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Scoping the potential for biochar in a Scottish context

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1 Executive summary

1.1 Introduction and aims

Removing greenhouse gases from the atmospheric cycle and into permanent storage is key to achieving net zero. Biochar is one of the most widely adopted methods of doing so globally.

Biochar is a solid carbon material similar to charcoal, made by decomposing biological material, typically plant biomass, at very high temperatures – a process known as pyrolysis. Biochar can store carbon in the long term, allowing for the transfer of carbon out of the active cycle and into permanent storage.

This report aims to assess the potential for biochar deployment in Scotland, drawing on a rapid evidence assessment (REA) of published literature and nine stakeholder interviews. It examines feedstock availability, biochar impacts related to carbon sequestration, soil health and yields, international experience with biochar, potential deployment pathways for Scotland, and key barriers and enablers for biochar deployment.

1.2 Key findings

1.2.1 Feedstock sources

Scotland has substantial biomass resources that could supply biochar production, including residue and waste streams from forestry, sawmills, whisky production, agriculture and municipal sources. The availability of these feedstocks is not likely to limit biochar deployment, in particular given forestry processing volumes are projected to almost treble over the next 20 years.

However, a significant gap exists regarding biochar-relevant analysis of Scotland's largest potential feedstock streams, including agricultural residues, sewage sludge and waste wood.

1.2.2 Carbon sequestration and stability

Biochar provides stable, long-term carbon storage. For woody feedstocks such as forestry residues (one of the most feasible for Scotland) each tonne of biochar removes roughly 3 tonnes of carbon dioxide from the atmosphere after accounting for production emissions. This has been confirmed by operational data in the UK.

Scotland's conditions are favourable for long-term carbon storage. Biochar typically degrades more slowly in cooler climates. Most Scottish agricultural soils are mineral soils, favourable to biochar retention. Scotland's high rainfall may reduce measurable soil carbon gains over time, but this is a measurement consideration rather than a reduced storage benefit.

1.2.3 Soil health, land productivity and climate resilience

Biochar has been shown to increase crop yields in tropical systems, and in degraded soils, but there is limited data from studies in Scotland.

A limited pilot study involving Scotland’s Rural College (SRUC) in 2023-2025 showed an increase in grassland (16-18%) and arable (34%) yields through co-application of biochar with organic fertiliser, compared with fertiliser alone. This suggests that biochar can deliver benefits under Scottish conditions when used as part of existing farm practice.

In a separate study, biochar has been found to raise soil pH, benefitting approximately half of Scottish agricultural soils (low pH can reduce productivity). It has also reduced nitrous oxide emissions from mineral soils by 12 to 38%. Application to peat should be avoided given uncertainty around potential to increase emissions.

1.2.4 Lessons from international experience

Scotland can learn from biochar policy development in other European countries.

Denmark has the most advanced policy framework in Europe for biochar, but there is a significant gap between ambition and deployment. In Sweden, the biochar sector has grown through public co-financing, municipality-level support – a collaborative approach where biochar plants are treated as learning sites alongside production infrastructure.

Germany benefits from strong industrial capacity in pyrolysis technology and regulatory recognition of pyrolysis as an acceptable method for phosphorus recovery from sewage sludge, creating a market pull for the technology.

1.2.5 Potential biochar deployment pathways for Scotland

We have identified seven potential pathways that could be explored for biochar deployment in Scotland. The viability of each depends on the match between feedstock, production conditions and end-use. There is a trade-off between optimising for carbon permanence and optimising for immediate soil benefits.

Use of biochar as an agricultural soil amendment offers the highest carbon sequestration potential. The most promising approach for Scotland is co-application with organic fertilisers at low doses, requiring minimal change to current farm practice. The carbon storage benefit is delivered regardless of the agronomic outcome.

1.2.6 Wider barriers and enablers

Biochar manufacture is classified as a waste management activity in Scotland, with pyrolysis facilities processing over 50 kg per hour requiring full waste management licensing. This was consistently identified by stakeholders as the primary barrier to investment.

The market for biochar is at an early stage. Production costs are highly variable, carbon credit revenue will be critical for most pathways, and no mechanism currently exists to support the transition from demonstrator to commercial operation.

Public awareness of carbon removal technologies is very low, and farmer adoption is constrained by limited Scottish evidence and uncertainty over returns. Trust will depend on credible, independent evidence.

1.3 Areas for future action and research

We have identified several areas where action or research could be undertaken to support a move towards biochar use in Scotland. These are:

- Taking steps to bridge the gap between demonstrator and commercial stages through targeted support for early commercial operations. Both UK and Scottish stakeholders have identified that current funding mechanisms leave this gap, which acts as a distinct constraint to deployment.
- Developing end-of-waste criteria for qualifying biochar through engagement with the Scottish Environment Protection Agency, in parallel with any future biochar policy commitment. International experience identifies this as a critical-path enabler for deployment.
- Commissioning Scottish agricultural field trials at economically realistic application rates across priority feedstocks and soil types, including long-term monitoring of both carbon persistence and soil health outcomes.
- Opportunity mapping for biochar production at different scales, identifying where existing and future infrastructure might favour investment, considering the feedstock logistics and end-uses, including the heat product.
- Conducting comparative LCAs across major Scottish feedstock resources and supply chains, to assess biochar against credible alternative uses rather than in isolation.
- In the short term, agreeing a standardised framework for biochar characterisation, traceability and monitoring, covering both climate claims and environmental safeguards.

Contents

2 Glossary / Abbreviations table

Term	Definition
AD	Anaerobic digestion
BBF	Biochar-based fertiliser
BECCS	Bioenergy with carbon capture and storage
°C	Degrees celsius
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH_4	Methane
CNI	Carbon Neutral Islands
CO	Carbon monoxide
CO_2(e)	Carbon dioxide (equivalent)
DACCS	Direct air capture and carbon storage
DDGS	Distillers Dried Grains with Solubles
DEFRA	Department for Environment, Food & Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DKK	Danish krone
ETI	Energy Technologies Institute
EU	European Union
GGR	Greenhouse gas removal
GHG	Greenhouse gas
Ha	Hectare
HTC	Hydrothermal carbonisation
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	kilometres
LCA	Life cycle assessment
M	Million
mm	millimetres
MW	Megawatts
MRV	Monitoring, reporting, and verification

Term	Definition
NETs	Negative Emissions Technologies
NGO	Non-governmental organisation
N_2O	Nitrous oxide
OPEX	Operational expenditure
PESTEL	Political, economic, social, technological, environmental, legal
PM	Particulate Matter
REA	Rapid evidence assessment
RHI	Renewable Heat Incentive
SEPA	Scottish Environment Protection Agency
SOC	Soil organic carbon
SRC	Short rotation coppice
SRUC	Scotland's Rural College
t	tonnes
TRL	Technology Readiness Levels
US	United States

3 Introduction

3.1 Background and context

Biochar is a solid carbon material similar to charcoal. It is made from biological material, or biomass, through pyrolysis. Pyrolysis involves the decomposition of organic materials at high temperatures in the absence of oxygen. As a stable material, biochar can store carbon in the long term. Biochar therefore represents the transfer of carbon out of the active cycle and into permanent storage.

Greenhouse gas removal (GGR) technologies have been identified as a key tool for Scotland and the United Kingdom (UK) to achieve net zero, to offset residual emissions of carbon dioxide (CO_2) from fossil fuels and address the emission of non-CO_2 trace gases (mainly from land use). Globally, biochar is currently the most widely adopted method of permanent GGR, accounting for 90% of all GGR removal credits delivered by the global voluntary carbon market (IBI, 2023).

The Seventh Carbon Budget, presented to the UK Government by the Climate Change Committee in February 2025 is the first to include biochar in its pathways for net zero (Climate Change Committee, 2025). The Department for Energy Security and Net Zero has also recently consulted on "non-Carbon Capture and Storage reliant" GGRs, where biochar has become the focus, recognising the importance of geological carbon storage for achieving net zero. Biochar is expected to be included in the integration of GGR into the UK Emissions Trading Scheme (UK ETS), a step predicted to become operational by the end of 2029 (subject to further consultation and regulatory assessment) (UK Government, Scottish Government, Welsh Government, and Department of Agriculture, Environment & Rural Affairs for Northern Ireland, 2025).

Strategies to develop a viable biochar carbon removal sector have rested on three principles:

1. Biochar provides end-user value at the same time as permanently storing carbon;
2. The benefits of using biochar are scalable, i.e., local benefits are equally valuable regardless of the aggregate scale of adoption; and
3. The societal benefits of making biochar exceed the short-term benefits gained by the end-user.

These principles suggest a win-win opportunity for delivery of GGR. However, commercial biochar production has only recently begun in the UK, largely due to UK Government investment in demonstration and pilot projects. It is in this context that our report examines the existing evidence and experience on the properties of biochar materials, efforts to commercialise biochar use, and pathways to accelerate and/or increase its deployment.

3.2 Report aims and structure

In this report, we aim to present an overview of existing evidence of relevance to the potential for deploying biochar in Scotland. The key objectives are to:

- Assess the supply chain viability for biochar in Scotland, considering feedstock sources, necessary infrastructure and logistics, and costs, benefits, risks and barriers;

- Review existing evidence on the effects of biochar on carbon sequestration, soil health, and agricultural performance, under Scotland's climate and soil conditions;
- Outline lessons learned from a selection of countries where biochar implementation is further advanced.

We also aim to identify where key evidence gaps exist, to indicate where new work could efficiently and effectively inform future biochar deployment pathways in Scotland.

4 Methodology

For the study, we used a Rapid Evidence Assessment method for literature review, reviewing in detail 10 pieces of academic literature on feedstocks, 13 on carbon impacts, and 27 on soil impacts, plus 66 pieces of grey literature. This was supplemented by a series of 9 online stakeholder interviews, with 12 individuals from the fields of industry, government, research and the NGO sector. Our methodology was designed to identify information relevant to the key research topics, including: feedstock sources, carbon impact, effect of biochar on soil health, land productivity and climate resilience, processing infrastructure, supply chain logistics, and capital and operational expenditure. It also aimed to capture information for the economic assessment and political, economic, social, technological, environmental and legal (PESTEL) analysis. The methodology is described in detail in Appendix A.

5 Evidence base for biochar potential in Scotland

In this section, we focus on the application of biochar to agricultural soils as part of crop and livestock production systems, since that is the main use explored in the literature we have reviewed. The chapter concludes with the consideration of some potential alternative biochar deployment pathways for Scotland (other than direct application to soils).

5.1 Feedstock sources

Feedstock availability is not likely to be a limiting factor for biochar production in Scotland. Scotland has substantial biomass resources across forestry, agriculture, whisky production and waste streams, which are set to grow. These have been assessed for their potential role in the energy system and in non-fuel uses, leading to a Draft Bioenergy Policy Statement (Scottish Government, 2024). Pyrolysis has not been considered as a lead use option for potential feedstocks in Scottish policy, but most of the resources identified could theoretically supply biochar production. Estimated national potential of biochar production in the research literature reviewed is shown in Table 5-1.

Year	Million tonnes of carbon dioxide equivalent (Mt CO_2e)
2009	0.4-2.0
2030	1.4-4.2
2050	1.5-4.8

Table 5-1: Estimated national potential of biochar production for Scotland (Ahmed, et al., 2012)

A key challenge encountered in this research is the **significant gap in evidence related to Scotland's largest potential feedstock streams for biochar**. Some of these feedstock streams have no Scottish biochar-specific research, though United Kingdom (UK)-level volume and characterisation data exists for most. The studies identified primarily assess feedstock availability, competing uses, and calorific properties, not biochar production potential or agronomic outcomes from biochar produced from these feedstocks.

5.1.1 Summary of evidence on feedstocks

Here, we briefly outline the areas of confident knowledge, issues under active debate and key evidence gaps in relation to feedstocks for biochar in Scotland. In the following sections, we discuss specific feedstock types in a little more detail. In Appendix B, we include a table with an overview of the level of confidence of the evidence presented on feedstocks.

Areas of confident knowledge. Scotland has substantial and diverse biomass resources that could theoretically supply biochar production. Forestry and sawmill co-products are the most immediately viable feedstock, with well-characterised volumes and existing processing infrastructure concentrated in Scotland. Timber processing volumes are projected to grow significantly over the next two decades. The whisky industry produces large, well-characterised point-source residues, though existing evidence suggests competing uses (particularly animal feed) currently deliver climate benefit.

Issues under active debate. The central question is how biochar compares to existing uses in terms of overall climate benefit, including both carbon sequestration and avoided emissions. Most feedstock streams have established end-uses, and any diversion to biochar production could alter existing supply chains. For feedstocks within Scotland, comparative evidence is largely missing, meaning the relative climate benefit of biochar versus current uses is unknown rather than demonstrated to be lower. The economics of feedstock collection, transport (particularly for wet wastes) and pre-processing also remain under-evaluated in a Scottish biochar context.

Key evidence gaps. The most significant gap is the absence of research into the potential of Scotland's largest feedstock streams to be used to produce biochar. There is a lack of Scottish biochar research for agricultural residues, sewage sludge, waste wood, and horticultural residues despite them having the largest available volumes and the fewest competing high value uses. The peer-reviewed literature is biased toward whisky industry co-products and specific forestry sites, while quantitative volume data exists primarily for forestry products (through Forest Research statistics) and whisky co-products (through industry reporting) (Forest Research, 2025b). For agricultural residues, sewage sludge and waste wood, Scottish-specific availability data were not identified in the peer-reviewed literature. No comparative LCA has been conducted weighing biochar against other uses across Scottish feedstock streams.

5.1.2 Forestry residues and sawmill co-products

Evidence base: Multiple studies on sawmill throughput, pellet production, and forestry brash volumes. One Scottish lab-scale biochar characterisation study (Flow Country brash). No Scottish field trials. No peer-reviewed data on arboricultural arisings in Scotland.

Forestry residues is the feedstock stream with the most extensively documented supply data and the most immediate relevance for Scottish biochar production, in contrast to agricultural residues where no biochar-specific research was identified. Currently 5.5 million tonnes per year of softwood (2.25 M dry t) pass through UK sawmills, with half of UK processing conducted in Scotland. Ten mills account for 60% of total throughput (Forest Research, 2025b). Woodchip, bark and sawdust are sawmill co-products with established competing markets including bioenergy, panel board, and horticultural products.

Conversion of sawmill co-products into saleable pellets has been a marked trend over the past decade: of the 327,000 t of softwood pellets produced in 2024, more than half were derived from sawmill co-products (Forest Research, 2025b). Scottish softwood availability is forecast to increase by approximately 40% from the current period to the late 2030s, rising from 8.8 to 12.3 M meters cubed overbark standing (Forest Research, 2025b), which suggests a rapidly expanding supply base that could support biochar production.

Beyond sawmills, forestry harvesting generates substantial brash residues. Gaffney, et al. (2024) estimated 80 t of forestry brash per hectare are available post-harvest from Scottish forest plantations. If left on-site this can release organic carbon, potassium and phosphorus into sensitive waters, dependent on specifics of the site (Gaffney, et al., 2024). Brash removal has been proposed as a management option that could also supply pyrolysis feedstock, though the logistics and costs of collection at scale have not been assessed for Scottish conditions (Gaffney, et al., 2024).

The properties of biochar produced from Flow Country conifer brash have been examined at laboratory scale (Pap, et al., 2022). The biochar may be more appropriately used to recycle phosphorus to new plantations rather than for bulk soil application (Pap, et al., 2022). No field-scale trials using Scottish forestry brash biochar have been conducted.

Arboricultural arisings, material from tree surgery and urban tree management, are currently the feedstock used by one of the few operational biochar production facilities in the UK (WoodTek, Surrey). This suggests commercial viability at small scale, though Scottish-specific volumes and supply chain data could not be identified in the peer-reviewed literature.

5.1.3 Whisky co-products

Evidence base: Well-studied feedstock stream with four recent studies including three life cycle assessments (LCAs). All examined animal feed, anaerobic digestion (AD), or biorefinery routes. No studies assessed examined biochar production from whisky co-products.

The Scottish whisky industry produces around 7.65 Mt of pot ale and 1.34 Mt of draff per year from 136 individual distilleries (Andrews, et al., 2025). These are well-characterised, point-source residues with established supply chains. However, pot ale is approximately 96% water, meaning the dry mass available for thermal processing is a small fraction of the headline volume (Edwards, et al., 2022).

From the evidence assessed, this is the most-studied Scottish feedstock stream, although none of the studies examined biochar production. All studies identified instead focused on use in animal feed, AD, or biorefinery routes (Andrews, et al., 2025; Duffy, et al., 2023; Schestak, et al., 2022; Edwards, et al., 2022). Three recent LCAs compared established end-use options and found that animal feed use (displacing imported soy) delivers 2.5–8.0 times greater greenhouse gas (GHG) mitigation than AD (Duffy, et al., 2023). This finding suggests that any diversion of these resources would need comparative life cycle analysis, as any future biochar pathway would need to demonstrate comparable or greater benefit unless excess volume is used.

Pot ale has also been used for nutrient recovery through reapplication to land as a fertiliser (Edwards, et al., 2022). No evidence was found for integration of biochar into the whisky supply chain, for example in barley growing. Scotland's brewing industry produces similar co-product types but at substantially smaller volumes, and no biochar-relevant research was identified for this sector.

5.1.4 Agricultural residues

Evidence base: UK-wide volume and characterisation data available. One international study showed straw-to-biochar conversion benefits. No studies identified examining biochar production from Scottish agricultural residues (barley straw, oat straw, horticultural waste).

The UK produces around 15 M dry t of agricultural waste per year, including 6.6 Mt as wheat straw (Bolaji, et al., 2021). Scotland accounts for a disproportionately high share of barley and oat straw (26% and 21% of UK totals respectively), but also a markedly higher proportion of livestock farming (Bolaji, et al., 2021). The Department for Environment, Food & Rural Affairs estimates 2–3 Mt of straw per year is potentially available for alternative uses across the UK (Bolaji, et al., 2021).

The fate of crop straw is an economic decision between sale into existing markets for animal bedding and feed, or direct return to the soil during harvest. In terms of soil carbon, converting straw to biochar before soil application should be more effective than direct incorporation, since straw is readily degradable. This has been demonstrated experimentally: the amount of carbon stored in the soil was increased four-fold by prior conversion to biochar (Liu, et al., 2024).

Livestock manures and slurries present a different picture. The economic limits to transport of wet wastes (liquid manure, slurry) may be as low as 10 kilometres (km), compared to 30–50 km for dry biomass (Bevan, et al., 2021; Edwards, et al., 2022). Manures are not well suited as a pyrolysis feedstock due to their high moisture content but they contain more reactive nitrogen, so provide a more valuable vehicle for directly delivering biochar to land. In contrast, dry low-nitrogen residues like straw are a better primary feedstock for pyrolysis.

No recent studies were identified examining biochar production from Scotland-specific agricultural resources such as barley and oat straw, or wastes arising from protected horticultural crops including soft fruit. Given that agricultural residues represent the largest biomass stream in Scotland, and one with fewer competing high-value uses than whisky co-products, this gap is significant.

5.1.5 Other waste streams

Evidence base: UK-level studies on food waste management and hydrothermal carbonisation of digestate. One village-scale feasibility study. No national assessment of sewage sludge pyrolysis potential in Scotland. No Scotland-specific waste-to-biochar studies identified.

The UK generates 13.1 Mt of food waste annually, managed through AD or composting (14–41%, depending on the stage in the food supply chain at which the waste is generated), incineration (13–48%), landfill (1–23%), animal feed (4–27%), or land spreading (30–60% of primary production waste) (Jeswani, et al., 2021). Converting wet wastes to biochar depends on efficient mechanical extraction of organic solids, and energy for pre-drying of feedstock that is roughly equivalent to the heat product from pyrolysis. The life cycle benefits depend on the alternative end-use, particularly whether biochar production avoids the need for incineration and ash disposal.

Recent academic work has examined conversion of food waste digestate to hydrochar via hydrothermal carbonisation (HTC), noting that the UK currently produces 1.11 Mt per year of wet digestate (Gamaralalage, et al., 2025). Hydrochar is not biochar, but has comparable processing and feedstock requirements. A village-scale HTC study (Bevan, et al., 2021) projected only 99 t of hydrochar per year from food waste and sewage from 2,250 residents. This evidence, while tangential, suggests that biochar from municipal waste sources is likely better suited to centralised facilities or AD integration rather than dispersed, small-scale production.

No national assessment has been made for the potential pyrolysis of sewage sludge in Scotland (digested or non-digested), only part of which arises in large facilities operated by Scottish Water. Waste wood and green waste represent additional potential feedstocks, but Scotland-specific availability data were not identified in the peer-reviewed literature reviewed.

5.1.6 Biomass and energy crops

Evidence base: One UK-wide bioenergy assessment and one ClimateXChange report on perennial energy crops in Scotland. No evidence found linking energy crop production to biochar pathways in Scotland.

Perennial energy crops, including short rotation coppice willow and miscanthus, have been assessed for their potential contribution to UK bioenergy. An Energy Technologies Institute-funded assessment identified short rotation forestry as having relevance in Scotland, with willow coppice and miscanthus less well suited to Scottish conditions (the latter due to day-length constraints). A previous ClimateXChange report on land-use impacts of perennial energy crops in Scotland (ClimateXChange, 2020) provides further context, though uptake has been slower than projected. Woody energy crops could in principle supply pyrolysis feedstock, but no evidence was found assessing this pathway for Scotland. In addition, the scale uptake of energy crops to date means the practical feedstock contribution is currently small.

5.2 Carbon impact of biochar

Our evidence review suggests that biochar provides reliable, long-term carbon storage. For dry woody feedstocks most relevant to Scotland, net removal values are typically above 2.5 tCO2e per tonne of biochar, confirmed by UK operational data. Scotland's cool soils are favourable for carbon permanence. The Intergovernmental Panel on Climate Change (IPCC) methodology estimates 72-88% of biochar carbon remaining after 100 years, although new methods adopted in some carbon markets infer much higher levels of permanence.

5.2.1 Summary of evidence on carbon impact

Here, we briefly outline the areas of confident knowledge, issues under active debate and key evidence gaps in relation to evidence on the carbon impact of biochar. In the following sections, we discuss in a little more detail soil carbon impacts, biochar carbon permanence in soils, and life cycle emissions considerations.

Areas of confident knowledge. Biochar provides stable, long-term carbon storage. Net removal values for dry woody feedstocks, the most relevant for Scotland, are typically above 3 tCO_2e per tonne of biochar, with UK operational data confirming values of 2.5–3.1 tCO_2e/t under real-world conditions. Carbon permanence is determined primarily by pyrolysis temperature and soil temperature, both of which are favourable for Scotland.

Issues under active debate. The role of soil moisture and rainfall in long-term permanence is not fully resolved and is not accounted for in the IPCC methodology. The relative persistence of biochar carbon in different Scottish soil types (particularly sandy vs clay-rich soils) has not been directly tested. It remains uncertain whether secondary effects on native soil organic carbon are significant at low application rates.

Key gaps. No long-term field studies exist for Scottish soils. The 11-year German trial is the best available analogue. The interaction between Scotland's high rainfall and cool temperatures on biochar permanence has not been quantified. There is no published full-chain LCA for biochar production under Scottish conditions.

5.2.2 Soil carbon impacts

The primary carbon value of biochar lies in the direct transfer of carbon from the active biological cycle into long-term storage. When biomass is pyrolysed, its carbon, which would otherwise return to the atmosphere through decomposition within months to years, is converted into a highly stable form that can persist in soil for centuries or longer. This represents a net removal of CO_2 from the atmosphere. After accounting for production emissions (including energy use, transport, and any offset from heat generated), life cycle calculations show net removal values in the range of 1.15–3.1 tCO_2e/t biochar applied; Scottish figures are likely to be above 2.5 (Gamaralalage et al., 2025; Woolf et al., 2021). The lower end of this range reflects high-moisture feedstocks such as food waste; dry feedstocks such as straw or wood, which are the most likely Scottish feedstocks, are typically within the higher end of the range. These values are confirmed by UK operational data from the Black Bull Biochar demonstrator programme, which reported net carbon removal certificate factors of 2.5 and 3.1 tCO_2e removed per dry t of biochar at two production sites, after accounting for full value-chain emissions (Bagaria et al., 2025).

Separately from this direct carbon store, biochar application can cause small changes in existing soil organic carbon (SOC) pools, through effects on plant growth, soil chemistry, or interactions between stable biochar carbon and native organic matter. These secondary effects are small relative to the direct carbon storage value and are highly dose-dependent. The distinction is important: even where biochar shows no measurable effect on soil processes, the carbon stored within the biochar material itself persists. In-field studies report total soil carbon increases of 25–35% at experimental doses of 10–30 t/ha (Bekchanova et al., 2024; Chagas et al., 2022; Huang et al., 2023), but most of this increase reflects the biochar carbon itself being measured as part of the soil carbon pool, rather than biochar stimulating additional carbon accumulation by the soil (Jaufmann et al., 2025).

Equally important is to distinguish between the residence of biochar in the soils, and the storage of carbon by biochar. In sandy soils some biochar is likely to migrate through the soil profile (to deeper layers). This should not negatively affect the carbon storage aspect of the biochar is maintained but can complicate site-based validation. Little longer-term monitoring of carbon storage impacts was available: we identified only one study in soils comparable to Scotland that tracked impacts beyond 10 years. An 11-year German trial found that on loamy soil (26% clay), the biochar-induced soil carbon increase remained stable, while on sandy soil (94% sand) the measurable increase declined by 88% over 9 years (Gross et al., 2024). However, to reiterate, biochar structures persisted at both sites; the loss on sandy soil was likely due to physical transport of fine particles through the sand matrix. The authors conclude that soil carbon sequestration through biochar is achievable, particularly in loamy and clay-rich soils, while the measurable effect on total soil carbon is less well sustained on sandy soils.

5.2.3 Factors determining biochar carbon permanence in soils

When compared to global evidence, Scottish soils are generally cool (mean annual soil temperature ~10°C), high in organic carbon, and are typically exposed to high rainfall (>600 millimetres (mm) across most agricultural land). These characteristics affect how biochar performs and how its impact is measured.

The IPCC has developed a methodology for biochar carbon accounting (Woolf, et al., 2021), establishing the key factors that determine how much biochar carbon persists in soil. Table 5-2 summarises these factors and their relevance for Scotland. Further detail on the IPCC methodology is included in Appendix C. IPCC methodology estimates that 72–88% of biochar carbon remains after 100 years at Scottish temperatures, although recent research suggests that levels of permanence could be much higher (Sanei et al, 2024).

Table 5-2: Factors affecting biochar carbon permanence and relevance for Scotland

Factor	Effect on carbon permanence	Relevance for Scotland
Pyrolysis temperature	Higher temperatures (>600°C) produce more stable carbon with longer permanence (potentially >500 years). The hydrogen to organic carbon ratio is used as a predictor of biochar longevity in soil.	Controllable at production stage. Trade-off with application requirements.
Mean annual soil temperature	Cooler soils slow biochar degradation. At ~10°C, IPCC estimates 72–88% of biochar carbon remains after 100 years.	Scotland's cool soils are favourable for long-term carbon storage.
Soil moisture	Not included in IPCC methodology. Waterlogging inhibits biological activity (slows loss). Frequent wetting may accelerate surface oxidation.	Scotland's high rainfall (>600mm) means soils rarely dry out. Effect on permanence not yet quantified for Scottish conditions.

Soil moisture is not included in the IPCC methodology, mainly because water is likely to be more limiting in the field than in laboratory conditions (and therefore the omission is conservative). However, one global analysis noted that sites receiving >600 mm of annual rainfall showed lower soil carbon gains from biochar application than drier sites (Chagas, et al., 2022), likely due to aggregate breakdown and accelerated biological oxidation when soils are frequently wet. Scotland receives well over 600 mm across most agricultural land, and this effect warrants consideration when interpreting reported changes in soil carbon storage.

This finding should be interpreted with caution. The quantity of carbon stored through biochar addition is not affected by baseline soil carbon or rainfall. In soils already rich in organic carbon, as is typical in Scotland, the same amount of biochar carbon is stored but it represents a smaller proportional increase relative to the large existing pool. This is a measurement consideration, not a reduced benefit (Huang, et al., 2023; Zhang, et al., 2023).

5.2.4 Life cycle emissions considerations

Biochar production has **life cycle emissions** related to feedstock collection, transport and the pyrolysis process, contributing 1.4–16% of the total system carbon footprint (Han, et al., 2025), with transport and pyrolysis accounting for over 70% of this. Most studies do not fully account for upstream emissions arising from sourcing of biomass, and full consequential LCAs consistently show smaller net benefits than field-only studies (Han, et al., 2025; Schmidt, et al., 2021). The full carbon benefit of biochar production considers the fate of the heat generated during pyrolysis and the effects of biochar in its end-use beyond carbon storage. The results of these analyses are sensitive to assumptions of future energy mix, particularly where substitution of electrical energy is involved, as the electricity grid is decarbonised (Bagaria, et al., 2025). In comparing the benefit of biochar production with alternative end-uses for biomass, an appropriate unit of analysis could be carbon removal per tonne of biomass, rather than per tonne of biochar produced.

5.3 Soil health, land productivity and climate resilience impacts

Our Rapid Evidence Assessment (REA) demonstrates that biochar is generally beneficial to measures of soil health, but the impacts are dependent upon the initial soil conditions, and the quantity and qualities of the biochar. **It also demonstrates that:**

- Most research uses rates likely to be uneconomic in the current ‘real world’;
- Many papers measure the short-term yield benefits associated with liming or nutrients from the feedstock remaining with the biochar, rather than biochar-specific effects; and
- Few papers look at the long-term impacts of biochar.

Applied and long-term research is therefore needed on the yield and wider soil health impacts of low-dose, nutrient-enriched, targeted applications of biochar.

The impact of biochar on the soil-crop system is fundamentally affected by dose and method of application. Although small, targeted doses may produce effects comparable to high doses mixed evenly into soil, almost all of the literature reports high-dose, even-mixing experiments. The findings below should therefore be interpreted as indicating the potential direction and mechanism of effects, rather than as predictions of outcomes at the lower doses (0.5–2 t/ha) likely to be used in practice.

Biochar has two principal routes to improving agricultural returns. The first is as a carrier and retainer of nutrients, reducing losses to leaching and improving the efficiency of applied fertiliser. The second is through interactions with existing soil conditions. The improvement of nutrient use efficiency is likely to be the most economically viable route at low doses. The improvement of features like soil structure and water retention is more dose-driven and dependent on existing soil characteristics.

5.3.1 Impacts on yield

The global research base has focused heavily on yield as the primary measure of biochar's value. Biochar has been shown (under experimental conditions) to change crop yields from −32% to +974%, although most syntheses showing averages between 13–17% (Huang, et al., 2023; Schmidt, et al., 2021). These results are strongly influenced by studies of poor or degraded soils in tropical and subtropical regions where biochar helps to address yields constrained by low pH, poor nutrient retention and water stress.

Global meta-analyses pinpoint the alleviation of pH constraints of acidic tropical soils as particularly important in terms of yield gains from raised pH. Importantly, the temperate evidence base is limited by short study durations and high application rates. A major synthesis of 56 papers found no significant yield benefit from biochar alone in regions with mean annual temperatures below 10°C, *when nutrients were not limiting* (Schmidt, et al., 2021). Scotland's mean annual temperature is approximately 10°C, placing it at the threshold where these limitations apply. However, this finding draws primarily on two of the 26 meta-analyses reviewed (Ye, et al., 2019 and Jeffrey et al., 2017), both of which note that biochar properties, soil properties, and co-application with fertiliser were as relevant as, or more relevant than, climate in determining yield response. In temperate climates, field studies in Denmark, Germany and Norway have shown variable yield response (Jaufmann, et al., 2025; Bruun, et al., 2022; Budai, et al., 2024). One four-year German trial found that initial yield reductions in years 1–3 were reversed by year 4 through improvements in nitrogen cycling (Jaufmann, et al., 2025). These results suggest that short-term studies may underestimate longer-term benefits.

Where biochar is co-applied with fertiliser, the picture changes. A global meta-analysis of biochar-nitrogen interactions found that nitrogen fertiliser is the primary driver of yield gains, but that the interaction between biochar and nitrogen is synergistic — the combined effect is greater than the sum of the individual effects (Jia, et al., 2023). This synergy is likely driven by biochar improving nutrient retention and availability rather than directly increasing yield on its own. However, this analysis is weighted heavily toward tropical systems and does not isolate the temperate results, so the scale of this synergistic effect under Scottish conditions is uncertain. Using smaller amounts of biochar (<1 t/ha) combined with fertiliser has been shown to increase yields, reducing upfront cost while building carbon stores over time (Melo, et al., 2022), though the evidence for temperate climates specifically is limited and wheat showed no response. The practical implication is that biochar's agronomic value in Scottish conditions is most likely to come from its use as a targeted amendment combined with a nutrient source, potentially allowing the same yield to be achieved with less fertiliser input.

The UK GGR pilot project implemented by Black Bull Biochar provides the first Scottish evidence for this targeted approach (Bagaria, et al., 2025). At Scotland's Rural College Crichton Farm, Dumfries, biochar was co-applied with organic fertiliser at low doses and compared against fertiliser alone. A grassland strip receiving slurry amended with biochar at 0.5 t/ha/yr produced 16–18% higher yields than slurry alone over two seasons. Arable plots with farmyard manure amended at 1 t/ha/yr showed a 34% yield increase compared to manure alone. No differences in crop quality were found, and soil analysis showed increased pH and soil carbon in treated plots. Notably, the grassland yield benefit was sustained into the second season without reapplication, suggesting a single low-dose application can deliver effects across multiple growing seasons. These are encouraging results at economically realistic doses (0.5–1 t/ha), though this is grey literature from a two-year pilot with limited replication and should be treated as indicative rather than definitive.

Taken together, this evidence suggests that biochar is most effective when co-applied with fertilisers already in use on farm, at low rates of 0.5-1 t/ha. At these doses biochar acts synergistically with the nutrient source, improving nutrient retention. It can thereby increase nutrient use efficiency, without requiring changes to existing farm practice or additional fertiliser inputs beyond those already applied. The carbon storage benefit is delivered regardless of the agronomic outcome.

5.3.2 Effects on soil chemistry and pH

Biochar acts as a mild liming agent, raising soil pH by 0.2–0.6 units depending on dose (Aurangzeib, et al., 2024; Sun, et al., 2022; Singh, et al., 2022). This could benefit the approximately half of Scottish agricultural soils that display reduced productivity due to low pH (Scottish Government, 2023c). Biochar can also improve nutrient retention, particularly for nitrogen and phosphorus, reducing leaching losses. These chemical effects are among the best-evidenced benefits and are relevant at the doses being considered for Scottish deployment.

5.3.3 Effects on water retention and climate resilience

Biochar can improve soil water-holding capacity, with the largest effects on coarse-textured soils. However, the evidence for benefits under Scottish conditions is limited. A Danish trial on sandy soil showed improved water retention but no grain yield gain (Bruun, et al., 2022). A UK study found no protective effect of biochar under drought or flood conditions (Rhymes, et al. 2024). While Scotland is widely seen as a wet country, it already relies on irrigation for some high-value crops, with exceptional levels required for potatoes in 2025 (Adam Christie, Managing Director, Scottish Agronomy, pers. comm.). There is currently no evidence on whether water retention benefits are relevant where rainfall exceeds water loss for most of the year (Brown , et al., 2023). Below 5 t/ha there is essentially no data on water retention outcomes, meaning the case at economically realistic doses remains largely untested.

The evidence base for biochar's contribution to climate resilience specifically, meaning the capacity of agricultural systems to withstand or recover from extreme weather, is very limited. No studies identified in our review directly tested biochar's role in climate adaptation under Scottish conditions. This is a significant gap given that climate resilience is a stated objective for Scottish agricultural policy, and the potential mechanisms (improved water retention, reduced nutrient leaching, enhanced soil structure) are plausible but untested at realistic application rates in Scotland's high-rainfall environment.

5.3.4 Effects on soil greenhouse gas emissions

On mineral soils, biochar reduces nitrous oxide (N_2O) emissions by 12–38%, with the strongest effect in the first 2–3 years and when used with nitrogen fertiliser (Huang, et al., 2023). When biochar and nitrogen are co-applied, the interaction on GHG emissions is antagonistic — meaning the combined effect on emissions is lower than the sum of their individual effects — while the interaction on yield is synergistic (Jia, et al., 2023). This is an encouraging combination for climate-smart agriculture: lower emissions with higher productivity. Methane (CH_4) emissions are reduced by around 15% overall. Soils naturally absorb small amounts of CH_4 from the atmosphere (a process called methane uptake). In some cases wood biochar combined with nitrogen fertiliser has been found to suppress this effect, though this needs quantifying in Scottish conditions (Jia, et al., 2023; Huang, et al., 2023).

The opposite effect may occur on peat soils. Finnish studies found that biochar applied at 10–30 t/ha increased N_2O emissions by over 200% on deep agricultural peat (Ronkainen, et al., 2025), confirmed by a second study (Saarnio, et al., 2024). These are high doses on soil types unlikely to be targeted under the deployment pathways considered in this report. A UK study on fen peat found that biochar combined with a raised water table reduced emissions by 30% and increased crop growth (Jeewani, et al., 2025). Biochar may therefore be beneficial when paired with rewetting on degraded peatland but poses a risk on undrained organic soils at high application rates.

5.3.5 Summary of evidence on soil health and productivity

Areas of confident knowledge. Biochar can raise soil pH (beneficial for around 50% of Scottish agricultural soils), reduce N_2O emissions on mineral soils (12–38%), and improve nutrient retention. These effects are well-evidenced across multiple meta-analyses. The interaction between biochar and nitrogen fertiliser is synergistic for yield and antagonistic for GHG emissions. The Black Bull Biochar pilot project provides indicative Scottish evidence that low-dose co-application with organic fertiliser can improve yields.

Issues under active debate. Whether the temperate yield response is genuinely weak or an artefact of short study durations and high application rates is actively debated. The relative value of biochar as a nutrient carrier versus a soil conditioner at low doses is unresolved. Whether water retention benefits translate to yield or resilience gains under Scottish rainfall conditions is unclear.

Key gaps. There are no peer-reviewed Scottish field trials at economically realistic application rates. We found no evidence on climate resilience effects under Scottish conditions. There is no data below 5 t/ha on soil health outcomes. There is no comparative assessment of biochar versus alternative soil amendments for Scottish farming systems.

5.4 Lessons from international experience

We chose Denmark, Sweden and Germany to compile lessons from international experiences with biochar. These countries were chosen due to similarity in climate and land conditions with Scotland, as well as their more advanced state of biochar deployment.

5.4.1 Denmark

Denmark is the most advanced country in Europe in terms of policy commitment to biochar deployment, making its experience particularly instructive for Scotland.

The 2024 Danish Strategy and Work Program for Pyrolysis (Danish Government, 2024) sets out a comprehensive countrywide framework. It establishes clear guidelines for biochar application to agricultural land, including guidance on permitting and pollution tailored to the Danish context, and creates a cross-governmental Pyrolysis Taskforce to coordinate implementation. 10 billion Danish krone (DKK) (£1.16 billion at March 2026 prices) has been allocated for biochar produced by pyrolysis on Danish agricultural land from 2027 to 2045, with a further DKK 100 M (£11.6 M) for testing, scaling and demonstration of pyrolysis plants. The strategy sets a target of 0.3 Mt CO_2 sequestration by 2030. It introduces mandatory emissions accounting, including emission factors for biochar in Denmark's GHG inventory by 2027 and monitoring, reporting, and verification for CH_4 from pyrolysis plants. Denmark is also the first country to introduce a carbon tax on livestock CH_4 emissions, and the first European Union (EU) member state to seek European Commission approval for a biochar subsidy scheme, though approval discussions remain ongoing. Some Danish pyrolysis projects have also received direct funding support from the European Commission.

Denmark already has multiple pyrolysis projects in operation, making it the European country with the most developed implementation experience of biochar production at scale. However, our interviews with Danish industry and government stakeholders reveal a gap between this policy ambition and practical deployment. Despite the scale of public commitment and operational production capacity, there is a lack of biochar application outside of testing. The primary barrier identified is end-of-waste permitting. Current Danish rules require local municipalities to grant environmental permits under Section 19 of the Environmental Protection Act before biochar can be applied to agricultural land, but municipalities have been reluctant to do so because of uncertainty around groundwater interactions and other risks. A Danish industrial stakeholder noted that the industry's own ambitious volume projections may have contributed to regulatory caution, with authorities responding to the scale of proposed deployment by adopting a more precautionary approach.

The Danish Ministry of Environment has commissioned contaminant testing through the Technical University of Denmark, with results showing levels below emission thresholds for most biochar types. New national environmental guidelines to replace the current case-by-case permitting approach are due to be published in 2026. Some Danish producers have exported biochar to Germany rather than applying it domestically. The subsidy auction has not yet launched, pending both EU state aid approval and finalisation of the environmental regulation. Denmark is aiming for clear national rules by mid-2026, which would provide the regulatory clarity needed for the subsidy scheme to become operational.

These implementation challenges are instructive. The Danish approach with dedicated funding, a cross-governmental taskforce, integration into national emissions accounting, and clear subsidy mechanisms provide a developmental roadmap that Scotland could draw on. The main finding was that regulatory readiness, particularly end-of-waste criteria and permitting pathways, needs to be developed in parallel with policy ambition rather than sequentially to prevent bottlenecking. This regulatory barrier mirrors the situation in Scotland, where biochar manufacture is classified as a waste management activity under the Scottish Environment Protection Agency's 2012 Position Statement. Multiple Scottish stakeholders identified waste classification and end-of-waste criteria as directly affecting investment decisions (see Section 7.6).

Our interviews also identified several operational insights relevant to Scottish deployment. A Danish industrial stakeholder uses low-cost agricultural and livestock residues as feedstock rather than woody biomass. They also reported that feedstock cost is the largest operational expenditure, with prices varying significantly between wet and dry biomass. The industry began with small pyrolysis units and faces significant challenges in scaling. The same stakeholder reported that scaling to commercial systems (20 Megawatts, processing 40,000 t/year of dry matter) introduces significant engineering complexity, and that cost does not scale linearly with capacity. Plants also need to be located close to heat customers to maximise value, constraining site selection. The biochar subsidy scheme has proved more challenging to establish than the equivalent Carbon Capture and Storage scheme, in part because foundational environmental regulations for pyrolysis were not in place when the policy commitment was made.

While Danish targets for biochar are ambitious, concerns have been raised. A Lund University study suggests that biochar carbon removal could result in mitigation deterrence if financed through carbon credits, meaning continued emissions that could otherwise have been reduced (Lund University Centre for Sustainability Studies, 2024). A Danish think tank has cautioned that emission removal targets based on biochar could be unrealistic given that operational scaling has not yet been achieved (Green Transition Denmark, 2024).

5.4.2 Sweden

Currently, biochar is seen as part of the mitigation plan for the forest and land sector. There is an overall target to remove 1.2 Mt CO_2e annually by 2030, but there are no specified targets for biochar.

State support for biochar in Sweden is limited and primarily channelled through the general Climate Leap scheme, Klimatklivet. More targeted, biochar-specific subsidies are not currently considered appropriate, given the need for further applied research on how biochar can most effectively contribute to Sweden’s net zero pathway (Carbon Gap, 2025). Nevertheless, Olsson et al. (2024) argue that the sector has reached its current scale largely because programmes such as Klimatklivet reduced the upfront capital burden associated with establishing pyrolysis facilities. The sector therefore has been co-financed through public grants, and private investments.

Olsson et al. (2024) also point out that municipality-level support has been critical for the biochar industry, where the high environmental safeguards of municipalities indirectly enabled domestic biochar producers over imported production. Lastly, biochar plants are not only seen as production infrastructure but also learning sites. Public support enables experimentation, monitoring and data generation, while bringing municipalities, researchers, and industry together and building institutional capacity. This collaborative, co-financed and knowledge intensive landscape has been essential for the Swedish biochar industry to develop.

5.4.3 Germany

The German biochar industry is empowered by notable industrial capacity in pyrolysis technology in the country, and also by regulatory developments on waste management.

Regarding industry, German companies were mentioned by three interviewees as frontrunners in supplying modern pyrolysis plants. Germany has a substantial base of technical expertise and operational knowledge, and is a key provider in the emerging global biochar supply chain.

On the regulatory side, the 2017 Sewage Sludge Ordinance required large wastewater treatment plants to recover phosphorus rather than simply spreading sludge on fields (effective by 2029). This led to the recognition of pyrolysis (carbonization) of sludge as an acceptable phosphorus recovery method. Germany's wider support to Bioenergy and Carbon Capture and Storage technologies has also positively impacted the biochar industry. Finaly, according to Carbon Gap, Germany's recent efforts to create a national carbon removal strategy could also incentivise the industry to scale up (Carbon Gap, 2026).

Our interviews suggest that Southern Germany (and Austria) largely rely on woody biomass as feedstock. Our REA indicates that biochar in Germany has been produced from different feedstocks, including but not limited to woody biomass, and applied across different soil types (Teichmann, 2014). Lastly, soil improvement benefits associated with biochar are viewed as important in the German context and there is ongoing research on these co-benefits (EU Cap Network, 2024).

5.5 Potential biochar deployment pathways for Scotland

This section identifies seven potential deployment pathways for biochar in Scotland, drawing on evidence from the REA and stakeholder interviews. These pathways are:

- Pathway 1: Agricultural soil amendment – application of biochar to agricultural land
- Pathway 2: Biochar-based fertiliser (BBF) – biochar combined with other nutrients to produce a fertiliser product
- Pathway 3: Anaerobic digestion (AD) integration – adding biochar to the AD process
- Pathway 4: Whisky co-product valorisation – use of whisky co-products as a feedstock for biochar production
- Pathway 5: Forestry residue pyrolysis – use of forestry residues as a feedstock for biochar production
- Pathway 6: Construction materials – addition of biochar to construction materials such as concrete, asphalt, and plasterboard
- Pathway 7: Water filtration – use of biochar in water treatment applications

The seven pathways vary in feedstock source, production context, application method, and end-use. Several pathways share the same end-use (agricultural soil application) but differ in how biochar is produced, processed, or delivered to the field.

Pathway 2 (Biochar-based fertiliser, BBF) represents a specific formulation of the approach described in Pathway 1, and Pathway 4 (whisky co-products) is distinguished primarily by feedstocks rather than end-use. The barriers and enablers that would need to be addressed to realise each pathway are discussed in Chapters 6 and 7. Each is assessed against the evidence base for its feasibility, considering feedstock availability and impacts on carbon and soil health (Sections 5.1 to 5.3). Table 5-2 provides a summary, including the key knowledge gaps identified for each pathway; the evidence is discussed below. Additional potential applications were identified by stakeholders, including livestock bedding, but were not developed into full pathways due to the limited evidence base. These are noted at the end of this section.

A key finding from the REA is that the viability of any use case (scenario) depends on synergies between feedstock, pyrolysis processing and end-use. There is no universal solution, and there may be compromise between permanence of carbon removal (achieved by high-temperature pyrolysis, >600°C) and certain immediate effects on soil properties (achieved by low-temperature pyrolysis, <500°C), suitability for water filtration (high surface area), or potential applications in the construction industry (specific particle size and stability). Use cases should be understood as an integration across the value chain and assessed over a defined time period, rather than alternative uses for a uniform product.

Table 5-2: Summary of potential biochar deployment pathways for Scotland

Pathway	Primary feedstock(s)	Evidence base	Potential advantages	Key constraints	Knowledge gaps
1. Agricultural soil amendment	Forest brash, agricultural residues, digestate	Strong global evidence (26 meta-analyses). Black Bull Biochar pilot project: 16–34% increase over fertiliser alone at 0.5–1 t/ha (grey lit). Norwegian analogue (Budai et al., 2024).	Highest carbon sequestration potential (1.15–3.1 tCO_2/t). Dual benefit: C storage + soil improvement when co-applied with existing organic fertilisers at low doses.	Temperate yield evidence limited by short-term, high-dose study designs. No Scottish peer-reviewed trials. Farmer knowledge gaps.	No Scottish peer-reviewed field trials at realistic doses. Long-term effects on Scottish soils untested.
2. Biochar-based fertiliser (BBF)	Various (blended with fertiliser at <1 t/ha)	One meta-analysis (Melo et al., 2022). +12% yield overall. Wheat showed no significant response.	Viable at low rates (<1 t/ha). Overcomes cost barrier of high-rate application.	No Scottish trials.	No UK field trials at significant scale of BBF formulations. Crop-specific responses under Scottish conditions unknown.
3. Anaerobic digestion (AD) integration	Green waste, food waste, sewage sludge	Multiple stakeholder reports. Biogas yield improvement reported (~20%, grey lit). Carbogenics commercial development.	Adds value to existing waste infrastructure. Revenue from biogas, heat and biochar.	Gate fee economics sensitive. Waste classification complexity.	No peer-reviewed data on biochar-AD integration under Scottish conditions. Nutrient efficiency gains vs biogas yield not compared.
4. Whisky co-product valorisation	Draff, pot ale (wet mass; pot ale ~96% water)	Well-studied (Andrews et al., 2025). Feed pathway delivers 2.5–8× better GHG mitigation than AD (Duffy et al., 2023).	Large, concentrated availability near arable land. Existing infrastructure. Potential closed-loop systems.	Feed may deliver superior climate benefits. Competing uses well-established.	No studies on biochar production from whisky co-products. Dry matter yields for biochar untested.

Pathway	Primary feedstock(s)	Evidence base	Potential advantages	Key constraints	Knowledge gaps
5. Forestry residue pyrolysis	Brash, thinnings, sawmill residues (568 kt wood waste classified as waste, 2023)	Scottish cost data (Pap et al., 2022: £370/t lab scale). Industry well-mapped. Carbon risk from residue removal flagged.	Large volumes. Established supply chains. Low-cost feedstock relative to energy crops.	Most wood waste already reprocessed (548 of 568 kilotonnes, kt).	No field trials using Scottish forestry brash biochar. Soil carbon impact of residue removal not quantified for Scotland.
6. Construction materials	Various (specification-dependent)	Limited peer-reviewed evidence for UK. Danish/Australian stakeholder experience. DESNZ greenhouse gas removal projects.	Long-term carbon storage in built environment (e.g. additive to concrete/asphalt). Co-location reduces transport costs.	Not included in UK building codes; without this, construction use cannot be insured. Acceptance likely to take decades.	No UK permanence data for biochar in construction materials. Building code pathway not yet investigated.
7. Water filtration	Conifer brash, woody biomass (low-ash biochar required)	Pap et al. (2022): partial nutrient removal but P leaching. Has shown potential for some water treatment applications.	Cost advantage (£370/t vs up to £33,760/t for activated carbon). Potential circular sewage sludge pathway.	Dual removal not achieved unmodified. Adsorption capacity substantially lower than activated carbon. Regulatory pathway unclear.	Biochar performance vs activated carbon not systematically compared. Regulatory pathway for water treatment use not explored.

5.5.1 Pathway 1: Agricultural soil amendment

Application of biochar to agricultural land is the most widely studied pathway and offers the highest carbon sequestration potential, estimated at 1.2–3.1 tCO_2e per tonne applied (see Section 5.2). In Norway, Budai et al. (2024) found biochar has the largest mitigation potential of nine carbon farming[1] methods assessed, equivalent to 20% of Norwegian agricultural emissions if deployed at scale. The Scottish Government's Negative Emissions Technologies feasibility study (Scottish Government, 2023a) identified this as the primary deployment route.

As discussed in Section 5.3.1, global meta-analyses (Schmidt, et al., 2021; Ye, et al., 2019; Jeffery, et al., 2022) suggest weaker yield gains in temperate conditions than tropical ones. However, it is actively debated whether this reflects a genuine climatic limitation or is an artefact of short study durations, high application rates, and/or differing soil conditions (with factors such as low pH, poor nutrient retention and water stress more common in tropical climates). Where biochar is co-applied with fertiliser at low doses, the yield response appears to depend more on soil properties, biochar characteristics and application method than on climate zone alone. The Black Bull Biochar project's results at 0.5–1 t/ha suggest that targeted co-application under Scottish conditions may produce yield benefits not captured by the broader meta-analytic averages (Bagaria, et al., 2025), though these are grey literature results from a two-year pilot with limited replication. Biochar's pH-raising effect could benefit the approximately half of Scottish agricultural soils that currently suffer reduced productivity due to low pH (see Section 5.3).

For Scotland, the primary carbon benefit is stable carbon storage rather than enhanced soil carbon cycling (Section 5.2). Localised biochar storage varies by soil type: loamy and clay-rich soils offer the most reliable long-term local storage, while sandy soils may not sustain measurable local gains over time (Gross, et al., 2021). However, while the loss of biochar from soils reduces soil fertility benefits, this does not equate to a loss of carbon storage. Instead, biochar lost from sandy soils remains as stable stored carbon elsewhere in the environment. At Scotland-relevant soil temperatures (~10°C), the IPCC methodology estimates 72–88% of biochar carbon remains after 100 years (Woolf, et al., 2021). Application to peat or peaty soils should be approached with caution given Finnish evidence on increased N_2O emissions at high doses (see Section 5.3), though biochar paired with rewetting may benefit degraded peatland (Jeewani, et al., 2025). The evidence reviewed in Section 5.3 indicates that biochar is most effective when integrated into existing fertiliser practice at low doses (0.5–1 t/ha), where it acts synergistically with the nutrient source to improve both nutrient retention and yield without requiring large changes to farm management. The deployment pathways considered here focus on mineral agricultural soils. A government agency interviewee questioned where biochar sits in Scotland's wider decarbonisation strategy, noting that the same feedstocks are sought for sustainable aviation fuel and AD, and that carbon offsetting via biochar is less direct than fossil fuel substitution for reducing scope 1 emissions.

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[1] Carbon farming is a set of agricultural practices designed to sequester atmospheric CO_2 into the soil and plant biomass, thereby using farms as carbon sinks.

5.5.2 Pathway 2: Biochar-based fertiliser

BBF represents a potentially significant shift in the economics of biochar deployment. Melo et al. (2022) demonstrated that BBF achieves equivalent yield gains to high-rate biochar application at less than 1 t/ha, compared to the 15–30 t/ha previously considered necessary. Field studies show a mean yield increase of 12%, with a median application rate of 635 kg/ha. The Black Bull Biochar project tested biochar co-applied with slurry and farmyard manure rather than a manufactured BBF product, but the principle is the same: biochar enhances the effectiveness of nutrient inputs already being applied, rather than replacing them.

The evidence base for BBF remains limited and is dominated by tropical maize systems. A single pot trial investigated BBF and wheat yield and showed no statistically significant yield responses. No Scottish or UK field trials of BBF formulations were identified in our evidence review. A whisky research interviewee noted that field trials examining biochar in combination with fertiliser on Scottish crops would be needed before practical recommendations can be made, and that any new input must work within the fixed localities of existing cereal supply chains.

5.5.3 Pathway 3: Anaerobic digestion integration

Integration with AD was identified by multiple stakeholders during our interviews as one of the most immediately viable pathways for Scotland. Adding biochar to the AD process can improve digestion efficiency by providing a surface for microbial colonisation, which stabilises the biological process. It can also reduce the sensitivity of digesters to variability in feedstock content and structure, like ash, moisture and calorific content, which is responsible for a large proportion of digester down time. This in turn increases biogas yield, with a Local Authority interviewee reporting approximately 20% improvement. It can also improve the quality of the digestate as a soil amendment. Biochar may also improve nutrient use efficiency within the digestion process, though the relative value of this compared to biogas yield improvement has not been directly compared in the literature we reviewed. Carbogenics, a University of Edinburgh spin-out, has developed a biochar additive specifically to enhance biological performance in biogas plants. One Scottish interviewee described this as the most advanced biochar commercialisation in Scotland, with a clear link between the additive and increased biogas output.

Scotland has an established AD sector with processing capacity for organic waste, and the Scottish Government has identified AD sector expansion as a factor in the development trajectory of biochar plants. However, gate fee economics are sensitive (break-even at >£74/t digestate), and waste classification requirements add complexity and cost (Gamaralalage, et al., 2025). An interviewee from a pyrolysis technology manufacturer reported that processing at 600°C can destroy Per- and polyfluoroalkyl substances (PFAS) and microplastics in digestate, which if verified for Scottish waste streams could reduce contaminant concerns associated with waste-derived biochar and support the case for end-of-waste reclassification. This pathway benefits from using existing waste management infrastructure and feedstock supply chains, reducing the need for new biomass sourcing.

5.5.4 Pathway 4: Whisky co-product valorisation

Scotland's whisky industry produces 7.65 Mt of pot ale and 1.34 Mt of draff annually (Andrews, et al., 2025). These figures are wet mass; pot ale is approximately 96% water (3–4% solids) (Edwards, et al., 2022), meaning the dry matter available for conversion is substantially smaller than these headline volumes. Distilleries are typically located near arable land, creating the potential for closed-loop systems. However, our evidence review found a fundamental challenge: the existing use of whisky co-products as animal feed (Distillers Dried Grains with Solubles, DDGS) delivers 2.5–8.0 times greater GHG mitigation than the AD route (Duffy, et al., 2023), and also offsets water scarcity impacts from avoided soy imports (Schestak, et al., 2022). UK renewable energy incentives have already driven a sub-optimal shift from feed to bioenergy use, with DDGS production declining by 57% between 2012 and 2019 (Duffy, et al., 2023). Diverting further co-products to biochar without careful LCA risks repeating this pattern. A whisky research interviewee indicated that the industry's 2040 net zero ambition could create demand, but confirmed that co-product allocation remains commercially sensitive and distillery-specific.

5.5.5 Pathway 5: Forestry residue pyrolysis

Scotland produced an estimated 568 kt of wood waste in 2023, of which approximately 548 kt was already recycled or sent for energy recovery (2022). This figure covers material classified as waste and does not include the wider volume of sawmill co-products already in productive use. Due to the lack of other evidence, forest brash is one of the most studied Scottish feedstocks in academic literature. Pap et al. (Scottish Forestry, 2025) demonstrated lab-scale potential production of biochar from conifer brash. The resulting biochar released phosphorus, improving its potential value as an agricultural amendment, but limiting its water treatment use.

The primary constraint for this pathway is feedstock competition. A timber industry interviewee reported being approached repeatedly to supply feedstock but finding no credible market for biochar product compared to existing feedstock pathways. The same stakeholder pointed out that Scotland's forestry product industry sustains over 16,000 jobs and contributes approximately £878 M/yr to the Scottish economy (Scottish Forestry, 2025). Any diversion of wood fibre into biochar production must be assessed against this existing economic contribution, and work to make biochar synergistic with existing industry. An industry stakeholder cautioned that removing forestry residues can release soil carbon through disturbance. Waste wood not currently finding productive use may offer a more viable route (SRUC, 2020).

5.5.6 Pathway 6: Construction materials

Several stakeholders identified potential for biochar in construction materials including concrete, asphalt, and plasterboard. Danish and Australian experience was cited, with PyroCore et al. (2021) valuing construction-grade biochar at £250–500/t for road applications. However, biochar is not currently included in UK building codes, without which its use in construction materials cannot be insured. Acceptance through building codes is likely to take decades. Peer-reviewed evidence for the UK context is limited. This is an emerging pathway that may become significant as the construction sector seeks to reduce embodied carbon, but currently lacks the evidence base and regulatory framework for deployment.

5.5.7 Pathway 7: Water filtration and remediation

Biochar has shown potential for some water treatment applications at substantially lower cost than activated carbon, which is used to control taste and odour and to remove organic chemicals (£370/t for biochar vs up to £33,760/t for activated carbon) (Pap, et al., 2022). The adsorption capacity of biochar is however substantially lower. Scottish Water has reportedly expressed interest, according to one industry stakeholder. A potential circular pathway exists in which sewage sludge is pyrolysed to produce biochar for water treatment. However, unmodified conifer brash biochar achieved only partial nutrient removal when tested: 63.6% of ammonium was removed but phosphorus was leached (Pap, et al., 2022). The focus on ammonium may also be too narrow, as nitrate is the main soluble nitrogen fraction driving eutrophication in watercourses. The regulatory pathway for biochar use in water treatment is also unclear. Further product development and systematic comparison with activated carbon are needed.

5.5.8 Other stakeholder identified routes

Livestock bedding was also identified as a potential application by several interviewees. A Local Authority interviewee reported that a mix of 75% wood fines and 25% biochar creates bedding that effectively absorbs ammonia and other pollutants that could otherwise run off to land or watercourses. This approach is currently being trialled for poultry bedding. Biochar used in bedding would subsequently reach agricultural soil through normal manure management, providing a practical route to soil application within existing farm systems. This approach could be significant given that ammonia emissions from agriculture are a key air and water quality pressure in Scotland and the UK. Biochar-amended bedding could potentially reduce ammonia emissions at source – though this has not yet been demonstrated at scale.

6 Economic assessment

This section brings together economic evidence from our Rapid Evidence Assessment (REA) and stakeholder engagement. It should be noted that the evidence has several important limitations. Cost and revenue data for biochar are highly variable, depending on feedstock type, production technology, scale, end-use application, and regulatory requirements. The data also comes from a limited number of studies, including pilot projects and modelling studies, which may or may not be representative. The estimates we present here are therefore indicative ranges, reflecting a market still at an early stage in the United Kingdom (UK). Table 6-1 summarises key cost components. The key findings are then discussed below, with reference to the deployment pathways identified in Section 5.5 where appropriate. Additional comments on uncertainties are briefly discussed in section 6.6.

Table 6-1: Summary of biochar cost components

Cost component	Estimate	Source(s)	Scottish applicability
Biochar production cost (breakeven)	£175–460/tonne (t) biochar (global range, converted from US$). £370/t from conifer brash (Scotland, lab scale).	(IBI, 2025); (Pap, et al., 2022)	Scottish costs likely mid-to-upper range due to feedstock competition and compliance costs.
Cost of carbon removal	£13–313/t carbon dioxide (CO_2) (literature range). Seventh Carbon Budget estimates around £95. For comparison, estimated costs from other sequestration routes: Bioenergy with Carbon Capture and Storage (BECCS): £100–350. Direct Air Capture and carbon storage (DACCS): £145–557. Afforestation: £10–12.	(Shackley, et al., 2011); (ClimateXChange, 2022); DESNZ (2026); (Climate Change Committee, 2025); (ClimateXChange, 2025)	Lower end with waste feedstocks and co-located heat. Upper end with virgin biomass at small scale. UK operational data confirms net removal of 2.5–3.1 tCO_2e/t under real-world conditions (Bagaria, et al., 2025).
Capital expenditure (CAPEX)	£9.5 million (M) for 20 kilotonnes (kt)/yr facility. CAPEX projected to fall from £5.5M (2025) to £4.2M (2030) for a plant with one pyrolysis unit using Compressed Air Energy Storage systems.	(Gamaralalage, et al., 2025); (PyroCore, et al., 2021)	Project Willow and Carbon Neutral Islands (£600,000 Phase 1) provide Scottish benchmarks.
Operational expenditure (OPEX)	£42–399/t biochar depending on plant scale and feedstock.	(Scottish Government, 2023b)	Ranges reflect variation from small (more costly) to industrial scale (less costly). Feedstock, transport and logistics are main drivers.
Comparative cost of biochar use as a soil amendment	Biochar costs approximately £80-630/hectare (ha). Compared with Lime: £4-12/ha. Manure: £16/ha	(Zhang, et al., 2023); (Melo, et al., 2022)	Most expensive amendment comparatively. Economic case requires both carbon storage and agronomic value. Comparison is not like-for-like since biochar delivers dual benefit of carbon storage and nutrient use.
Context: existing feedstock uses	Distillers Dried Grains with Solubles (DDGS): 2.5–8 times better greenhouse gas (GHG) offset than anaerobic digestion (AD). Wood fibre: £878 M/yr economy. 548 of 568 kt wood waste already used.	(Duffy, et al., 2023); (Scottish Forestry, 2025); (Scottish Government, 2025c)	If biochar is the highest-value use, competition is the market working. The challenge is demonstrating this.
Carbon	£600–800/t biochar current	(PyroCore, et	Current prices reflect early-

Cost component	Estimate	Source(s)	Scottish applicability
credit market (sale price)	voluntary market. £250–500/t biochar projected for construction applications. 47% of producers certify globally.	al., 2021); (IBI, 2023); (IBI, 2025)	mover pre-purchase agreements. UK Emissions Trading Scheme (ETS) inclusion (expected 2029) could support larger volumes at lower per-unit prices.

Note: Cost estimates are drawn from sources spanning 2011–2026 and vary in methodology. Where possible, figures are identified as breakeven production costs, sale prices, or modelled estimates. CAPEX and OPEX ranges are strongly influenced by production scale, feedstock type, and logistics. All figures originally reported in US$ or € have been converted to approximate £ at March 2026 rates. Figures reported before 2022 have been adjusted to March 2026 prices to account for inflation.

6.1 Production costs

Biochar production costs vary substantially with technology, feedstock, and scale. At the global level, IBI (2025) reports a breakeven production cost range of approximately £175–460/t (US$220–580). In Scotland, the only production cost data comes from (Pap, et al., 2022), who demonstrated production from Flow Country conifer brash at £370/t at lab scale. The Scottish Government's Negative Emissions Technologies feasibility study (Scottish Government, 2023a) provides a full cost breakdown for various plant sizes, noting that the six-tenths or 0.6 rule[2] can be used to extrapolate costs for different production rates.

Operational expenditure ranges from £42–399/t of biochar produced depending on plant scale and feedstock (Scottish Government, 2023a). Shackley et al. (2011) estimated costs from production to field application at £0–430 per applied t, with the lowest costs for systems using waste feedstocks (where biochar producers may be able to charge a fee to those disposing of the waste feedstock) and the highest profitability where both biochar and renewable energy are produced. These estimates included on-farm application costs but did not include costs of regulatory compliance or monitoring, reporting, and verification (MRV), which add disproportionate costs at smaller production scales.

A Department for Energy Security and Net Zero (DESNZ)-funded demonstration project projected CAPEX falling from £5.5 M in 2025 to £4.2 M by 2030 for a representative plant with one pyrolysis module and nine Compressed Air Energy Storage systems, suggesting that costs may reduce as the technology matures (PyroCore, et al., 2021). Stakeholders identified that CAPEX also varies significantly depending on whether wet or dry feedstock is pyrolysed. Industry data indicates costs of approximately €1–1.5 M (~£870,000 – 1.3 M) per Megawatt (MW) of calorific input capacity for wet biomass systems (which require pre-

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[2] The six-tenths or 0.6 rule is an economic scaling method used to estimate changes in capital costs relative to scale, i.e. that a change in capacity will change the capital cost by 0.6 times the capacity ratio.

processing including drying and pelletising), compared to approximately €0.5–0.75 M (~£0.44 – 0.65 M) per MW for dry feedstock systems, according to one industry interviewee (see Section 5.4), underscoring that scaling introduces engineering complexity that is not proportional to capacity.

Biomass procurement is usually the largest operational cost, and prices can be highly volatile. One Danish industry interviewee reported straw prices rising by 70% in a single year due to a poor harvest. However, this is a standard commercial challenge manageable through forward supply contracts, as other biomass-dependent industries have demonstrated.

6.2 Feedstock competition and opportunity costs

The economic assessment of any pathway must account for the opportunity costs of diverting feedstocks from current uses. However, feedstock competition is not inherently a barrier: if biochar represents the highest-value use of a given biomass resource, competition is the market operating as intended. The challenge is demonstrating that biochar does deliver greater overall value than alternative uses. The clearest example where this has not been demonstrated is whisky co-products (Pathway 4). Here, the feed pathway (DDGS) delivers 2.5–8.0 times greater GHG mitigation than bioenergy alternatives (Duffy, et al., 2023), and DDGS production has already declined by 57% between 2012 and 2019 due to sub-optimal policy incentives shifting co-products from feed to AD. For wood fibre (Pathway 5), Scotland's forest products industry contributes £878 M per year and sustains over 16,000 jobs (Scottish Forestry, 2025). If biochar were to become the highest-value use of this biomass, it could add to rather than detract from this economic contribution.

Waste streams with limited current productive use offer the strongest economic case, including lower-grade AD digestate, municipal green waste where composting capacity is saturated, and specific industrial residues. These pathways do however carry the heaviest regulatory and compliance burden. Waste-derived feedstocks require full waste management licensing in Scotland (Section 7.6), face more stringent contaminant testing requirements for heavy metals, polycyclic aromatic hydrocarbons, and microplastics (Section 7.5), and incur MRV and certification costs that are disproportionate for smaller operators. These costs partially offset the gate fee advantage, and the net economics will depend on the specific feedstock and production scale. Over 27 Mt of biomass arisings were generated in Scotland in 2014, many with limited valorisation (Zero Waste Scotland, 2022). Matching underused streams to appropriate pyrolysis pathways is likely to offer better economics than competing for feedstocks with established markets.

6.3 Revenue streams and market context

Revenue for biochar producers can come from three main sources: sale of biochar as a product, carbon credit certification, and heat or energy co-generation. The relative importance of each varies by pathway (Section 5.5).

For agricultural soil amendment (Pathway 1), carbon credit revenue is critical because agronomic value alone does not justify the purchase price of biochar for most farmers. Current voluntary market prices of £600–800/t of certified carbon removal reflect early-mover pre-purchase agreements that are not expected to represent long-term equilibrium prices (IBI, 2023). As the market matures and compliance mechanisms develop, prices are likely to settle lower. A key uncertainty is whether carbon removal credits will command a higher price than emissions reduction credits, or whether buyers will be required to balance the two in an evolving ratio. An interviewee from a government economic development agency identified aviation as a potential demand-side driver: airlines face limited near-term decarbonisation options and could purchase biochar carbon credits as a bridge until sustainable aviation fuel matures, providing a defined buyer segment for Scottish producers. For construction uses (Pathway 6), an achievable price of £250–500/t has been projected for road applications. For water filtration (Pathway 7), the cost advantage over activated carbon provides a product-based revenue stream independent of carbon markets.

The distinction between carbon stored directly in the biochar and any additional effect on native soil carbon matters in evaluating the potential of carbon credits as a revenue stream for biochar producers. Most of the reported increase in soil organic carbon (SOC) reflects the stable biochar carbon being measured as part of the soil pool, rather than biochar stimulating new carbon accumulation (Jaufmann, et al., 2025). The economic value of biochar for Scotland's carbon-rich soils is, therefore, best calculated on the basis of the stable carbon it adds directly. At Scotland-relevant temperatures (~10° C), the Intergovernmental Panel on Climate Change methodology estimates 72–88% of biochar carbon remains after 100 years (Woolf, et al., 2021). To assess the potential of sequestration and hence the carbon credits it can claim, cost-benefit models should not additionally claim native SOC gains unless independently demonstrated under Scottish conditions.

Where waste feedstocks are used, producers can charge a gate fee for accepting material that would otherwise incur waste management costs, generating an estimated £89–124/t of biochar produced (Scottish Government, 2023a). This represents a genuine revenue stream, not a constraint: waste-derived pathways benefit from being paid to receive their input material. Electricity generated from pyrolysis co-products provides a further revenue stream, estimated at £37/t of biochar, though this will depend on energy prices (Scottish Government, 2023a). Currently, 47% of global biochar producers currently certify their carbon removals to recognised standards (IBI, 2023). While this demonstrates emerging practice, it also means that over half of production is not independently verified, highlighting the need for mandatory or standardised certification to ensure consistent quality and legitimate carbon claims as the market matures.

Heat co-generation is a significant but undervalued revenue source. An interviewee stated that one demonstration project in Shropshire reported approximately 1.2 MW of excess thermal energy from a single pyrolysis unit, although proximity to heat customers is required, constraining site selection.

6.4 Cost-effectiveness relative to alternatives

When assessed purely as a soil amendment (i.e. application of biochar to agricultural land for yield improvement – see section 5.5.1), biochar is the most expensive option per unit of yield gain. Zhang et al. (2023) calculated the cost per 1% yield increase: at pH 5.0–5.5, biochar costs approximately £120/ha compared to £12/ha for lime and £16/ha for manure. The Black Bull Biochar project achieved encouraging yield results (16–34% increases) at low doses (0.5–1 t/ha co-applied with organic fertiliser), but these have not been independently replicated. Biochar for this project was provided to farmers at half the market price, with 6 farmers purchasing biochar after the project. The economic case for farmers remains unproven at current prices. There is a clear opportunity to explore the potential for profitable applications through this targeted, low-dose approach, where both carbon storage and agronomic benefits are delivered together. It is useful to note, however, that some studies suggest the relationship between biochar application rate and benefit is non-linear, with diminishing and potentially negative returns at higher rates (Huang, et al., 2023; Wu, et al., 2022). Hence, exploring the potential in low doses might draw a limited picture.

When assessed as a carbon removal technology, the economics are more favourable relative to other options. Comparisons of greenhouse gas removal (GGR) technologies have estimated biochar costs at £13–120/tCO_2, compared to BECCS at £100–350/tCO_2, DACCS at £145–557/tCO_2, enhanced weathering at £37–350/tCO_2, and afforestation at £10–12/tCO_2 (ClimateXChange, 2022; Climate Change Committee, 2025; ClimateXChange, 2025). All of these technologies are expensive in absolute terms, and the relevant question for policy is relative cost-effectiveness and the level of public investment society is willing to commit to sequestering carbon. Biochar’s cost range overlaps with, and in some scenarios falls below, that of other methods of engineered removal technologies. This suggests it could be cost-competitive in attracting carbon removal investment, particularly in places where feedstock and heat are co-located to reduce costs. Arup (2022) estimated a 2025 cost of approximately £300/tCO_2 removed by biochar. Several DESNZ-funded demonstrator projects targeted costs by 2050 below £200/tCO_2 removed by biochar, though these targets were conditions of grant funding and may not reflect market costs without subsidy. Norwegian data suggests breakeven production costs of approximately £590/t (Budai, et al., 2024), indicating that additional revenue streams or policy support are needed to close the viability gap.

Regarding other potential uses of biochar, it may offer potential for some water treatment applications at substantially lower cost than activated carbon (£370/t vs up to £33,760/t) (Pap, et al., 2022).

6.5 Investment landscape

Public grant funding for biochar-related infrastructure in Scotland is at an early stage, and private investment capital has not yet followed in significant volumes. The UK Government allocated over £100 M to develop GGR technologies through the GGR Innovation Programme, of which £31.5 M supported five land-based demonstrator projects including biochar (Scottish Government, 2023a). This programme has now concluded. The Grangemouth Just Transition Fund (£25 M) includes pyrolysis-related project sets within the Project Willow feasibility study. An additional £200 M is available from the UK National Wealth Fund for investible propositions (Scottish Government, 2025c). The Carbon Neutral Islands programme has allocated £600,000 for a Phase 1 biochar trial on agriculture, peatland and clear-fell land, plus £46,000 for a peatland restoration trial using biochar (Scottish Government, 2025d). The same feasibility study estimated that the gross value added of a biochar sector within Scotland could reach approximately £24.3M (Scottish Government, 2023a; Scottish Government, 2023a).

Industry stakeholders consistently identified commercial viability as the primary constraint on private investment. The question for policy is what level and form of public investment is required to bridge the gap between current grant-funded pilot activity and a self-sustaining commercial market. One Scottish interviewee observed that considerable R&D activity has not yet translated into commercially viable projects, and that the most advanced Scottish biochar company still imports raw biochar from Europe for post-processing in Scotland. Multiple interviewees noted that a clearer policy signal, comparable to Denmark's 10 billion Danish krone (DKK) commitment to agricultural carbon sequestration subsidies, would be necessary to unlock private investment at scale. The anticipated UK ETS inclusion of biochar by 2029 was identified as potentially the most significant catalyst for market development, though compliance market prices are likely to be substantially lower than current voluntary market prices, as discussed above in section 6.2. A recurring theme from industry interviewees was the absence of funding to bridge the gap between demonstrator and commercial stages. A biochar industry interviewee projected that the UK biochar sector could reach market maturity between 2030 and 2035, but that achieving this timeline depends on sustained policy signals and early commercial revenue to bridge current funding gaps.

Current public funding supports research and pilot activity, but there is no mechanism to support early commercial operations during the period when producers need to generate revenue but cannot yet compete on price. This was identified as a distinct constraint from the availability of R&D funding, and one that other emerging low-carbon technologies have also faced.

6.6 Key uncertainties

The economic evidence base we present here has several important limitations. Most cost data derives from modelling studies and pilot projects rather than established commercial operations in Scotland. Carbon credit market projections are inherently uncertain, and small shifts in policy or sentiment could substantially alter the economics of all pathways. The relationship between biochar application rate and benefit is non-linear, with diminishing and potentially negative returns at higher rates (Huang, et al., 2023; Wu, et al., 2022). This means cost-benefit analyses based on average effects may be misleading. Biochar carbon persistence also varies by soil type: Gross et al. (2024) found that on loamy soil, biochar-derived SOC remained stable after 11 years, while on sandy soil 88% of the initial gain was lost after 9 years. Site-specific assessment will therefore be essential for any further evaluation of the potential of biochar as both a revenue stream and an emissions removal strategy in Scottish soils and deployment contexts.

7 PESTEL analysis

This section evaluates the political, economic, social, technological, environmental and legal (PESTEL) factors affecting biochar deployment in Scotland. It draws on evidence from our REA, stakeholder interviews, and policy document analysis, distinguishing between inherent barriers and risks associated with scaling. The analysis complements the evidence base presented in Chapter 5 and our economic assessment in Chapter 6. Where those sections address the same topic, this section cross-references back to them, rather than repeating the information.

Table 7-1 provides a summary, with each dimension discussed further in the following sections. A full analysis with additional detail is provided in Appendix D.

A general observation relevant to several risks discussed here is that biochar effects are strongly dose-dependent, when considering application to land. Many of the environmental concerns reported in the literature derive from experimental studies using application rates of 10–50 tonnes per hectare (t/ha), which are not economically realistic for Scottish farming (see Chapter 6). At the lower rates identified as viable in our evidence review (0.5–2 t/ha), some of these risks may be substantially reduced, though the evidence base at these rates is itself limited. It is also important to assess biochar against current agricultural practice rather than against zero impact: slurry, mineral fertiliser, and waste biomass are already applied to or generated from Scottish land, and each has its own environmental footprint.

Table 7-1: Summary of key PESTEL barriers and risks

Dimension	Key barriers	Key risks
Political	• No Scottish policy incentives. • Biochar absent from Climate Change Plan.	• Low price of carbon removals (and therefore low revenue) if included in United Kingdom Emissions Trading Scheme (UK ETS). • Lack of integration across devolved/UK frameworks. • Sustainability safeguards may constrain feedstock options.
Economic	• High and variable production costs (see Chapter 6). • Feedstock competition with existing uses. • Immature carbon credit markets. • High upfront capital expenditure. • All greenhouse gas removal (GGR) technologies are expensive in absolute terms.	• Biomass price volatility (manageable through supply contracts). • Carbon credit price uncertainty.
Social	• Low public awareness (75% unfamiliar with carbon dioxide removal (CDR) generally). • Farmer knowledge gaps on biochar application and returns. • Limited skilled workforce.	• Public perception of pyrolysis as incineration. • Renewable Heat Incentive (RHI) scandal precedent for biomass distrust. • Land-use conflicts if non-waste feedstocks used.
Technological	• Core pyrolysis technology is commercially ready (Technology Readiness Levels (TRL) 7–9) but integrated value chain less mature. • No standardised monitoring, reporting, and verification (MRV) for soil application. • Scaling requires proximity to heat customers.	• Market development, not technology, is the primary constraint on deployment.
Environmental	• Limited Scottish field data at economically realistic application rates. • No full-chain Life cycle assessment for Scottish conditions.	• Demonstrated nitrous oxide (N_2O) increase on deep peat soils at high doses (10–30 t/ha). • Increased ammonia from slurry co-application at realistic doses. • Risk of contaminants associated with certain feedstocks.
Legal	• Biochar classified as waste in Scotland (SEPA, 2012). • Rules are clear but restrictive; Scotland's framework more restrictive than England's Low risk waste positions (LWRP) 60/61. • No UK-specific carbon certification standard.	• Compliance costs for permitting as non-exempt waste process disadvantage smaller producers.

7.1 Political considerations

There are currently no Scottish policy incentives specifically targeting biochar deployment. The Draft Bioenergy Policy Statement (Scottish Government, 2024) describes biochar production as an emerging and experimental approach, anticipating deployment from 2030 onwards, but does not commit to specific support mechanisms. The Climate Change Plan Monitoring Report (Scottish Government, 2025a) makes limited reference to biochar, and it does not feature as a named measure in the current plan.

At UK level, the policy landscape is shifting. The Seventh Carbon Budget, presented to the UK Government by the Climate Change Committee in February 2025, is the first to include biochar in its pathways to net zero. The Department for Energy Security & Net Zero (DESNZ) has consulted on integrating GGRs into the UK ETS, with biochar expected to be included by the end of 2029. The UK Government's GGR Innovation Programme allocated over £100 Million (M) to develop GGR technologies, of which £31.5M supported five land-based demonstrator projects including biochar; this programme has now concluded. The Grangemouth Just Transition Fund (£25 M) and UK National Wealth Fund (£200 M) could potentially support biochar-related infrastructure at the Grangemouth site (Scottish Government, 2025c).

However, biochar competes with other policy priorities for the same resources. For example, scaling up dedicated biomass crops could compete with nature restoration commitments (Environment Agency, 2025b). However, the same report notes the potential for biochar to free up land for nature restoration through yield gains. Energy crops and woody feedstocks also compete with other bioenergy pathways including Bioenergy with Carbon Capture and Storage (Scottish Government, 2023a).

7.2 Economic considerations

The detailed economic evidence we have identified is presented in Chapter 6. One key barrier is commercial viability (consistently highlighted by industry interviewees), with Denmark's experience confirming that even substantial public investment (DKK 10 billion committed) has not yet translated into commercial deployment where regulatory barriers remain unresolved (see Section 5.4). Immature carbon credit markets create complexities around additionality and certification (IBI, 2023), limits a key revenue stream, and may lead to further cost, particularly for smaller operators.

The key risks are feedstock competition with established uses (Duffy, et al., 2023; Scottish Forestry, 2025). Any feedstock diversion would need to demonstrate competitive value in the context of Scotland's existing bioeconomy. Biomass price fluctuations are a commercial challenge but are manageable through standard mechanisms such as forward supply contracts. The anaerobic digestion (AD) sector may offer the most immediate route to market. Biochar additives can increase biogas yield from AD, creating a commercial entry point for producers while the wider carbon credit market matures (Scottish Government, 2023a).

7.3 Social considerations

Public awareness and acceptance. Public familiarity with CDR technologies generally is very low. Cox et al. (2025), in a UK-wide deliberative study, found that 75% of participants had never heard of biochar, and CDR as a category was met with negativity and uncertainty. The lack of awareness of biochar was noted as a potential issue by several of our interviewees. Participants in the Cox et al. (2025) study perceived carbon removal as shifting responsibility for environmental issues from individuals to government and industry, raising moral hazard concerns. It should be noted that this finding relates to public attitudes towards CDR as a whole, not biochar specifically.

Participants in Scotland in the Cox et al. (2025) study expressed distrust of novel technologies. The Northern Ireland RHI scandal, where a failed biomass scheme effectively brought down the government in 2020, was cited as creating a localised lasting distrust of biomass-based approaches (Cox, et al., 2025). This evidence suggests that public engagement will need to address not only awareness but also deeper concerns about accountability, trust, and the relationship between removal and reduction.

Farmer and agricultural sector readiness. The farming community currently lacks sufficient data to make informed decisions about biochar adoption (Scottish Government, 2023b). Knowledge gaps exist around application methods, appropriate rates, scaling pathways, and expected returns. Farmer opinion research on biochar is extremely scarce in the UK literature (Brown , et al., 2023; Budai, et al., 2024). Skills gaps are also present in the farming sector for biochar scaling (Bagaria, et al., 2025; IPCC, 2022; IBI, 2023). Apprehension may stem from disputed land-use priorities (Environment Agency, 2025b; Environment Agency, 2025d; Dalby, 2025), and the typical 'slow-adopter' characteristic of stakeholder groups like farmers, as suggested by a biochar industry interviewee. However, the evidence reviewed in Section 5.3 suggests that an approach for Scotland - co-application with organic fertilisers already in use at rates of 0.5–1 t/ha - may require minimal changes to current farm practice and no additional fertiliser inputs. Effective communication of this to the farming community could be one factor in reducing the barrier to adoption.

Employment and food security. An emergent biochar industry would support new employment in product development alongside design, installation and operation of pyrolysis equipment. A single pyrolysis facility typically requires 2–3 full-time equivalents to operate (PyroCore, et al., 2021) and building wider economic activity is consistent with the goals of Scotland's Green Growth Strategy. Spatial mapping could reveal where current and future infrastructure support feedstock logistics and end-uses for heat, including focused developments at Grangemouth. Pathways outlined in this report draw on waste-derived feedstock, mitigating the recognised risks of using dedicated biomass crops at scale (Environment Agency, 2025b). Whilst using non-waste feedstocks could present potential trade-offs for food production (Scottish Government, 2023a), this is unlikely to be of significant relevance in the Scottish context.

Health and Safety. Interviewees indicated that among the public, perception can be that pyrolysis is equivalent to incineration. This poses a social licence risk, particularly if facilities are proposed near communities. Feedstock processing can release volatile organic compounds and particulate matter if not appropriately managed, and airborne biochar particles during field application present a potential inhalation risk (Environment Agency, 2025d). Evidence on health impacts of large-scale application is however limited (Environment Agency, 2025a; Lapwing Energy, n.d.). Biochar is also flammable during storage, with documented risks of spontaneous combustion, requiring appropriate handling and storage protocols. These risks can be mitigated through existing frameworks (e.g. Personal Protective Equipment, emission abatement techniques, etc.), but our interviewees corroborated that health and safety concerns remain common.

7.4 Technological considerations

TRLs. The core pyrolysis technology for biochar production is commercially ready (TRL 7–9), with operational plants in the UK and Europe (Environment Agency, 2025c). The overall value chain, from feedstock preparation through application and verification, is less mature, but the primary constraint on deployment is market development rather than technology. Industry interviewees reported that real-world output from pyrolysis units typically reaches only 60–65% of manufacturer specifications, with implications for financial modelling, but noted that this is a refinement issue that will improve with operational experience. A Danish industry stakeholder reported that scaling from pilot (0.2 Megawatts, MW) to commercial output (20 MW) required substantial redesign, and that costs do not scale proportionally with capacity (see Section 5.4). This suggests that engineering challenges increase non-linearly with scale and that pilot-stage performance data should not be extrapolated directly to industrial-scale facilities. The Scottish Government (2023a), reflecting the gap between the proven core technology and the systems needed for deployment at scale. Nevertheless, biochar technologies may progress through TRLs rapidly and lower ratings may no longer be applicable in 2026.

MRV. For biochar carbon storage, MRV is primarily about recording the quantity, quality, and pyrolysis conditions of the biochar applied, and verifying these against certification standards. This is distinct from field-level greenhouse gas (GHG) monitoring, which relates specifically to quantifying any additional trace gas suppression benefits (such as N_2O reduction) and is a separate, additional claim beyond the carbon storage itself. Jaufmann et al. (2025) found that applied biochar carbon closely matched measured soil organic carbon increases, suggesting that input-based verification could be a practical and cost-effective approach. However, existing methods are either outdated - typically conducted without digitalisation across the entire supply chain (IBI, 2025) - or do not account for storage permanence and the varying decomposition rates of biochar depending on feedstock and temperature (Scottish Government, 2023a). Some farmers may be hesitant about additional record-keeping and monitoring requirements, especially regarding digitalised MRV, but this will depend on how such systems are designed and integrated into existing farm management practices (Bagaria, et al., 2025).

Process constraints. Not all feedstocks are compatible with every production technology (IBI, 2025), and optimal pyrolysis conditions vary by feedstock and end-use. Lower temperatures (<500° C) favour nutrient retention, whilst higher temperatures (≥600 °C) produce more stable carbon (see Section 5.3). Small-scale pyrolysis can have lower energy efficiency (Han, et al., 2025). Pyrolysis plants need proximity to heat customers for commercial viability. Industry interviewees also identified a skills shortage: few UK operators have experience running pyrolysis units, and few farming contractors are currently equipped to apply biochar at scale.

7.5 Environmental considerations

The environmental impacts of biochar are discussed in Chapter 5, including carbon permanence (Section 5.2), soil health and GHG emissions (Section 5.3), and yield impacts (Section 5.3.1). This section addresses additional environmental considerations relevant to deployment decisions.

Peat soils and N_2O. Finnish studies on deep agricultural peat soils found that biochar application at 10–30 t/ha increased N_2O emissions by over 200% (Ronkainen, et al., 2025; Saarnio, et al., 2024). These findings relate to deep peat soils at application rates well above those considered economically viable (0.5–1 t/ha). Peaty mineral soils, which are more common in Scottish agriculture, were not tested in these studies. The Intergovernmental Panel on Climate Change methodology for biochar carbon accounting explicitly excludes organic soils. Application to peat or peaty soils should be approached with caution, but this risk does not extend to mineral agricultural soils where the deployment pathways identified in Section 5.5 are focused. These findings derive from experimental studies using application rates of 10–30 t/ha, and this risk may be substantially reduced at lower rates, though the evidence base at these rates is itself limited (See section 5.3).

Ammonia and slurry co-application. Biochar mixed with cattle slurry has been found to increase ammonia volatilisation significantly. In a four-year German trial at application rates of 500–1,000 kilograms (kg) carbon/ha/yr (which is within the range considered economically viable) Sixt et al. (2025) found ammonia emission increases of 15–106%, caused by higher dry matter content and raised pH. This finding applies at realistic doses and contradicts the assumption, noted by several stakeholders, that biochar improves the environmental management of slurry. Slurry application already generates ammonia emissions under current practice; biochar co-application appears to increase those emissions further. Since ammonia emissions are subject to regulatory limits, this finding should be factored into assessment of Pathways 1 and 3. Further research would be needed to determine whether biochar exacerbates ammonia emissions under low-emission spreading methods.

Contaminant risk. The risk of contaminant transfer from biochar to soil is a feedstock selection issue rather than an inherent property of biochar. Sewage sludge and municipal waste feedstocks present the greatest concern for heavy metals, polycyclic aromatic hydrocarbons, or microplastics, while woody feedstocks are generally low risk (Environment Agency, 2025b). Quality standards and contaminant testing are essential safeguards for the waste-derived pathways identified in Section 5.5, and appropriate feedstock selection largely mitigates this risk.

Land-use change. There could be a risk of land-use change if virgin biomass were used as a feedstock, although both our REA and interviewees identified this as the least viable approach. If virgin biomass were to be considered, converting pasture to energy crops has been linked to biodiversity loss, particularly for farmland birds (Environment Agency, 2025b). An environmental NGO interviewee argued that dedicated energy crop production is generally not sustainable, citing risks to breeding bird populations and overlap with biodiversity and peatland restoration priorities. Regarding soil fauna, a three-year Dutch trial found biochar had no lasting impacts (Jeffery, et al., 2022). The waste-derived feedstock pathways recommended in Section 5.5 avoid this land requirement, and associated risks, entirely.

Production emissions. Biochar production has life cycle emissions from feedstock collection, transport and pyrolysis, contributing 1.4–16% of the total system carbon footprint (see Section 5.2). These emissions are already deducted in the net removal figures hroughout this report (e.g. the Black Bull Biochar pilot project's carbon removal certificate factors of 2.5 and 3.1 t carbon dioxide (CO_2)/t biochar account for full value-chain emissions). CO_2 is also released from stored biomass (Environment Agency, 2025d) via oxidation when the product is exposed to air (Lapwing Energy, n.d.), although this is not technically an additional emission. These issues were corroborated in our stakeholder interviews.

7.6 Legal considerations

Waste classification. In Scotland, biochar manufacture is legally treated as a waste management activity. The Scottish Environment Protection Agency's (SEPA) 2012 Position Statement allows small-scale production from certain woody forestry and agricultural wastes without a licence, but only for facilities with a production capacity of less than 50 kg/hour - a very low threshold equivalent to a small laboratory-scale unit. This constrains commercial investment (SEPA, 2012). Danish experience shows this as a primary barrier (see Section 5.4) reinforcing the case for early engagement with SEPA to develop end-of-waste criteria in parallel with any policy commitment, rather than sequentially. The waste status of relevant feedstocks is clear but restrictive. For example, biosolids and distillery residues are subject to full waste management requirements regardless of the quality of the biochar produced. These regulatory constraints were consistently reflected by our interviewees, with industry actors and Local Authorities identifying that waste classification and end-of-waste criteria directly affect investment decisions (Štrubelj, 2022).

Standards and certification. There are currently no UK-specific certification standards governing biochar for carbon offsetting. Six voluntary international standards exist, each with different requirements for feedstocks, technologies, testing, and permanence criteria (IBI, 2025). Only 47% of global biochar producers certify their carbon removals, which also provides a safeguard against indiscriminate application (IBI, 2023). The use of biomass for producing biochar should also comply with stringent sustainability criteria including land use and GHG emissions reduction requirements (DESNZ, 2025). This includes feedstock-specific sustainability requirements, such as Programme for Endorsement of Forest Certification for woody biomass, as noted in an industry interview. As a result, Scottish-tailored guidance on labelling, sustainability certification, and contaminant limits would help reduce uncertainty and support market development (IPCC, 2022).

Regulatory divergence. In England, the Environment Agency has issued two low-risk waste positions (LRWP 60 and 61) for biochar production and application, providing a significantly more permissive framework than currently exists in Scotland (Environment Agency, 2025f). This creates a competitive disadvantage: English operations can produce and apply biochar from a wider range of waste feedstocks under simplified compliance, while equivalent Scottish operations require full waste management licensing. Multiple stakeholders identified this asymmetry as a barrier to investment. The UK ETS integration of GGRs, expected by 2029, will be a significant milestone for producers, though compliance market prices are likely to be lower than current voluntary market prices, affecting the revenue side of the business case.

8 Conclusions

This report aims to assess the potential for biochar deployment in Scotland, drawing on a rapid evidence assessment of published literature and stakeholder interviews. Our brief conclusions below are structured around supply chain viability, the effects of biochar on carbon sequestration and soil health, lessons from international experience, and key evidence gaps to be addressed to support future biochar use in Scotland.

8.1 State of evidence on biochar impacts

Carbon sequestration. Biochar provides stable, long-term carbon storage, with net removal values for dry woody feedstocks (most relevant for Scotland) typically above 3 tonnes (t) carbon dioxide equivalent (CO_2e) per t of biochar. Carbon permanence is primarily determined by both pyrolysis temperature and soil temperature. Scotland's cooler climate is favourable for long-term storage of biochar carbon, with the Intergovernmental Panel on Climate Change methodology estimating 72–88% of biochar carbon remaining after 100 years. However, no long-term field studies exist for Scottish soils, and a full life cycle assessment (LCA) under Scottish conditions has not been conducted. The role of soil moisture and rainfall in long-term permanence is also not yet fully clear.

Soil health and agricultural performance: Biochar generally benefits soil health, but impacts depend on initial soil conditions, and on biochar quantity and quality. Average crop yield increases globally range from 13–17%, but in temperate climates comparable to Scotland yield improvements from biochar applied alone are not consistent in the short term. However, indicative results from the Black Bull Biochar demonstrator in Scotland show 16–18% higher grassland yields and 34% higher arable yields when biochar was co-applied with organic fertilisers at low doses (0.5–1 t/hectare, ha). Biochar can also raise soil pH and reduce nitrous oxide emissions on mineral soils by 12–38%. Application to peat should however be avoided, due to potential increased emissions. A significant limitation is the lack of peer-reviewed Scottish field trials at economically realistic application rates.

8.2 Supply chain viability for biochar in Scotland

Feedstock availability. The availability of feedstocks is not likely to be a limiting factor for biochar production in Scotland. There are substantial biomass resources, including from forestry, agriculture, whisky production, and other waste streams. Forestry and sawmill co-products seem to be the most immediately viable feedstock, with well-characterised volumes and existing processing infrastructure in Scotland. Co-products from the whisky industry are also reliable in quantity, but current use as animal feed also delivers climate benefits. There is a significant lack of biochar-specific research for Scotland’s largest feedstock streams, such as agricultural residues, sewage sludge, waste wood, and horticultural residues. This needs to be addressed.

Infrastructure and logistics. The core pyrolysis technology for biochar production is commercially ready (Technology Readiness Levels 7–9), and operational plants already exist in the United Kingdom and in Europe. However, the integrated value chain, from feedstock preparation through application and verification, is less mature. Scaling up biochar production can present engineering complexities, and proximity of production to heat customers can be a key factor for commercial viability. The economic limits to transportation of feedstocks impacts on logistics and site selection. For wet wastes (liquid manure or slurry) this may be as low as 10 km, whilst for dry biomass it can be 30–50 kilometres.

Costs, benefits, risks and barriers. Biochar production costs are highly variable, ranging from £175–460/t globally, with Scottish lab-scale production from conifer brash at £370/t. Costs vary based on feedstock availability, technology configuration, plant scale, and regulatory requirements. High upfront capital expenditure – around £9.5 Million for a 20 kilotonnes/yr facility – is a potential barrier to scaling up biochar deployment. Operational expenditure (OPEX) also varies significantly from £42–399/t of biochar. The overall cost of biochar as an option for permanent carbon removal at £13–208/tCO_2, overlaps with some non-permanent removal options. Carbon credit revenue is an important component for most deployment pathways, particularly for application to agricultural soil, with a current value of £600–800/t biochar in the voluntary market. However, this value may decrease as the carbon removals market matures.

Other barriers to deployment include the classification of biochar manufacture as a waste management activity in Scotland, requiring full waste management licensing for facilities processing over 50 kilograms/hour. Stakeholders consistently identified this as a key impediment to investment. Several feedstocks also have existing, economically established uses, so it needs to be demonstrated that biochar can offer greater overall value. Public awareness of carbon removal technologies is low, and farmer adoption is constrained by limited Scottish evidence and uncertainty over returns. Health and safety concerns related to pyrolysis, such as the potential release of hazardous air pollutants and the flammability of biochar, also need to be addressed.

8.3 Lessons from international experience

Denmark has the most advanced biochar policy framework in Europe, with substantial funding and a governmental taskforce. Nevertheless, there is still a significant gap between the level of ambition related to biochar and its actual deployment. This is primarily due to regulatory hurdles related to end-of-waste permitting, highlighting the critical need for supportive regulation to advance in parallel with policy ambition. The Danish experience also highlights feedstock as the largest OPEX, and that scaling up of biochar production can introduce significant engineering complexity.

The Swedish biochar sector has been able to grow due to public co-financing and municipality-level support, treating biochar plants as both production infrastructure and learning sites. This collaborative, knowledge-intensive approach has been essential for its development.

Germany benefits from strong industrial capacity in pyrolysis technology and regulation that recognises the use of pyrolysis for phosphorus recovery from sewage sludge. This has helped to create a market for the technology, and demonstrates how specific regulatory frameworks can drive growth.

8.4 Key evidence gaps and areas for future action and research

Several critical evidence gaps need to be addressed. There are a number of related actions that could help to address these gaps, to inform and support future biochar deployment in Scotland.

Targeted support is needed to bridge the gap between pilot projects and expanding commercial operations. Stakeholders have identified that this critical stage is not addressed by current funding mechanisms. This would also help to support operations until mature markets provide stable revenue from each value stream, including carbon removal.

There is an absence of **biochar-specific research** for Scotland's largest potential feedstock streams, including agricultural residues, sewage sludge and waste wood. It is critical to address this to provide a sound evidence base and commercial case for future deployment. Comprehensive **comparative LCAs** are needed for major potential Scottish feedstock streams, to evaluate the benefits of biochar against alternative uses. In addition, a comparative assessment of **biochar versus alternative soil amendments** for Scottish farming systems would be beneficial.

There is a need for **Scottish field trials** to establish economically realistic application rates for biochar derived from different feedstocks and to different soil types, particularly through integration with nutrient management. Such trials could offer sites for benchmark monitoring of biochar under Scotland's cooler, high rainfall climate, including secondary effects on nitrous oxide emissions, native soil organic carbon, and the contribution of biochar to soil resilience.

Further **opportunity mapping** should be carried out for biochar production at different scales, identifying where existing and future infrastructure might favour investment, taking into consideration the feedstock logistics and end-uses, including the heat product.

Early engagement with the Scottish Environment Protection Agency would be beneficial to explore how **end-of-waste criteria** can support biochar deployment, in parallel with any future policy commitments. A **standardised framework** for biochar characterisation, traceability, and monitoring would also be beneficial, covering both climate claims and environmental safeguards.

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10 Appendices

Appendix A Study methodology

This appendix summarises the study methodology. The key research elements were to undertake a rapid evidence assessment (REA) of academic and grey literature, and carry out a series of stakeholder interviews carried out to complement the REA.

Our methodology was designed to identify information relevant to the key research topics, namely:

- Feedstock sources (including availability, scalability and competing uses);
- Carbon impact (life-cycle emissions considering carbon sequestration potential);
- Effect of biochar on soil health, land productivity and climate resilience; and
- Processing infrastructure, supply chain logistics and capital and operational expenditure (CAPEX and OPEX).

In addition, we aimed to capture information relevant to the economic assessment and PESTEL (political, economic, social, technological, environmental and legal) analysis.

10.1 Rapid evidence assessment of literature

To fit within the short study timeline, we chose an REA method, and to supplement other recent reviews rather than reproduce them (for example on feedstock availability). REA involves targeted search strategies, streamlined screening of sources, prioritisation of synthesised evidence (meta-analyses and systematic reviews), and streamlined quality appraisal. Our review prioritised breadth and policy relevance over exhaustive coverage, enabling research evidence to be synthesised whilst still maintaining methodological rigour and a transparent evidence base. Our approach followed guidance from the Department for Environment, Food & Rural Affairs (DEFRA) (Joint Water Evidence Group, 2015).

To ensure relevance of the sources to the Scottish context, we focused first on evidence collected in the context of the Scottish or United Kingdom (UK) land, climate and economy, supplementing with evidence from comparable contexts (e.g. northern Europe or temperate maritime regions). To maintain a manageable quantity of sources to review, we focused on literature published since 2020, with the exception of earlier meta-analyses, seminal or highly cited work where they remain the best available evidence.

We identified sources via a combination of indexed academic databases and targeted organisations publishing grey literature.

For **academic literature**, we used the academic databases Web of Science & Scopus. Keywords used for the search were:

- **General:** biochar, pyrolysis, char, biocarbon, biomass, feedstock, forestry residue, agricultural waste, co-product, sewage sludge, draff, spent grain
- **Geography/climate:** (priority) Scotland, Scottish, UK, United Kingdom, Britain; (secondary) temperate, northern Europe, Scandinavia, Ireland, maritime climate, cool humid, boreal, New Zealand
- **Feedstock:** Supply, volume, resource, generation, waste stream, circular economy

- **Carbon impact:** sequestration, abatement, removal, storage, durability, permanence, stability, recalcitrance, persistence, half-life, H:C ratio, N_2O, nitrous oxide, CH_4, methane, greenhouse gas, GHG, life cycle assessment, LCA, GWP, global warming potential, carbon footprint, net zero, emissions profile
- **Soil, land and climate:** yield, crop productivity, biomass, barley, wheat, grassland, silage, pasture, nutrient use efficiency, liming, soil organic carbon, SOC, water holding capacity, pH, bulk density, porosity, drought tolerance, water stress, waterlogging, flood recovery, climate adaptation, extreme weather, soil moisture
- **Infrastructure, supply chains, costs:** techno-economic analysis, TEA, cost benefit analysis, CBA, CAPEX, OPEX, supply chain, logistics, infrastructure, pyrolysis, transport, storage

We screened identified academic literature using Covidence, a systematic review management platform. Search results were imported into Covidence and titles and abstracts were first screened using Covidence’s scoring system (include/exclude/maybe), then reviewed by the study team. We then carried out a full-text screening for the most relevant literature, based on geographical relevance, literature since 2020, quantitative studies (where possible), English language, and relevance to the key research topics.

For **grey literature**, we focused first on known sources, including: Scottish Government, Scottish Forestry, Zero Waste Scotland, the Scottish Environment Protection Agency, Scotland’s Rural College (SRUC), UK Biochar Research Centre, Scotch Whisky Association, International Climate Research, ClimateXChange, UK Government (Department for Energy Security & Net Zero, DEFRA), International Biochar Initiative (IBI) and European Biochar Industry Consortium. We hand-searched their websites and used keywords in on-site searches (biomass, biochar, residues, organic waste, carbon sequestration, soil carbon). We supplemented this with Google Scholar searches using simple keyword phrases:

- Scotland biomass availability assessment
- Scottish forestry residues volume potential
- Scotland agricultural waste resource
- Scotland distillery co-products "spent grain" OR draff
- Scottish wood fuel supply chain

Review of search results was limited to the first two pages of results per search string.

Each relevant piece of academic and grey literature was reviewed by a team member, who extracted salient points and recorded them in shared data extraction Excel sheet, noting key document details and information of relevance to the research questions. In total, we reviewed in detail: 10 pieces of academic literature on feedstocks, 13 on carbon impacts, and 27 on soil impacts (15 global papers and 12 papers from Scotland or similar climates), plus 66 pieces of grey literature. This is a small fraction of the global literature referencing biochar (13,000 items), which has inherent biases but on which we have drawn (via comprehensive syntheses) to provide some contextualisation.

10.2 Stakeholder engagement interviews

To validate and complement the findings of the REA, we carried out a series of interviews with stakeholders involved in biochar supply and use chains. The study team drew up a longlist of potential interviewees, based on existing knowledge of relevant actors and reflections gained from the REA. We selected participants to invite for interview with the intention of engaging with:

- Different **categories of stakeholders** (academia, industry, forestry/agriculture, Government and Non-Governmental organisations, NGOs)
- Stakeholders with knowledge across the **key research topics**
- Stakeholders with knowledge relevant to **economic costs** (CAPEX, OPEX, economic benefits; scale-related cost variations; potential funding; how biochar valorisation can be increased; and
- Stakeholders with knowledge on **political, economic, social, technological, environmental and legal factors** that can affect the deployment of biochar as a climate and land use solution in Scotland.

We sent personalised invitations for interview to 15 individuals. This resulted in 9 online interviews with 12 people, held over a four-week period in February and March 2026. Five interviews were held with industry (covering pyrolysis technology, biochar production and feedstocks), one with a government agency, one with a local authority, one with a research institute, and one with an NGO. Ten interviewees were male, and two female.

The interviews were around one hour long and semi-structured, based on a list of questions shared with the interviewees in advance (see Table 9-1). With informed consent from the interviewees, interviews were recorded and transcribed using Microsoft Teams auto-transcription. Interviewers also took separate notes to record key insights. The recordings and notes were stored on the secure study SharePoint site for access by team members, with recordings deleted on conclusion of the study. We collated key points into a sheet in the study's data extraction Excel sheet and integrated these into the relevant chapters of this report.

Table 9-1: Overview of questions for stakeholder interviews

Theme/topic	Questions
Introductory question	• How would you briefly define/describe biochar? *(To gauge stakeholders' understanding)*
Feedstocks and use cases/pathways	• Which feedstocks offer potential for biochar production in Scotland? Do you have any insights or evidence on availability and scalability of these feedstocks for biochar? *e.g. forestry waste/residues, wood chip, whiskey draff, food waste, purpose grown biomass* • What do you see as the potential use cases for biochar in Scotland? *e.g. application to land, peat replacement in growing media, construction/low-carbon ingredient to concretes, sorbent for effluent water/gas treatment or contaminated land remediation, non-fossil reducing agent for metallurgy, animal feed additive to repress ruminant methane emissions, management of N emissions in livestock sheds/ manures/fertilizers* • What scale might be appropriate for biochar production and use in Scotland – from single-farm, through small local clusters, to large-scale production?
Carbon impacts	• Can you share any insights or evidence on the life cycle emissions of biochar production (in the Scottish soil/climate context)? *e.g. biomass*

Theme/topic	Questions
	handling/processing, transportation, use, pyrolysis, carbon sequestration potential
Effects on soil health, land productivity and climate resilience	• Can you share any insights or evidence on the soil health impacts of biochar application? • Can you share any insights or evidence on the impacts of biochar application on land productivity? • Can you share any insights or evidence on the potential climate resilience impacts of biochar application?
Costs and economic aspects	• Can you share any insights or evidence on the various costs related to biochar use? *e.g. feedstock acquisition and processing; use or sale of biochar or co-products; storage and handling; capital, infrastructure and equipment costs; operational costs – energy, labour* • In your experience, have any of these costs varied, or are they likely to be subject to future volatility? • How do these costs interact with prices – e.g. costs to produce high-value biochar vs price that can be charged for biochar product? • To what extent can these costs be offset by benefits of biochar use, and what might those benefits be? *e.g. sale/value of carbon removal credits* • What funding models could be used to support biochar deployment in Scotland? *e.g. funding by end-users, extended producer responsibility*

Risks and barriers / supporting factors for biochar deployment in Scotland	• What are the key factors or considerations that may positively or negatively affect the deployment of biochar as a climate and land use solution in Scotland, in relation to:
	  ○ Political aspects
	  ○ Economic aspects
	  ○ Social aspects
	  ○ Technological aspects
	  ○ Environmental aspects
	  ○ Legal aspects

International lessons	• Are you aware of any good practices from other countries' experiences with biochar implementation, which could be applicable in Scotland?
General / concluding questions	• Are there any major knowledge gaps that inhibit the use of biochar in Scotland? • What could the Scottish Government or other stakeholders do to help address these gaps? • Are there any issues or points you'd like to raise that we haven't yet discussed?

Appendix B Summary of confidence regarding evidence on feedstock availability

This appendix provides additional background for the discussion presented in Section 5.1.

Table 10-1 below summarises our confidence ratings based on volume of evidence, agreement between studies, and applicability to Scottish conditions. The main columns draw on the full international evidence base including temperate climate analogues. The final column indicates the availability of Scottish-specific evidence.

Table 10-1: Confidence ratings of evidence assessed

Feedstock	Volume of evidence	Agreement	Applicability	Overall confidence	Scotland-specific evidence	Limitations
Sawmill co-products	High	High	High	High	High	Strong volume and characterisation data for Scotland; biochar conversion studies limited to international analogues
Forestry brash	Medium	Medium	High	Medium	Medium	Scottish lab-scale characterisation exists (Flow Country); no Scottish field trials; phosphorous leaching flagged as a concern for Scottish waterways
Arboricultural arisings	Low	Medium	Medium	Low	Low	Commercial biochar production operational in England; no peer-reviewed data on Scottish volumes or supply chains
Whisky co-products	High	High	High	High	High	Extensively studied in Scotland but not for biochar; competing uses (animal feed) deliver 2.5–8.0 times greater greenhouse gas mitigation than anaerobic digestion
Cereal straw (barley, oat)	High	Medium	Medium	Medium	No evidence	International evidence supports straw-to-biochar

Feedstock	Volume of evidence	Agreement	Applicability	Overall confidence	Scotland-specific evidence	Limitations
						conversion; no Scottish-specific studies despite barley and oat straw being major Scottish crops
Livestock manure and slurry	High	Medium	Medium	Medium	No evidence	International manure-biochar evidence exists; Scottish applicability limited by transport economics (<10 kilometres for slurry) and wet climate
Food waste and digestate	Medium	Medium	Low	Low	Low	United Kingdom (UK)-level hydrothermal carbonisation and digestate studies available; scale and pre-drying challenges not assessed for Scottish waste infrastructure
Sewage sludge	Medium	Low	Low	Low	No evidence	International pyrolysis studies exist; no assessment of Scottish Water facilities or sludge volumes for biochar
Energy crops (Short rotation coppice (SRC) willow)	Medium	Medium	Low	Low	No evidence	International evidence for willow biochar; Scottish uptake of SRC has been slower than projected; day-length limits miscanthus suitability

Note: 'Volume of evidence', 'Agreement', and 'Applicability' draw on the full international evidence base, including studies from temperate climate analogues (UK, Scandinavia, Germany). 'Scottish-specific evidence' rates whether studies have been conducted using Scottish feedstocks, facilities, or conditions. Several feedstocks have strong international evidence but no Scotland-specific research.

Appendix C IPCC methodology for biochar carbon accounting

The information here provides additional background on the Intergovernmental Panel on Climate Change (IPCC) methodology referred to in Section 5.2.3.

The IPCC methodology for biochar carbon accounting (Woolf, et al., 2021) establishes two **key factors that determine biochar carbon permanence**, i.e. how much carbon persists in soil over the longer term. The first is the temperature used during pyrolysis, with higher temperatures (>600° Celsius, °C) typically resulting in longer permanence, even exceeding 500 years. The second is the mean annual soil temperature, with biochar typically breaking down faster in warmer soils. This suggests that biochar may degrade relatively slowly in Scottish soils, although studies have not yet quantified this.

1. **Pyrolysis temperature.** During pyrolysis above 500°C, the carbon is reconfigured to structures that are the most resistant to breakdown. The hydrogen to organic carbon ratio is used as a predictor of the permanence of biochar, since only carbon remains in pure biochar formations. Ratios in this below 0.6 indicate that at least 63–82% of carbon will remain stored after 100 years. Wood-based biochars typically meet this threshold (Woolf, et al., 2021; Jalali, et al., 2025), possibly owing to the relative ease of pyrolysing wood. In local studies, biochar produced from forestry brash resulted in 71.9% fixed carbon - a proxy for aromatic carbon (Pap, et al., 2022) - while biochar from food-waste digestate can achieve higher at 88% (Gamaralalage, et al., 2025). Meta-analyses suggest that mean residence of biochar in soil can exceed 500-year high temperature biochar (600°C+) (Schmidt, et al., 2021). Low-temperature biochar (250–400°C) include more labile forms of carbon that break down within the first year, providing short-term biological benefits analogous to more conventional organic inputs (Jalali, et al., 2025; Liao, et al., 2022).
2. **Mean annual soil temperature affects degradation rate.** Biological activity is higher in warmer soils, accelerating biochar breakdown, while in cooler soils it is slower. One meta-analysis found temperate studies showed an 86% relative increase in soil carbon, compared to 55% in tropical studies (Chagas, et al., 2022), although dosage and initial soil carbon levels may also differ. Scotland's low mean annual temperature (around 8–9°C) should favour slower degradation compared to the warmer climates where most biochar research has been conducted. However, this benefit remains unquantified in Scottish conditions specifically.

Appendix D Full PESTEL analysis

This appendix provides our full Political, economic, social, technological, environmental, legal (PESTEL) analysis, with additional discussion to that contained in Section 7 of the report. It outlines our main findings in relation to the key political, economic, social, technological, environmental and legal considerations to be taken into account when exploring future options for biochar deployment in Scotland. It should be emphasised that these findings identify key risks and barriers from literature and stakeholder consultation, and do not focus on the benefits of biochar in comparison to other technologies. Efforts have been made throughout to qualify the significance of barriers and concerns for Scotland.

10.3 Political considerations

Biochar stands out as a technological solution in its infancy. Stakeholders are expressing significant interest in biochar due to its versatility across various sectors. It has been suggested that deployment could be substantial, even without additional support (Scottish Government, 2023a).

However, stakeholders broadly recognise the need for Scotland to develop or advance regulation to support biochar deployment pathways. Scottish Government has indicated an interest in exploring opportunities for biochar use in agriculture and related carbon market opportunities (Scottish Government, 2024). However, there are as yet no Scottish policy incentives for biochar deployment at scale.

Stakeholder interviews indicate a range of views on which government actions would most effectively support the sector. Some interviewees highlighted the importance of clearer political signals on subsidies, grants and supply chains, as well as alignment with wider strategies such as United Kingdom (UK) timber utilisation or carbon roadmaps. Others suggested that a dedicated strategy, similar to those developed for sustainable aviation fuels or hydrogen, could help drive action, as it is marginally easier for firms to make progress with a strategy that backs action. However, some interviewees argued that progress may be faster through targeted funding schemes and technology de-risking rather than through a comprehensive biochar strategy.

The demonstrated potential of biochar to permanently store carbon is not sufficiently recognised in regulations and policies (Scottish Government, 2023a). Reducing policy uncertainty could indicate government support and provide long-term guarantees (Department of Energy and Climate Change, 2013) to incentivise market development. Lack of incentives also creates uncertainties in feedstock supplies. Several policy incentives to encourage market deployment have been suggested. Fertiliser taxation and fiscal incentives for integrated biorefinery clusters and anaerobic digestion (AD) to use and treat bio-wastes and residues could incentivise biochar application to soils (Circle Economy, 2022; Scottish Government, 2023b). Biochar could be also incentivised through inclusion in agricultural reforms (Scottish Government, 2023b).

Despite a lack of targeted policy incentives, Negative Emissions Technologies (NETs) projects and a mature market for biochar, respondents to a Scottish Government study anticipate significant expansion. There are over 700 AD plants across the UK that could leverage biochar products to enhance efficiency and increase biogas yield. This anticipated growth is driven by the urgent need for NETs to address climate goals. The development of certified, verifiable negative emissions credits is considered crucial for this sector, with other char products and AD additives like carbon black contributing to a broader emerging char market the industry in Scotland aims to cultivate (Scottish Government, 2023b).

The following Government interventions related to biomass could potentially support biochar deployment:

- UK Government funding of over £100 Million (M) has been allocated to develop Greenhouse Gas Removal (GGR) technologies and assess GGR potential to deliver negative emissions, improve cost effectiveness and enhance scalability. Biochar is explicitly included as a pilot pathway, creating opportunities for implementation and

research. Of this total, £31.5 M will be delegated to five land based GGR demonstrator projects (including biochar and perennial bioenergy crops) under the Strategic Priorities Fund (Scottish Government, 2023a).
- The ‘Project Willow’ feasibility study, jointly funded by the UK and Scottish Governments in 2024, to examine the long-term industrial future for the Petroineos Grangemouth refinery site. This study is referenced in multiple interviews as offering potential for biochar. It identifies nine initial viable “project sets” suited to the site, including some related to wastes and bio-feedstock. Proposals most relevant to biochar include second generation bioethanol using Scottish timber, and AD of organic waste and biogas upgrading to produce biomethane. The Scottish Government has made £25 M available through the Grangemouth Just Transition Fund to support immediate opportunities arising from Project Willow, with an additional £200 M available from the UK Government’s National Wealth Fund to support investible propositions (Scottish Government, 2025b).

In the development of future biochar policy, it will be important to consider sustainability and safeguards. Firstly, the use of biomass must comply with stringent sustainability criteria, including land criteria and greenhouse gas (GHG) emissions reduction criteria (Scottish Government, 2024), as well as key standards such as the Programme for the Endorsement of Forest Certification and the UK Forestry Standard. Secondly, safeguards are necessary to consider the limits and availability of sustainable biomass in order to avoid excessive demand of biomass for energy and associated negative effects on carbon sinks and stocks, biodiversity, air quality and the bioeconomy (European Commission, 2022). One interviewee also found biochar to be politically sensitive due to political debates on supporting climate investments. To communicate the benefits of biochar and overcome political barriers, they suggested that biochar’s positive economic impacts on farmers and ecologic impacts on rivers and air quality could be emphasised.

10.4 Economic considerations

10.4.1 Circular economy impacts and systemic risks

Scotland’s circular bioeconomy is relatively advanced, with well-tracked biomass resources. However, imbalances in material use and land emissions remain. In addition, there are limited economic models examining trade-offs between alternative biomass uses, such as biochar, in terms of monetary costs and GHG benefits.

The agrifood sector makes up a significant share of Scotland’s material footprint, with two-thirds of all biomass feedstocks consumed heavily dependent on imported biomass (Circle Economy, 2022). This import dependence creates exposure to global supply chain volatility and externalised environmental impacts, limiting domestic control over resource security (Scottish Government, 2023d). Globally, sustainable biomass is increasingly recognised and pursued as a resource to be leveraged in response to emissions reduction commitments, which is expected to increase global prices for sustainable biomass (Scottish Government, 2024).

At the same time, Scotland generates substantial bio-based waste and by-products. The production of whisky, beer and fish alone, according to 2022 data, produces around 4.6 M tonnes (t) annually, indicating untapped potential for more efficient use of domestic biomass resources. However, barriers to improving circularity remain. Increased circularity and more efficient waste utilisation would require additional infrastructure and logistical support to collect, process and redistribute biomass streams (Circle Economy, 2022). Between 2003-2020, biomass production volumes declined even as economic value increased, indicating tighter resource availability (Scottish Government, 2023d).

Some economic opportunities related to AD could contribute to supporting future biochar deployment, particularly where policies and markets support parallel growth of both sectors. The Scottish Government has explicitly acknowledged that expansion of the AD sector will influence the development trajectory of biochar plants (Scottish Government, 2023a). Beyond this interaction, AD also delivers co-benefits that strengthen the broader case for integrated biomass pathways. Digestate can improve nutrient management and reduce reliance on imported synthetic fertilisers, assuming stable sector growth and continued farmer uptake (Scottish Government, 2024). In addition, long-term institutional strategies reinforce this direction. For example, Scottish Water aims to maximise the value of sludge through AD or advanced AD, improving product quality while generating energy from the process, providing a signal for durable policy and infrastructure support for the sector (SRUC, 2020).

10.4.2 Market trends

There are some emerging risks concerning the potential deployment of biochar at scale. The evidence we have found covers global and UK-wide trends due to lack of evidence for Scotland.

In contrast to the increasing demand for biomass, biochar carbon markets are relatively smaller in scale: developing high quality markets will require improvements in the maturity of carbon markets to act as a source of income (IBI, 2023). There are UK biochar companies who have successfully sold their carbon removal credits to UK corporate buyers. Globally, ambition and interest for issuing and purchasing biochar credits are also growing. However, complexities in additionality requirements, costs of certification and markets mean many biochar producers do not yet generate biochar carbon removal credits (IBI, 2023).

In the UK, it is widely recognised that there is a market gap for cost effective GGR technologies, with the biochar market at early stage of development. This was consistently highlighted in our interviews. (Arup, 2022; Environment Agency, 2025b; Biochar Europe, n.d.). Thus far, biochar has struggled to scale up in the UK (Bagaria, et al., 2025). Scottish stakeholders interviewed emphasised that commercialisation has been a key bottleneck for many entrepreneurs seeking to develop viable biochar projects. Despite strong theoretical knowledge and investments in R&D, several initiatives have struggled to translate into commercially viable operations. Stakeholders also highlighted demand-side uncertainties for businesses, including unclear purchaser markets and concerns that current prices per tonne of product may not be economically viable.

Lastly, for market development, interviewees pointed to the need for stronger industry networks and clustering in Scotland to better connect actors across the value chain, such as linking feedstock suppliers with biochar producers. Interviewees noted that current efforts are more concentrated in academic research than in initiatives aimed at supporting business development and commercial collaboration.

10.4.3 Competing uses for feedstocks

Competing uses of feedstock resources is a primary concern for the viability and scalability of the biochar market in Scotland. According to Zero Waste Scotland, over 27 Mt of biomass arisings were generated in Scotland in 2014, many of which had limited productive use (Zero Waste Scotland, 2022). Agricultural biomass accounted for 16.7 Mt, and production was geographically concentrated, with about half arising from Aberdeenshire, Highland, Dumfries and Galloway, and the Scottish Borders. Within the agricultural category, slurry and manure make up the overwhelming majority at 14.4 Mt, with straw contributing 1.65 Mt (Zero Waste Scotland, 2022). Woody biomass represents another important feedstock stream for biochar production, with Forest Research reporting total production of 6.4 million tonnes in Scotland in 2024 (Forest Research, 2025a).

Feedstocks in the UK have already found multiple circular economy uses, meaning the biochar supply chain has to be commercially viable and sustainable to be competitive and to be able to secure feedstock.

AD and biogas sites are target customers for biochar and growth of the AD sector will affect the development of biochar plants. Biochar has potential to be used in AD sites as an additive to increase biogas production, as elaborated above in Section 5.5 (Pathways). Currently, biogas production targets (as a % of total gas demand) across Europe are much more ambitious than in the UK, which currently has no mandated target (and sits at 1% of total gas demand) (Scottish Government, 2023a). For example, targets in Denmark and Poland are 100% and in Germany 25%. In 2023, Carbogenics reprojected that the UK biochar sector would double in the following three years and that the UK biogas sector would double in less than a decade (Scottish Government, 2023a). This rate of growth was anecdotally confirmed during our interviews. Taking this projected growth as a proxy for establishing a market, a timeline of around 2030-2035 could be proposed for NETs development (Scottish Government, 2023a).

Biomass is used in the UK for electricity generation, heat, power, industry, and other Bioenergy with Carbon Capture and Storage (BECCS) technologies (Scottish Government, 2023a; Scottish Government, 2024; Scottish Executive, 2007). Industries in Scotland that currently use bioenergy include paper milling, wood panel manufacture, distilleries, breweries and wood pellet producers (Scottish Government, 2024). Electricity production from biomass is not yet a mature market in the UK, limiting potential competition for biochar feedstocks at present. In addition, generating electricity has low and decreasing carbon benefits in countries such as the UK, which already a large proportion of grid electricity from low carbon renewable sources. However, in other countries with similar biomass profiles such as Sweden, biomass supplies nearly half of the heat network (ClimateXChange, 2025b). Ultimately, whether use of biomass for industrial heat could lead to increased competition in the future depends on whether the economic value of biochar is higher than the alternative use of the feedstock.

Other potential biomass feedstocks mentioned by stakeholders during our stakeholder interviews include woody biomass, straws, and perennial energy crops such as willow and miscanthus. During the interviews, woody biomass stood out as a favourable material for biochar production in Scotland. However, wood fibre is a limited source, with increased demand in one pathway creating trade-offs with others (Forestry Commission Scotland, 2012). Scotland's forestry product industry is large, sustaining over 16,000 jobs and adding around £878M/year to the Scottish economy, excluding the contribution of forest tourism and recreation (Scottish Forestry, 2025).

Lastly, feedstock use for biochar has been described as potentially conflicting with the policy goal of maintaining current domestic food production levels and avoiding further land use change for growing biomass for the purpose of biochar production (Environment Agency, 2025b).

10.4.4 Cost-related considerations

Biochar costs are highly variable and depend strongly on feedstock availability and chosen type, technology configuration, plant scale, and regulatory requirements. Upfront capital expenditure needs for pyrolysis facilities are substantial, while operational expenditure (OPEX) includes feedstock procurement and transport, energy inputs, labour, and application to land. Uncertainties around costs and high upfront investment needs remain among the primary barriers to starting up and scaling biochar deployment (Scottish Government, 2023a).

Studies conducted in 2019 and 2020 to estimate the cost of carbon capture through biochar found a wide range of costs. The cost depends on the choice and availability of feedstock, pyrolysis technology and scale, ranging from £13-208/t carbon dioxide (CO_2) (Scottish Government, 2023a).

Across the literature we reviewed, concerns are repeatedly raised regarding high costs of feedstock, pyrolysis plants and legal expenses (Shackley, et al., 2011; Department of Energy and Climate Change, 2013; IPCC, 2022; Scottish Government, 2023a; Scottish Government, 2025a). Taken together, high costs constrain the development of a profitable biochar market. This was echoed by industry interviewees in comments on commercial viability. Further government supported research could help reduce uncertainty by **defining the economic value (market price) of biochar in regular operational use**. Cost pressures appear particularly acute for farmers, who face a high purchase price for biochar relative to other soil amendments and limited short-term financial returns (IBI, 2023; Han, et al., 2025; Bagaria, et al., 2025). Stakeholders from industry also shared that prices are geography and distillery specific, feeding into high variability of costs.

Technology related costs add further pressure to the economics of biochar production. Frequently cited are dryer/kiln technology to reduce moisture and pre-treatment infrastructure needs for lower grade biomass, power and grid safety related costs (Lapwing Energy, n.d.; CapChar Ltd, et al., 2022) . While some sources suggest smaller scale deployment could lower technological costs, such as when traditional artisan methods are used, other sources suggest that scaling up could help lower per-unit costs (IBI, 2025).

Where producers seek to generate revenue through carbon markets, additional layers of cost arise. This includes monitoring, reporting and verification (MRV), certification, and associated administrative requirements, which can materially increase overall project costs, particularly for smaller operators (IBI, 2025). In addition, testing requirements may present an additional cost for waste-derived biochar production. At the same time, stakeholder interviews and some literature suggest that some of these cost pressures may reduce over time through scaling up, technological learning, supply chain optimisation, and improved access to finance (Scottish Government, 2023a).

10.5 Social considerations

10.5.1 Food, yield, agriculture, farming and land use concerns

There are concerns, including amongst the public, about the risk of biochar deployment at scale in Scotland resulting in trade-offs in food production and security if using domestic non-waste feedstocks (Scottish Government, 2024; Environment Agency, 2025d). Changes in land use, from growing domestic food supply to biomass crops for feedstocks, could therefore increase the price of agricultural commodities like food, with a risk of disproportionately impacting the poorest households (Scottish Government, 2023a). Distributional impacts like these, and the risk of creating or exacerbating socioeconomic inequalities, must be considered (Environment Agency, 2025d). Though the application of the resultant biochar can increase yields of remaining agricultural land, evidence to support this effect is relatively limited in temperate regions like Scotland (IPCC, 2022), though biochar co-applied with organic fertiliser has been shown to be effective by one Scottish trial (Bagaria, et al., 2025). Refer to Section 5.3.1 for more detail on the impacts of biochar on yield.

This dispute in land use priorities risks conflict (Environment Agency, 2025b; Environment Agency, 2025d) and local objections (Dalby, 2025). These are particularly notable for farmers, with a total agricultural workforce in Scotland of 66,800 people (Scottish Government, 2025c) who as noted by a stakeholder from the research sector are key to engage throughout the supply chain. An interviewee from the biochar industry sector also noted that farmers are typically slow adopters and may need incentives to encourage uptake of new technologies like biochar, such as targeted interventions via farming groups paying preferential prices for products that meet certain targets. Two interviewees built on this point by emphasising the challenge of getting buyers to trust biochar as a product, but had confidence that this would develop with time and use, if economic barriers were tackled.

For the above reasons, using biochar feedstocks that originate from waste may be seen as more socially acceptable, mitigating risks of land-use change and resultant conflicts (Environment Agency, 2025b). A local authority stakeholder confirmed that they are attempting to steer away from crops grown specifically for feedstock for these reasons, citing ethical concerns.

10.5.2 Health and safety concerns

Health and safety concerns around biochar production and storage may also act as a barrier to broader implementation in Scotland. This section focuses on human health and safety concerns; environmental impacts are considered in Section 10.7. There is a longstanding public perception that pyrolysis is on a par with incineration, risking the process being denied public license to operate if scaled up (Scottish Government, 2023a). This was corroborated by multiple interviewees across government and industry stakeholder groups.

Drying, grinding and crushing feedstocks can release hazardous air pollutants including acrolein, volatile organic compounds and particulate matter (PM) if not appropriately managed (Environment Agency, 2025b; Environment Agency, 2025d). These concerns can be feedstock specific, as one interviewee highlighted a risk of cancer associated with wood dust, and impacts of air quality around wood pellet mills. Concerns about air quality and associated health risks (Environment Agency, 2025d; Dalby, 2025) also extend to biochar application, as being exposed to airborne biochar particles during spreading increases risk of lung disease (Lapwing Energy, n.d.). However, there is an evidence gap relating to the impact of these airborne pollutants on human health (Environment Agency, 2025a), and impacts of large-scale application of biochar on human health are yet to be explored (IPCC, 2022). Impacts may also be able to be mitigated by appropriate handling and proper Personal Protective Equipment. Nonetheless, health risks were raised as common concerns by interviewees across industry and non-governmental organisation (NGO) stakeholder groups.

There are also potential operational hazards related to the flammability of biochar (Lapwing Energy, n.d.), with a risk of unplanned ignition and combustion of the feedstock (CapChar Ltd, et al., 2022) and spontaneous combustion of the product during storage (Environment Agency, 2025b; Environment Agency, 2025d). An industry stakeholder noted this risk can be a barrier to getting insurance for the facility.

10.5.3 Knowledge, education and skills

There is generally low awareness about biochar (Environment Agency, 2025b; Environment Agency, 2025d; IBI, 2023), and an evidence gap on the social impacts of scaling up biochar technologies among the scientific community (Environment Agency, 2025a). The lack of awareness of biochar and scepticism of its benefits were noted as issues by several interviewees. Information needs extend to biomass more broadly, including equipping UK publics with information to understand how biomass use may influence their everyday lives, and monitoring of the impact biomass has on achieving net zero against transparent performance indicators (DESNZ, 2023). This is particularly relevant for key users like farmers.

There is also a lack of knowledge regarding scaling up biochar in the agricultural sector in Scotland, with a lack of permanent skilled on-site operators (Bagaria, et al., 2025; IPCC, 2022; IBI, 2023). This issue was also raised by an industry stakeholder. These skill requirements reportedly inhibit the feasibility of decentralisation. Another industry representative noted that despite high-skill requirements, the actual number of employees required to run a pyrolysis plant is minimal, and the low direct job creation potential could discourage government investment in the technology. Education and training would be needed in various areas to aid successful scaling (IBI, 2023). Moreover, a hesitancy towards digital tracking tools, which would likely be needed to implement biochar at scale, has been identified among farmers (Bagaria, et al., 2025).

10.6 Technological considerations

10.6.1 Technology readiness levels and need for R&D

Concerns regarding technology readiness levels (TRL) and the need for further research predominantly relate to technologies used for biochar production, such as pyrolysis units. A major barrier to scaling up biochar implementation in Scotland in the short term is the relatively early stage of technological development of biochar production (IBI, 2023; Scottish

Government, 2024), with application in the UK so far limited to trials (Environment Agency, 2025b). Biochar technologies were in their infancy in 2013 (Department of Energy and Climate Change, 2013), and even though substantial technological development has occurred recently globally, scaled-up deployment remains limited (IPCC, 2022). Large scale readiness is anticipated within a decade, but this is uncertain (Scottish Government, 2023a), with limited evidence on applicability at scale in Scotland (ClimateXChange, 2022) and the IPCC (2022) noting low current feasibility. Advancements in technology production and use are needed for biochar growth, since technology and equipment availability and capacity currently inhibits feasibility (IBI, 2023), though this landscape could change rapidly.

Described as 'experimental' by the Scottish Government (2024) and by a Local Authority interviewee, biochar technologies are rated as having a TRL between 3 and 9, depending on the technology and source. Biochar technologies may however progress through TRLs rapidly and lower TRLs may no longer be appropriate ratings in 2026. Biochar is presented as a technology option for many sectors in the UK, but is often labelled a 'wildcard' solution due to technological uncertainties and therefore varying confidence in its inclusion in net zero technology strategies (Government Office for Science, 2025). The Scottish Government (2023a) suggested that biochar production has a TRL of 3-6, placing it within the 'proof of concept' and 'large [pilot plant] scale' phases. Other studies have suggested a TRL of 7 (Arup, 2022), or between 4 and 9 depending on methods used (Environment Agency, 2025b). Specific biochar production technologies may be rated higher – for example, pyrolysis plants generally are at the full-scale commercial stage (Environment Agency, 2025c). The Environment Agency (2025d) suggest that pyrolysis and gasification have TRLs of 6-9, slightly lower for the latter if specifically for biochar production as the typical byproduct is an ashy waste with traces of char. Several interviewees across government and industry emphasised that R&D and projects on biochar technologies are not yet translating into fully commercially viable projects in the UK, typically remaining at a small-scale, trial or pilot basis. One industry stakeholder specifically noted that this small-scale, workshop level production will not suffice, requiring a 'big player' in the pyrolysis industry to scale biochar production. Larger scale facilities may however involve greater environmental implications, a concern raised by an NGO stakeholder.

Further research is required throughout the biochar supply chain, to build a strong knowledge and skills base (Scottish Government, 2023a). This will enable application of the most effective solutions in a given local context (Circle Economy, 2022). The Scottish Government (2024) notes a research need to understand the permanence of storage and optimum use for biochar. Additional research would also be useful to verify some biochar benefits, such as the potential of the pyrolysis process to effectively remove Per- and polyfluoroalkyl substance contamination (IBI, 2024) – a benefit also suggested by two interviewees. Increasing R&D to build deep knowledge could include public funding for research, development and demonstration activities, pilot projects and infrastructure development (Circle Economy, 2022).

Improving TRLs and increasing knowledge will support increased investment in biochar technologies, by addressing investors' lack confidence in its early stage, small-scale status which inhibits uptake (Lapwing Energy, n.d.). Similarly, the farming community and industry as primary stakeholders lack sufficient data to make informed decisions regarding biochar implementation, such as good understanding of technologies, or carbon calculators that incorporate up-to-date scientific knowledge (Arup, 2022; ClimateXChange, 2023). A research stakeholder emphasised that practical knowledge is needed at-scale in real world conditions to enable uptake. Research to support businesses, rather than academic research, was noted by a government stakeholder as a particular gap.

10.6.2 Process issues

Biochar scaling and implementation is also inhibited by technological issues in the processes of production and application.

One such aspect of **production** is the selection of appropriate feedstocks. For example, not all feedstocks are compatible with every production technology (IBI, 2025). One industry stakeholder noted that most pyrolysis technology is designed for wood feedstocks, introducing complexity and yield implications if other feedstocks are used, including cheaper options. Adjusting the unit is a three-to-four-month process, but this barrier can technically be overcome. A government agency stakeholder indicated that this process takes longer for larger plants. A Local Authority interviewee also emphasised that homogeny of feedstock is critical.

Other production process related technological constraints also exist. These often overlap with legal requirements (see Section 10.8). The production processes are highly specific, requiring specific temperature ranges for optimal production depending on feedstock. These processes, especially small-scale pyrolysis, can have low energy efficiency, exacerbated at higher temperatures (Han, et al., 2025). Furthermore, several interviewees noted that units have not been operating long enough to provide sufficient information to accurately predict outputs.

Technological constraints also arise with the **use and application** of biochar products. This links to the economic constraints detailed in Section 6. Very low contaminant levels are required in biochar for use in agriculture and horticulture. For use in construction and agricultural fertilisers, characteristics such as stability, specific surface area and cation exchange are critical (PyroCore, et al., 2021). This specificity in application was highlighted by multiple industry stakeholders. Stakeholders in the research sector noted the need for UK and Scotland trials examining applications of biochar, including in combination with fertilizer, various farming activities, and for different crops.

There is also a lack of standardised approach to **MRV** once biochar has been applied to soils. Existing methods are either outdated - typically conducted without digitalisation across the entire supply chain (IBI, 2025) - or do not account for storage permanence and the varying decomposition rates of biochar depending on feedstock and temperature (Scottish Government, 2023a). Improved MRV procedures will require improvements in modelling biochar spread, which is complex (Scottish Government, 2023a). Lessons could be learned from international examples, for example an industry stakeholder reported that Denmark's farming sector uses an established digital MRV system for carbon capture, also supporting compliance requirements. This issue relates to uncertainty surrounding the assessment of biochar characteristics, such as its durability (IBI, 2025) and predictors for its effect on nitrous oxide emission rates from soil. Methods can also be costly and rely on a high degree of specialist knowledge, making them difficult to scale (ClimateXChange, 2024).

10.7 Environmental considerations

10.7.1 Carbon storage

Other carbon removal technologies depend on geological storage of captured CO_2. In contrast, deploying biochar for carbon removal (i.e., as a net carbon negative product) depends on permanent storage of the carbon in biochar in-situ in soil or alternative place of use (Scottish Government, 2023a; Arup, 2022).

As stated in Section 5.2, academic evidence strongly supports that biochar offers long-term carbon storage, at time scales of multiple centuries. Though field studies consistently also show biochar carbon durability in the short term, it should be noted that the stated 1000-year durability of biochar can never be usefully demonstrated in real time, especially when aiming for deployment on a 2045 timescale. Evidence of long-term stability therefore relies on the structural characteristics of biochar. Certified carbon removal using biochar is currently traded under accounting protocols published by Verra, Puro, or Isometric against 100- or 1000-year durability. However, biochar carbon accounting is still under development and depends on understanding of the potential for mobilisation of the stored carbon and its possible emission (Scottish Government, 2023a).

Several sources reviewed state that the permanence of carbon in biochar when applied to soils is an evidence-gap, or an area of uncertainty, requiring more research (Environment Agency, 2025a; ClimateXChange, 2022; Environment Agency, 2025c). This suggests that the scientific confidence in biochar carbon durability (in both soil and other applications such as construction) has not yet been successfully disseminated into public knowledge and understanding, including at a governmental and policy level (Scottish Government, 2023c; Biochar Europe, n.d.). This social aspect may present a barrier to deployment, despite a lack of environmental concern. Despite this, some specific applications of biochar could still raise environmental concerns regarding soil carbon. Particularly relevant to Scotland, one industry stakeholder noted the relatively high potential for biochar to release carbon from peat bogs.

Moreover, biochar is not entirely homogenous. Extrapolating permanence based on initial decomposition overestimates longer term decomposition in laboratory experiments. On the other hand, microbial communities in biochar-rich soils could become tuned to a change in substrate, resulting in enzymatic shifts that increase decomposability over time (Feng, et al., 2023). Permanence should also not be over-stated without proper biochar characterisation (Schmidt, et al., 2021).

The carbon storage of biochar also varies depending on the feedstock used, with waste-derived biochar exhibiting the lowest carbon removal potential (Scottish Government, 2023a). This could be problematic in approaching biochar as a carbon mitigation tool based on the current legislative landscape in Scotland as discussed in Section 10.8. Paper, cardboard, food waste, and sewage sludge feedstocks also do not typically result in net GHG removals compared to bioenergy crops and agricultural arisings, though do still contribute to carbon mitigation if pyrolysed (Environment Agency, 2025b). They are also considered by an industry interviewee to be high-quality feedstocks in terms of biochar quality. Interviewees noted the importance of knowing feedstock origin and ensuring that any biomass removed is being replaced to ensure net carbon negativity within a reasonable timescale.

Carbon storage potential is also altered by pyrolysis conditions, specifically temperature. With increasing temperature, the carbon content and aromaticity of biochar also increase (Environment Agency, 2025d), although the research bias towards lower pyrolysis temperatures results in less data availability for higher temperatures.

10.7.2 Emissions and impacts on climate change

Concerns have also been expressed regarding potential climate change impacts of biochar throughout its value chain, including feedstock, production, storage, transport, and application. It should be noted that biochar's effect on emissions in various life cycle stages is not fully understood and requires further research (Scottish Government, 2023c). These emissions pose health risks (discussed in Section 7.3) and environmental impacts. The life cycle emissions of biochar production are summarised in Section 5.2.4.

Biochar production technologies have associated emissions, since they require heat generation. Biochar production is noted to lead to increased non-GHG emissions, an example of burden shifting (Scottish Government, 2023a). For example, Volatile Organic Compound emissions are generated by wood chip burners, as well as nitrous oxides, sulphur oxides, and carbon monoxide (CO) (CapChar Ltd, et al., 2022). Heat can also be generated by combustion of pyrolysis co-products, which emits a small amount of CO_2, steam, nitrogen dioxide, CO, methane, and sulphur dioxide (Clarke, et al., 2021). In addition, emissions vary with the type of feedstock used (Scottish Executive, 2007). These effects are exacerbated if the feedstock materials have a high moisture content, due to greater energy demand for drying before pyrolysis (Environment Agency, 2025e). The impact of these emissions can be mitigated to an extent through appropriate abatement technologies.

Emissions are also released from stored biomass (Environment Agency, 2025d), for example through CO_2 loss via oxidation when the product is exposed to air (Lapwing Energy, n.d.). During storage, as well as in transport, handling, and application, biochar can also emit PM, including black carbon aerosol (Environment Agency, 2025d). During transportation, emissions from road transport – currently a significant emissions source in the bioeconomy – need to be considered (Scottish Government, 2024). These issues were all corroborated by several stakeholders.

For application, impacts tend to be context specific. For example, biochar application to cultivated soils can decrease surface albedo (how much sunlight is reflected), though this does depend on dosage, application method, land use, and soil moisture content (IPCC, 2022). High experimental doses of biochar can also stimulate microbial activity in the short term, as a small labile fraction of carbon becomes relevant. Emissions are minimised at 5-10 t/ha, then rebound due to stimulation of native soil organic matter decomposition (Han, et al., 2025).

10.7.3 Land-use change

Another environmental concern is the potential impact on land-use change and competition for land (Environment Agency, 2025b; IPCC, 2022; DESNZ, 2025), as strongly emphasised by an NGO stakeholder, who corroborated several of the following points. This is separate to land use concerns from a social perspective as discussed in section 10.5.1. The Scottish

Government (2023a) has identified this as a major challenge when virgin feedstock is used. This risks species loss and reduced biodiversity and has a greater land requirement than other carbon removal technologies like BECCS (Scottish Government, 2023a). However, this comparison does not account for the carbon value of heat generated by pyrolysis and electricity required by BECCS. Converting pasture to miscanthus, for example, has been linked to biodiversity loss, particularly for farmland bird species (Environment Agency, 2025b). Negative impacts have also been identified in the conversion of grassland and woodland to biomass crop (Environment Agency, 2025d). It was suggested that impacts on species is an area requiring further research.

If these land requirements cannot be met domestically, raw biomass may need to be imported, transferring potential negative externalities to other countries. This would be highly likely if biochar were to be scaled up. Growing dedicated crops for climate-relevant biochar production is likely to be unfeasible in the UK, as they require significant land and water resources which would have a large environmental footprint (Environment Agency, 2025e).

10.7.4 Impacts on soil and water, including contamination

Biochar has several potential negative impacts on soil and water health, mostly related to its application to soil. As with several other issues relating to biochar, its long-term soil health impact is poorly understood (Environment Agency, 2025b). There are potential – and uncertain – impacts on soil microbiomes (including viruses and protists that affect soil bacteria and fungi), microbial food web interactions, the abundance of microbial genes in the soil (which in turn affects nutrient transformation processes and microbes beneficial to plant growth and health), and interactions with plant roots (Environment Agency, 2025d). Properties of biochar upon application are also not yet fully characterised due to their variability (Arup, 2022). Similarly, large-scale impacts of biochar application on the full GHG-balance of soils have not been explored (IPCC, 2022).

Relating to feedstock growth and biochar production, demands for fertiliser and grid electricity increase, raising risks of acidification, eutrophication and ecotoxicity (Scottish Government, 2023a). Use of forestry residues as feedstock is feasible, but can risk soil health degradation over time, due to interference with natural nutrient cycling and soil carbon, as corroborated by an NGO interviewee who also raised the threat to soil invertebrates. Concerns have also been raised about the risk of deforestation (Environment Agency, 2025d).

The application of biochar to soil introduces the risk of contaminants (Arup, 2022; Bagaria, et al., 2025; Environment Agency, 2025d; ClimateXChange, 2022). This may include polyethylene terephthalate (SRUC, 2020), polycyclic aromatic hydrocarbons (IPCC, 2022), heavy metals if produced from paper and pulp mill sludge or wood (Environment Agency, 2025b; Environment Agency, 2025d), and plastics if produced from waste (Scottish Executive, 2007). However, multiple stakeholders did emphasise that the temperature of the pyrolysis system, combined with scrubbing abatement systems, can remove plastics and pollutants, and levels of pollutants in the material are always lower after pyrolysis than before.

Additional risks to soil and water health from biochar application include potential increases in plants' susceptibility to insects and pathogens (IPCC, 2022), and risk of nutrient losses and subsequent deposition through wind and water erosion (Lapwing Energy, n.d.).

All these threats are exacerbated by a risk of overapplication (Environment Agency, 2025d), especially near farms, AD plants, and distilleries (SRUC, 2020), a concern also raised by an NGO stakeholder. High biochar rates of >20 t/ha may reduce soil aggregate stability, negatively affecting soil structure, though evidence we found on this focuses on short-term rather than long-term effects (Han, et al., 2025).

10.8 Legal considerations

10.8.1 Relating to feedstock and waste

Legal definitions and classifications create constraints on the effective use of available of feedstocks. In particular, waste regulations can limit the ability to rely on exemptions and introduce additional compliance requirements.

Guidance on the waste status of relevant feedstocks remains unclear, increasing regulatory uncertainty for biochar producers and increase costs ((Lapwing Energy, n.d.; PyroCore, et al., 2021). For example, forest residues are not legally classified as waste according to the Scottish Environment Protection Agency (SEPA), and there is currently no specific exemption permitting the use of certain waste materials in biochar applications (Scottish Executive, 2007; SEPA, 2012). Additional clarification is also required for materials such as biosolids and less conventional waste streams, including distillery residues (SRUC, 2020). Legal frameworks that require biowaste and farm wastes to be collected instead of going to landfill or energy recovery could present a significant opportunity for biochar, if the guidance regarding status and classification could effectively be improved (SEPA, n.d.).

Biochar's classification as a waste material also limits its use and results in greater investment needs, permitting related costs and longer implementation times (Arup, 2022).

In Scotland, biochar manufacture is legally treated as a waste management activity. While the Scottish Environment Protection Agency's 2012 Position Statement allows small-scale production from certain woody forestry and agricultural wastes (codes 02 01 03 and 02 01 07) without a licence, this remains a temporary position pending formal exemption (SEPA, 2012). Facilities producing above 50 kilograms/hour fall outside this small-scale threshold and face full regulatory requirements, which constrains commercial investment and limits scale-up (Arup, 2022). One interviewee also noted that current regulations restrict producers from experimenting with biomass feedstocks beyond the waste categories currently permitted, including coffee grains and sewage sludge for example.

Similar ambiguity exists across the wider UK framework (Štrubelj & Singh Ghaleigh, 2025). Biochar is generally treated as waste because it is derived from discarded biomass, unless produced from purpose-grown or otherwise non-waste materials such as wood pellets or virgin timber offcuts. This creates uneven incentives: producers may avoid residual biomass streams that attract regulatory controls and instead rely on dedicated feedstocks, contrary to circular economy principles.

These regulatory bottlenecks were consistently reflected in our stakeholder interviews. Industry actors and local authorities identified waste classification, end-of-waste criteria and recycling definitions as key sources of confusion, directly affecting implementation timelines and investment decisions. End-of-waste criteria, particularly, was raised as a major barrier by majority of the stakeholders interviewed. Finally, more clarity or guidance is needed on pyrolysis use in waste processing (DESNZ, 2025).

Another legal barrier is the lack of guidelines regarding the agricultural and soil-related applications and impacts of biochar (Bagaria, et al., 2025). As highlighted in earlier sections, biochar's benefits to soil quality could be leveraged if regulations enabled biochar created from sewage sludge to be returned to the soil (Scottish Government, 2023a).

10.8.2 Standards, certification and regulation relating to product use

There are significant concerns about the standardisation of biochar quality and composition analysis across the UK and internationally (Schmidt, et al., 2021). This includes complexities around selling carbon credits as a source of income for biochar producers.

Biochar producers are expected to align their activities with reputable carbon credit certification standards and comply with those standards' requirements. Six international carbon certification standards allow biochar producers to issue carbon credits. Each standard sets different requirements for certification, eligible feedstocks, approved technologies, end use, tracking, leakage assessment, testing, and permanence criteria such as hydrogen to carbon ratios (IBI, 2025). Due to regulatory and commercial barriers, only 47% of global biochar producers certify the carbon removals (IBI, 2023).

Governance mechanisms are needed for unified industry standards and market development. Guidance could be on but not limited to: labelling standards, sustainability certification schemes and regulation of biochar production and use, such as limits on contaminant/pollutant concentration or data monitoring requirements, for Scottish biochar developers, which could help with reducing the risks of adverse outcomes and developers to understand application of standards tailored to Scottish context, with easier transition to adapt international carbon crediting requirements (IPCC, 2022; Environment Agency, 2025d). There are currently no UK-specific certification standards governing the use of biochar for carbon offsetting (Arup, 2022). An industry interviewee highlighted that, in the absence of unified certification or standards, lower quality biochar would enter the market alongside higher quality products. This could create trade-offs between quality and scale, creating disincentives for producers investing in higher standards.

As biochar capacity increases, stronger carbon permitting frameworks and waste regulations are likely to be introduced to prevent environmental releases and manage impacts (Scottish Government, 2023a). While these measures are important for environmental protection, they may also increase compliance costs and administrative requirements for producers seeking to expand. As biomass availability is already a potential barrier, and imported biomass already constitutes a significant share of biomass used in Scotland, scaling biochar operations could introduce additional legal and governance complexities. In particular, concerns have been raised that imported biomass may not be subject to equivalent environmental regulation or robust carbon accounting frameworks in the country of origin. In the context of limited governance and standardisation for biochar, these uncertainties have contributed to UK farmers' caution regarding the use of imported biomass in certified biochar production.

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