns over the sustainability of biomass feedstocks, it is imperative to adopt and promote sustainable biochar production practices. Policies and guidelines that ensure the responsible sourcing and use of biochar feedstock through sustainable practices could alleviate fears and promote greater acceptance (Tisserant & Cherubini, 2019).

Similarly, in terms of biochar production, sustainable feedstock production practices, such as the utilisation of agricultural waste or sustainably harvested biomass, are likely to be more readily accepted by the public (Morone, 2020). This is because they minimise deforestation, biodiversity loss, and soil degradation—factors that directly affect community livelihoods and well-being. A critical factor in the social acceptability of feedstock production is the level of community engagement and perceived social equity. Projects that involve communities in the planning process and offer clear benefits, such as infrastructure improvements or community services, tend to be more socially acceptable. Conversely, projects perceived as benefiting external stakeholders at the expense of local communities face opposition.

The perceived benefits of biochar, such as soil health improvement, carbon sequestration, and agricultural yield increase, contribute positively to its social acceptability (Latawiec, 2017). However, concerns over potential negative impacts of feedstock sourcing, such as the over-extraction of biomass leading to soil nutrient depletion, deforestation, and competition with food sources can diminish its acceptability (Latawiec, 2017; Beuchelt, 2017). The social acceptability of biochar feedstock sourcing is, therefore, closely tied to how well these benefits and drawbacks are communicated and managed. Inclusive decision-making processes that involve local communities, farmers, and other stakeholders in discussions about feedstock sourcing can enhance acceptability (Latawiec, 2017; Morone and Imbert, 2020; Steiner 2018). Policies and regulations that ensure sustainable sourcing practices, mitigate potential negative impacts, and distribute benefits equitably are crucial (Hounnou et al.  2024).

**Summary:** Social acceptability of biochar feedstock relies on sustainable sourcing that avoids food competition and deforestation. This should be supported by clear communication and inclusive policies for community endorsement.

## Impacts on local communities

The establishment of biochar production facilities requires a workforce for the sourcing of feedstock, leading to job creation, and potentially additional income for local workers, in regions where biochar feedstock is sourced. These opportunities can stimulate local economies, as higher levels of income and a larger workforce would increase spending in the local area (Oni et al.  2019).

However, if not carefully managed, biochar feedstock sourcing can lead to social tensions, especially if it competes with traditional or current land uses (Morone and Imbert, 2020). This impact could be particularly prevalent among agricultural communities. Ford et al. (2024) conducted interviews with farmers in England to explore their views and attitudes towards switching from traditional food crops to energy crops. These interviews highlighted the concerns held by farmers over the challenges of growing energy crops, as well as over the limited availability of markets for perennial energy crops, such as willow and miscanthus. Government policy was also highlighted as a barrier to farmers, as there was concern over the distribution of benefits from the provision of feedstock. Acceptance amongst farmers relies on additional incentives for the agricultural industry to make energy crop production viable in both the short- and long-term. Currently, awareness of the technology is relatively low amongst farming communities (Nerlich et al.  2023). As policies are developed, social acceptance amongst farmers could increase with proper engagement and communication of the potential benefits of biochar.

Biomass-based energy places significant pressure on land resources, as it requires ~1,000 times as much land as fossil fuel alternatives (Chatham House, 2023). As the bioenergy feedstock market in the UK grows, the competition between conventional and energy crop farming will increase resulting in higher land prices. This is supported by research into the relationship between biomass demand and land prices in Europe (Choi and Entemann, 2019; Kralik et al.  2023). Local communities in areas where competition for bioenergy feedstocks is high could be implicated due to the decreased affordability of land. Careful planning and the delegation of marginal lands not suitable for conventional food crops could decrease this risk (Supergen Bioenergy Hub, 2022).

Biochar production may also pose health risks for local populations. The production of biochar involves thermal processes like pyrolysis, which can raise concerns about emissions and air quality in nearby communities. Operational inefficiencies or outdated technology can lead to the release of particulate matter and other pollutants, potentially impacting the health and wellbeing of local residents.

Ensuring that local communities are involved in decision-making processes and share in the benefits of biochar projects is crucial to mitigating the risks outlined above. It is important to engage with local communities early in the planning stages of biochar projects to understand their needs, concerns, and preferences. It is also beneficial to design biochar projects in a way that ensures equitable distribution of benefits among all stakeholders, including local communities, landowners, and workers. Strategies may include the implementation of mechanisms for revenue sharing, profit-sharing, or community development funds to directly benefit those affected by the project (Sovacool et al.  2023).

**Summary:** Biochar feedstock sourcing can boost local economies through job creation but may cause social tensions if not managed well, particularly regarding land use conflicts. Engaging communities early and ensuring fair benefits distribution are key to mitigating these risks.

## Government policy

The role of government policy in shaping the social impacts of biochar feedstock sourcing and biochar production may be facilitated by regulatory frameworks, incentives, and participatory governance (Sekera et al.  2020).

### Regulatory frameworks

Government regulations play a foundational role in setting the standards for sustainable biochar feedstock sourcing and production. These regulations can cover a wide range of issues, including the types of materials that can be used as feedstock, the methods of collection and processing, and the environmental impacts of sourcing practices (Tisserant & Cherubini, 2019). For instance, the UK’s Biomass Strategy (DESNZ, 2023) details several scenarios for future biomass availability and outlines its ‘proceed with caution’ policy around the use of food and feed crops for energy. The Biomass Feedstocks Innovation Programme also provides funding for the innovation of sustainable feedstock that address barriers to their production (BEIS, 2021).

Enforcement of regulations can also facilitate the sustainable use of agricultural and forestry residues, ensuring that their removal does not deplete soil nutrients or harm ecological balances (Zubizaretta-Gerendiain et al. 2016). Such policies are essential for maintaining the long-term viability of local ecosystems, upon which communities depend for their livelihoods.

To ensure sustainable biochar projects, strong enforcement of novel policies is essential, as well as ensuring least impactful biomass streams can supply enough biomass for expansion of biochar use. There are potentially concerning practices that may be used by industry to provide enough biomass supply. This could potentially include the use of virgin wood, and have been the focus of media interest (BBC News, 2024). Due to the complexities of biomass supply chains, greater consideration of the global environmental implications of feedstock sourcing could help to ensure the sustainability of the entire biochar life cycle. This should be coupled with rigorous enforcement, for example through accounting for carbon emissions in the country where the feedstock is sourced, to protect ecosystems and community livelihood.

**Incentives for sustainable practices**

Government policy can also influence the social impacts of biochar feedstock sourcing through incentives. Financial incentives, such as subsidies, tax breaks, or grants, can encourage producers to source feedstock sustainably. For example, incentives for using waste products as feedstock can promote a circular economy, reduce pollution, and generate local employment, all of which have positive social and environmental implications. Conversely, the lack of incentives for sustainable sourcing can lead to cost-cutting measures that might exacerbate social and environmental issues, such as over-extraction of biomass, competition with food production, or conflicts over land use (Devadoss and Bayham, 2010).

Farmers in England currently receive subsidies for sustainable farming practices (Defra 2023). These subsidies do not include farming for biomass feedstocks. Introducing subsidies for biomass production has been cited as a main driver for UK farmers to switch from traditional crops to energy crops (Ford et al. 2024). Doing so could be a source of competition for differing land uses. However, these subsidies would likely be required to stimulate a market where established policies and subsidies for feed crops are already in place (Choi and Entemann, 2019). Previous funding programs, such as the BEIS Biomass Feedstocks Innovation Programme, have demonstrated that financial incentive is a key motivator in driving sustainable biomass production (BEIS, 2021).

**Participatory governance**

Participatory governance mechanisms are another important aspect of government policy related to biochar feedstock sourcing. These mechanisms allow local communities, indigenous peoples, and other stakeholders to be involved in decision-making processes. This involvement can ensure that the policies and practices of feedstock sourcing align with the needs, values, and priorities of local communities, thereby enhancing social acceptability and mitigating conflicts (Steiner et al. 2018).

Development of policy for biochar production faces potential challenges, especially concerning the use, classification and regulation of waste products for biochar production. This highlights the need for clear policies and regulations to support the broader adoption and implementation of biochar technologies.

**Summary:** Government policies shape biochar feedstock sourcing's social impact by setting sustainability standards, offering incentives for eco-friendly practices, and involving communities in decision-making, ensuring environmental protection and community alignment.

## Socio-economic impacts

Biochar production from various feedstocks, ranging from agricultural residues to forestry waste, presents an opportunity for rural development, job creation, and innovation in sustainable practices. However, these benefits are accompanied by challenges and potential downsides that require careful management and policy intervention (Sekero, 2020).

Economically, the demand for biochar feedstock can stimulate local markets. For rural communities, particularly those with access to abundant feedstock resources, biochar projects can offer vital new income streams and economic diversification, contributing to more resilient local economies and environments. For instance, agricultural residues that were previously considered waste or had minimal value can become a significant source of revenue when used for biochar production. A study by Tang et al. (2024) produced a spatial framework to analyse biochar production systems in two regions in England. It modelled changes in the price of straw, a relatively low-cost material, as a biomass feedstock, and the associated unit costs of GGR benefits, exploring the ranges of feedstock prices that saw the greatest environmental benefit. Utilising these kinds of materials as feedstock could not only boost the income of agricultural communities but would also encourage the adoption of sustainable farming practices by providing an economic incentive to maintain and manage land responsibly.

Conversely, the socio-economic impacts are not universally positive. Farmers are deterred from growing some energy crops, such as straw feedstock, as they require certain soil sustainability considerations which are more challenging and costly to maintain (Tang et al. 2024). The potential for competition between biochar feedstock and other uses of the land or material for biomass, such as for food production or animal feed, raises concerns about food security and the cost of raw materials. In regions where agricultural or forestry residues are limited, diverting these resources to biochar production could inadvertently increase prices or limit availability for traditional uses, impacting local economies and livelihoods (Zhang et al. 2024). In addition, the initial cost of establishing energy crops is high, and represents an element of risk as the market fledges and there may be no guarantee of desirable offtake contracts (Ford et al. 2024).

Moreover, the economic benefits of biochar feedstock sourcing are not always evenly distributed (Tang et al. 2024). The risk of creating or exacerbating socio-economic inequalities exists, particularly if large-scale biochar operations benefit from economies of scale, potentially marginalising smallholders and traditional practices. Whilst traditional practices, such as the use of fertiliser, can be outdated and harmful to the environment, they are often ingrained in agricultural communities and can be a significant barrier to social acceptance of biochar. It is important to engage with farmers to understand how these practices can be built upon in order to not marginalise these communities. This inequality does not stop at national borders: if developed countries such as the UK explore multiple methods of CCS using biomass, demand is likely to outstrip supply, as the different methods of biomass CCS compete for feedstock. This could mean that the UK may import biomass feedstock from developing countries to meet demand, shifting the economic balance in supplying countries (Smith et al. 2019).

Ensuring equitable access to the benefits of biochar production, such as through cooperative models or community-based projects, is imperative for maximising its positive socio-economic impact.

**Summary:** Biochar production could boost rural economies and promote sustainability but faces challenges like resource competition and socio-economic inequality. Equitable policies and inclusive models are crucial for balancing benefits and risks.

## Feedstock transport

### Social acceptability

Communities are increasingly aware of, and sensitive to, the ecological impact and environmental footprint of industrial activities, and in particular activities related to transport (Witte, 2021). Thus, local sourcing and efficient transport methods should be sought and communicated to ensure community values and perceptions align with sustainability and decarbonisation. The movement of feedstock requires infrastructure that may not always be welcomed by local residents, especially if it leads to increased traffic, noise, or pollution. The planning and implementation of transport routes and methods must consider these factors to maintain social acceptability. Transparent communication and engagement with communities about logistical plans and potential impacts are essential to garnering support.

Social acceptance issues revolve around justice and ethical considerations, particularly the fair distribution of the burdens and benefits of deploying biochar technologies. These concerns highlight the need to protect vulnerable populations from the potential negative impacts of these technologies (Tisserant, 2019).

**Summary:** Social acceptability of biochar feedstock centres on sustainable production, local sourcing, addressing traffic and pollution concerns, and engaging communities transparently to align with local values and interests.

## Impacts on local communities

The transport of biochar feedstock significantly impacts local communities, particularly due to environmental changes, such as local traffic, noise, and air pollution, which can be detrimental to local community well-being (Tisserant & Cerubini, 2019).

However, importantly, biochar transport can stimulate local economies by creating jobs in the transport and logistics sector. However, little research has been conducted into the benefits of an expansion of the transport sector to local communities, and so gathering more evidence and real-world examples would be required to quantify this benefit.

**Summary:** Biochar production and transport pose health and wellbeing concerns to local communities due to the potential creation of air pollution, traffic, and noise. However, economic growth is also anticipated through job creation and income opportunities in rural communities, supporting local economies.

## Government policy

Policies focused on sustainability and environmental protection are particularly relevant to biochar transport (Jeffery et al.  2015). These policies can mandate the use of best practices that minimise environmental impacts, such as emission limitations for vehicles used during transport.

Furthermore, zoning laws and operational permits would determine where biochar production facilities can be located in relation to sourcing and application sites, directly impacting the transportation distances and routes of feedstock sources. Policy frameworks, including life cycle assessments and carbon accounting standards in relation

**Summary:** Policies can guide biochar production and transport by enforcing emissions control and determining facility locations, while also quantifying biochar's climate benefits to influence funding, approvals, and market growth.

to transport, can help quantify the carbon benefits of biochar, reinforcing its role in meeting national and international climate goals. This, in turn, could influence public funding priorities, regulatory approvals, and the market development for biochar and related technologies.

### Socio-economic impacts

The transport of biochar itself is an economic activity that can stimulate local economies, especially in areas where the production facilities are located. Establishing these facilities requires investment in infrastructure, machinery, and labour, injecting financial resources into local economies (Kumar et al.  2022). This investment often leads to the development of ancillary businesses, including transport. Most importantly, transportation of biochar from production sites to points of use or sale involves logistics and distribution networks, offering additional employment opportunities in trucking, logistics, and distribution sectors. However, this effect may not be universally applicable, especially in regions where the economy has significant reliance on fossil fuel industries, including Scotland (Swennenhuis et al.  2020).

Further, while the biochar industry can generate economic growth and job opportunities, it’s essential to consider how these benefits are distributed within communities. There’s a risk that the economic advantages could be concentrated among a small segment of the population, potentially exacerbating socio-economic inequalities. Ensuring equitable access to the benefits generated by biochar transport—such as by supporting local employment and businesses—is crucial for maximising positive socio-economic outcomes.

**Summary:** Biochar production could stimulate local economies and create jobs, however, ensuring these benefits are equitably distributed is essential to prevent socio-economic inequalities in communities.

## Biochar application

### Social acceptability

The two main factors determining levels of social acceptance of biochar application are the perceived environmental and agricultural benefits. Whilst the perceived environmental benefits are more likely to appeal to climate conscious corporate organisations, the perceived agricultural benefits would appeal more to the farming industry. Complexities may arise when considering application scenarios and who would potentially receive the benefit. For example, varying application rates will determine which stakeholder will receive the greatest share of benefits. Therefore, the degree to which each of these aspects are emphasised and balanced will determine the level of social acceptance amongst each of these stakeholders

One of the primary drivers of social acceptability for biochar application is its perceived environmental benefits (Ippolito et al.  2012). Biochar is lauded for its ability to improve soil health, increase agricultural yields, sequester carbon, and reduce greenhouse gas emissions. These benefits align well with growing societal concerns about climate change and environmental degradation. Raising general awareness of biochar and ensuring that these benefits are communicated to the public and stakeholders, could increase the social acceptability of biochar (Devine-Wright et al.  2017). However, it should also be noted that the degree of acceptability can vary depending on local environmental priorities and the perceived immediacy and relevance of biochar’s benefits to a particular community. For example, communities facing severe soil degradation or water scarcity issues may be more receptive to biochar application due to its potential to address these specific challenges, whereas those who hold negative associations around biochar application, for example that it may contain carcinogens from contaminated biomass (Price & Morris 2023), may be less so.

Cultural attitudes and traditional agricultural practices also play a crucial role in the social acceptability of biochar application. Innovations that are perceived as too disruptive or not in harmony with local practices and beliefs may face resistance. Therefore, integrating biochar application into existing agricultural systems in a way that respects and builds upon traditional knowledge can enhance its acceptability. Engaging with local communities, involving them in the design and implementation of biochar projects, and demonstrating respect for local customs and knowledge are all essential for gaining social acceptance (Devine-Wright et al.  2017).

**Summary:** Effective communication, respect for traditional practices, and community engagement are key for the social acceptance of the application of biochar.

## Impacts on local communities

Biochar’s primary impact on local communities comes through its effect on soil health and agricultural productivity. By improving soil fertility, water retention, and nutrient cycling, biochar could significantly enhance crop yields. This is particularly beneficial for communities in areas facing soil degradation or nutrient depletion, as it could lead to better food security and resilience against climate variability. Increased crop yields can also translate into higher incomes for farmers, which have the potential to uplift the entire community (Alkharabsheh et al.  2021).

As the long-term effects of biochar application on soil are not known, some communities may be reluctant to use it, however a lack of robust evidence could have shorter term impacts. Price and Morris (2023) found that farmers in England had concerns about how biochar could impact existing auditing and contract requirements, for example if the Red Tractor assurance permitted the use of biochar, and if its use would impact on their ability to acquire supermarket contracts. This demonstrates that the benefits of biochar may not be widely communicated or understood.

However, while biochar is generally considered safe, there are potential health and safety concerns related to its production and application that can impact communities. Dust from biochar can pose respiratory risks if not properly managed, and the handling of biochar requires proper training to avoid such risks (Sigmund et al.  2017). Ensuring that communities are informed about the safe use of biochar is crucial to mitigating health concerns and ensuring the wellbeing of local communities.

**Summary:** Biochar application can benefit communities by improving food security and increasing farmers' incomes, especially in areas with degraded soils. However, it's important to manage biochar's application safely to prevent respiratory risks.

## Government policy

Government policy on biochar application can have a profound influence on the social fabric of communities, particularly those engaged in agriculture or living in areas susceptible to environmental degradation (Hounnou, 2024).

Government policies promoting biochar application often include components aimed at educating and engaging with communities. Through outreach programs, workshops, and demonstration projects, these policies can increase awareness about the benefits of biochar, such as improved soil health, enhanced crop yields, and carbon sequestration. By fostering a deeper understanding of biochar’s environmental and agricultural benefits, policies can encourage community buy-in and participation in biochar initiatives. Government policies that support community-led biochar projects or cooperative models further reinforce this cohesion with community by ensuring that projects are aligned with community needs and values (Pourhashem et al.  2018).

It is also important to consider providing subsidies or financial assistance to smallholder farmers and marginalised groups to afford biochar. By addressing the cost barrier, government policies can democratise access to biochar’s benefits, ensuring that economic gains, such as increased agricultural productivity and resilience to climate change, are equitably distributed (Pourhashem et al.  2018).

Biochar currently has limited land application use in the UK. In England, application of biochar is currently governed by a low-risk waste position (LRWP 61: Storing and spreading biochar to benefit land). This states that biochar can be applied as a soil amendment providing that the biochar has been applied sparingly to benefit land (less than 1 tonne per hectare), and that it is a low-risk waste that has been produced from pyrolysis of a restricted list of waste codes (comprising plant, wood and vegetable wastes only).

Currently, limited governance of biochar standards is partly responsible for the lacklustre biochar market, with UK farmers expressing concern about its application (Price & Morris, 2023). This study also highlighted concerns around the lack of available data to inform the creation of robust standards and regulations around biochar application. For example, there are currently no soil carbon codes designed to gauge the impact of carbon sequestration when applied to soil in the UK (Price & Morris, 2023). As most research conducted to date is theoretical or based on small-scale application, wider research is required to establish suitable application rates to guide future regulation for biochar from different waste sources, or of different compositions.

**Summary:** The implementation of workshops and outreach that boosts awareness of biochar's benefits can enhance community engagement and acceptance. The provision of financial assistance to smallholder farmers could help to ensure equity and access to the whole community.

## Socio-economic impacts

One of the primary socio-economic impacts of biochar application is the potential for enhanced agricultural productivity. By improving soil health, biochar can increase crop yields, directly affecting the livelihoods of farmers and the economic resilience of rural communities (Shoudho et al.  2024).

This increase in productivity can lead to higher incomes for farmers, reducing poverty levels and contributing to overall economic growth within the community. The economic benefits of biochar application could strengthen social ties, as successful agricultural practices are often shared and adopted among community members, fostering a sense of solidarity and mutual support. By ensuring benefits are equally distributed and supportive policies are implemented, the application of biochar could contribute to sustainable development and enhanced social well-being (Müller et al.  2019). In the UK, biochar could offer cost savings to farmers over traditional fertilisers, owing to it being a low-cost method to reduce GHG emissions, especially if the biochar could be produced on farm, contributing to a circular economy. In the UK, biochar could bring efficiencies to farming practices by offering an alternative to traditional fertilisers, such as biosolids and manures which have concerns around contaminants. This could also contribute to a circular economy if the biochar is produced at source or supplied locally. Much of this benefit would be lost, however, if biochar is produced on an industrial scale, where prices would likely outstrip the benefits (Price & Morris, 2023).

**Summary:** Biochar application could enhance agricultural productivity and community resilience, leading to improved farmer incomes and stronger social ties. This could promote sustainable development and social well-being.

# Conclusions

## Summary of environmental and social impacts

This report explored the environmental and social impacts of feedstock sourcing, production and transport for biochar as well as its application. While it is clear that biochar can have many positive impacts, such as carbon capture and providing a use for some wastes, there are negative and unknown long-term environmental impacts as well as socio-economic considerations that require further exploration.

### Feedstock availability

The UK has the potential to scale up the existing biochar industry to climate relevant levels, with multiple Mt of feedstock available from forestry and agricultural residues that could translate into multiple Mt of $CO_2$ removal per year if used to produce biochar. There is, however, competition for these residues for other, more established UK markets for animal bedding, manufacture and energy that may conflict with biochar production. The availability and accessibility of these residues also varies significantly across regions in the UK (Tang et al. 2024). If the demand for biochar grows, the UK should consider importing from sustainable sources, or using surplus biomass from within the EU, as importing from developing countries could potentially impact food sources leading to land degradation, loss of biodiversity, food scarcity and increased food price in these supplying countries (Smith et al. 2019).

### Environmental impacts

From the available evidence, there is no one-size-fits-all biochar due to its heterogeneity. But rather a context-specificity when considering which positive impacts are worth any potential negative impacts that may be realised in any given environment.

In general, clean wood residues or waste is a favourable biochar feedstock for preventing the worst contaminant load in the produced biochar, although other factors like the receiving environment and pyrolysis temperatures are important. Many of the potential environmental impacts could be minimised or mitigated with appropriate environmental management and permitting.

There are potentially a large number of use cases for biochar including emissions curtailment from agriculture, livestock production efficiency gains, soil contamination remediation, and improvements to soil functioning. However, there are a wide variety of potential negative environmental impacts that may be dose dependent or based on production conditions that are still poorly understood and under-researched in real-world contexts. A more comprehensive understanding of these effects is needed in the UK context. This is in-part being addressed by a circular business-to-business biochar platform that is being trialled in the UK that involves hundreds of dairy farms and a forestry and sawmilling business, enabling farmers to trial biochar in slurry management and animal beddings with the aim of facilitating a self-sustaining UK biochar industry (Clarke et al.  2021). However there is still potential for unintended co-applied metals or compounds to cause negative environmental impacts, and mitigations may be needed.

Consideration of which environmental benefits are worth sacrificing to maximise others should be considered in the context of the prevailing environmental remediation strategy that biochar is intended for. For example, whether it is acceptable for biochar to function as a relatively short duration climate mitigation tool in order to maximise yield and minimise PM emissions (through low-temperature pyrolysis).

### Social impacts

Public perceptions and social acceptability of biochar are influenced by its perceived environmental benefits and potential drawbacks. Sustainable sourcing practices and transparent communication can bolster its acceptability. However, apprehensions regarding feedstock competition with food production and deforestation can tarnish public perception, indicating the importance of inclusive policies and community engagement in biochar initiatives.

The potential impact of biochar on local communities is highly significant, offering avenues for economic growth through job creation and agricultural productivity enhancements. Nevertheless, potential social tensions arising from resource allocation and land use highlight the necessity for equitable benefit distribution and early community engagement. Government policy plays a critical role in biochar’s integration into broader agricultural systems and carbon management strategies. Policy that provides supportive frameworks, balancing incentives with environmental safety, is required to improve social acceptance of biochar as a CCS technology.

### Conclusion

In conclusion, biochar is a promising technology for climate change mitigation and agricultural enhancement. Its successful implementation hinges on a comprehensive understanding of both its environmental advantages and social considerations, requiring stakeholder engagement, sustainable practices, and robust policy support. Through such a concerted approach, biochar’s full potential can be harnessed, contributing to a more sustainable and equitable future.

## Evidence gaps and research priorities

There remain several evidence gaps that necessitate further investigation. Addressing these gaps is essential for building a more robust and predictive understanding of biochar’s environmental impacts across its life cycle and the context-specificity of these impacts. Key evidence gaps for the environmental impacts include:

- **Long-term stability of sequestered carbon**: Current research provides varying estimates on the permanence of biochar’s carbon sequestration capabilities. Long-term studies would help in better understanding the stability of biochar in different soil types and climatic conditions. Additionally, the extent to which low-temperature pyrolysis affects the long-term durability of biochar is important for decision making around climate mitigation. This understanding is important not only for environmental sustainability but also for carbon markets, as precise carbon accounting throughout the life cycle of biochar is essential for effective carbon sequestration strategies.

- **Impacts of airborne pollution**: In particular, the long-term impacts (on human health, biodiversity and radiative forcing) of airborne emissions, including an improved understanding of the resources (e.g. water for dampening biochar) required to ameliorate such impacts. This is important for keeping updated inventories to guide biochar producers and users (Luyima et al. 2021).

- **Emissions from pyrolysis systems:** Including a wider range of both pollutants and feedstocks investigated, and the effect of more stringent emission filtering technologies on state-of-the-art pyrolysis technologies (Sormo et al. 2020).

- **Livestock applications**: Including the mechanisms by which biochar may selectively absorb toxins in the digestive tract and how this leads to improved animal metabolic functions (Schmidt et al. 2019) as well as its adsorption of volatilised NH3 from animal manure.

- **Biochar toxicology and dosage-related impacts**: More research is needed to constrain safe thresholds of all variables involved in biochar production and application where toxins in biochar and other dose-dependent effects like competition for plant nutrients can be controlled at safe levels. For example, the International Biochar Initiative has produced a white paper on the production, hazard analysis and detection of dioxins, and unified standards are needed for a wider range of substances and application media (Xiang et al. 2021).

- **Soil microbiome and nutrient cycling impacts:** Study on the effects of biochar soil amendment on various aspects of the soil microbiome is needed, such as its effects on viruses and protists, understanding key microbial food web interactions, community composition changes and microbial functioning, coupling of nutrient transformation processes and which genes are associated with these, the microbes that benefit plant growth and health and how they interact with plant roots (Dai et al. 2021).

- **Developing novel remediation methods**: The testing and continued development of innovations that can prevent or circumvent the risks of biochar's negative environmental impacts should be further pursued (Xiang et al. 2021). For example, testing the effects of using macroscopic biochar structures like sheets on biochar leaching into water bodies.

- **Standardised research methodologies:** To address the variability in research findings, there is a need for standardised research methodologies, notably in the biochar LCA literature (Tisserant & Cherubini, 2019), but also in terms of pyrolysis conditions, feedstocks, and application context for a clearer picture of the context-specificity of biochar's impacts. This would also develop professional expertise around application and management of biochar for facilitation of consistent industrial standards (Xiang et al. 2021).

Key evidence gaps for the social science relating to biochar include:

- **Socio-economic impacts at scale:** The socio-economic impacts of biochar, particularly on rural communities, smallholder farmers and deployment within a UK setting, are under-researched, possibly due to a lack of real-world applications. There is a gap in understanding how biochar production and application can be scaled up in the UK without exacerbating socio-economic inequalities or negatively impacting food security.

- **Public perception and policy frameworks:** Further research is needed to explore the social acceptability of biochar across specific communities and stakeholders in the UK. This includes understanding public perceptions, identifying barriers to acceptability, and developing policy frameworks that support sustainable biochar practices. Further research into public perceptions of biochar pilot projects in the UK would be beneficial to gauge acceptability of the technology in practice, rather than solely in theory.

- **Policy and economic analysis:** There is a need for in-depth policy and economic analyses to understand the frameworks and incentives required to promote sustainable biochar practices. Research should focus on policy mechanisms that can support biochar's adoption while ensuring equitable benefits for stakeholders.

- **Engagement and education strategies:** Developing effective engagement and education strategies to increase public awareness and acceptability of biochar is essential. Research should explore best practices for stakeholder involvement and the dissemination of biochar knowledge to diverse audiences.

# Appendices

## Methodology

Parameters for including suitable sources in the review were devised according to academic best practice based on the timeliness, accuracy, authority and objectivity of the research, thereby excluding sources of insufficient quality to contribute to the required quality of results. All sources used as part of this research were assessed against this source reliability protocol (included in Table 6 overleaf).

Relevant literature was identified, including 'grey' literature (e.g., conference papers, government publications, social surveys, industry standards, market reports, and policy statements) and scientific papers, using a range of search strings on both public and academic platforms.

A framework of research questions was used to form the basis for collating information. Following the assessment of all relevant literature, a gap analysis was undertaken to identify research gaps in the available evidence. A final search relating to these specific gaps was conducted to ensure that no relevant literature was missed.

**Table 6 The source reliability protocol used to assess the and suitability reliability of sources used in the research.**

| Criteria | Red | Amber | Green | Grey |
|---|---|---|---|---|
| **1. Currentness** | | | | |
| **How up to date is the information?** | 20-30 years' old | 10-20 years' old | 0-10 years' old | Date not identifiable |
| **2. Accuracy** | | | | |
| **Does the item have a clearly stated aim or brief?<br>Is it detailed and factual?<br>Does the work contradict itself?<br>Does the work appear to be carefully prepared (e.g. well-written or designed, mostly free of errors, easy to navigate)?<br>Does it have a stated methodology?** | No clear aims or methodology, contains several errors, contradicts itself | Aims and methodology explored in less detail, some errors | Detailed aims and clear methodology, very few errors | N/A |

| Criteria | Red | Amber | Green | Grey |
|---|---|---|---|---|
| **3. Authority** | | | | |
| **Is the author associated with a reputable organisation? Do they have relevant professional qualifications or experience? Are they cited by others? If published by an organisation, is the organisation reputable? Is the organisation an authority in the field? Does the item have a detailed, credible reference list? Has it been peer reviewed? Has it been edited by a reputable authority?** | No clear expertise and / or not reputable organisation, no reference list, no reference to review/editing process, | Some relevant expertise, review/editing process unclear | Reputable organisation, considerable expertise, reviewed and / or edited by technical experts and well-supported by credible sources, | N/A |
| **4. Objectivity** | | | | |
| **Is the author presenting their opinion or factual evidence? Is the goal of the work to inform or persuade? Does the work seem to be balanced and** | Clear vested interest, strong opinions presented, written | Possible vested interest, opinion-driven | Independent expert, balanced views / factual evidence presented, clearly identified funding | No evidence of funding source |

| | | |
|---|---|---|
| **consistent?**<br>**Independent expert or vested interest?**<br>**Who funded/sponsored the work?** | to persuade rather than inform | source with lack of vested interest |

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# List of abbreviations

| Abbreviation | Definition |
|---|---|
| **BECCS** | Bioenergy with carbon capture and storage |
| **CDR** | Carbon dioxide removal |
| **$CO_2$** | Carbon dioxide |
| **CRCF** | Carbon Removal Certification Framework |
| **DACCS** | Direct air carbon capture and storage |
| **DGRTD** | Directorate General for Research and Innovation |
| **ERW** | Enhanced rock weathering |
| **GGR** | Greenhouse gas removal |
| **GHG** | Greenhouse gas |
| **HTC** | Hydrothermal carbonization |
| **JRC** | European Commission Joint Research Centre |
| **LCA** | Life cycle assessment |
| **MRV** | Monitoring, reporting and verification |
| **MSW** | Municipal solid waste |
| **Mtoe** | Mega tonnes of oil equivalent |
| **NOx** | Nitrous oxides |
| **PAH** | Polycyclic aromatic hydrocarbons |

| Abbreviation | Definition |
| --- | --- |
| **PM** | Particulate Matter |
| **TRL** | Technology readiness level |
| **VOC** | Volatile organic compound |

# Glossary

| Term | Definition |
|---|---|
| Carbon sequestration | The process of capturing and storing atmospheric carbon dioxide |
| Greenhouse gas | Gases in the atmosphere that raise earth's surface temperature; consisting of $CO_2$, $CH_4$, $N_2O$, HFCs and PFCs |
| Greenhouse gas removal | Also known as negative emissions technologies, greenhouse gas removal technologies encompass a range of techniques for reducing the concentration of GHGs in earth's atmosphere |

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