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Environmental and economic spatial analysis system for biochar production – Case studies in the East of England and the East Midlands

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ABSTRACT

Biochar is made from organic materials and plays an important role in greenhouse gas removal (GGR) and achieving net-zero target. However, economic feasibility has become a primary constraint hindering the large-scale production of biochar. Existing research lacks consideration of practical factors such as feedstock supply, pricing, and factory scale, and cannot accurately evaluate the greenhouse gas (GHG) reduction effect and corresponding costs at scale. We develop a space-based environmental economic model to quantify the impact of feedstock supply and plant strategies on costs and benefits. The results show that biochar production in the East of England and the East Midlands could achieve significant net GHG reduction and GGR benefits. Environmental benefits are not related to factory strategy but are positively correlated with feedstock supply strategy. Biochar production imposes additional financial burdens that are affected by feedstock supply and factory strategy. The main factors influencing biochar scalability are the quantity and pricing of feedstock and the price of byproducts. Spatial heterogeneity significantly influences the unit cost of GGR benefits. Compared to previous studies, spatial analysis provides a more detailed understanding of the costs associated with scaling up biochar production and the spatial distribution of production costs. This has crucial implications for biochar promotion and the implementation of effective policies.

1. Introduction

Biochar is a carbon-rich solid material produced from organic materials such as crop residues, food and forestry wastes, and animal manures [1]. Biochar has received extensive attention in the literature due to its important role in soil amendment [2], climate change mitigation [3] and other environmental management applications [4].

Biochar has been identified as one of the key greenhouse gas removal (GGR) methods for the UK to achieve its 2050 net-zero emissions target [5]. Its GGR effect primarily comes from its own stored stable carbon, achieved through soil application. However, despite its advantages, biochar has yet to be widely adopted on a large scale [6,7]. Existing studies highlight economic and environmental impacts as significant challenges to widespread biochar adoption [8] and further research is necessary to support policy promotion. The production of biochar involves the collection and transportation of feedstock, as well as energy consumption during the pyrolysis process. These processes result in additional greenhouse gas (GHG) emissions and financial burden. Therefore, it is necessary to quantitatively analyse the GHG impacts of biochar production and accurately assess the costs associated with achieving GGR benefits. Life cycle assessment (LCA) is a decision support tool used to understand the environmental impacts (e.g. climate change) associated with the life cycle of commercial products [9]. Techno-economic analysis (TEA) is a systematic method for evaluating the economic performance of a design process [10]. Recently, TEA and LCA have been applied to the analysis of biochar systems. However, previous analyses mainly relied on process simulators such as Aspen Plus, HYSYS, and SuperPro to conduct comprehensive simulations of specific biochar processes [10–14], without considering the impact of scale, feedstock type, and feedstock availability on biochar production. Therefore, an integrated TEA and LCA analysis of regional biochar production is necessary to understand the GGR potential and corresponding unit costs.

Many studies have emphasized that the main reason for its lack of large-scale deployment is economic feasibility [15–18]. The production cost of biochar primarily depends on the feedstock availability [19–21], the location of the production sites [22] and production scale [23]. Factors such as the supply and pricing of feedstock and factory size show

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significant differences across regions. The spatial implications of this variations have not yet been fully elucidated. Therefore, this study uses a geographic information system (GIS) to deepen the understanding of regional differences in feedstock availability, transportation distance, and plant size and provide essential insights for improved biochar production planning. Utilising spatial models can assess the achievable GGR potential of biochar within a research area, identify weaknesses in biochar scalability, and prioritise policy and investment support. Although spatial analysis has been applied to identify priority areas for biochar soil application [24–26] and to assess the availability of biomass feedstock [27–29], it has not been systematically used to evaluate and compare the economic and GGR benefits of biochar production.

Here, we estimate and describe the GHG emissions, GGR benefits, and costs of biochar production from wheat straw in the East of England and the East Midlands, which are the regions in the UK. To achieve this, we develop a space-based environmental and economic assessment model to compare the impacts of different feedstock supplies and factory strategies. The study also analyses key factors contributing to environmental and economic impacts and provides policy recommendations for these key factors. This study discusses the potential for biochar production and the impact of spatial heterogeneity on minimum break-even biochar prices. These findings could help facilitate the scaled-up biochar production.

2. Methods

In this study, we develop a spatial optimisation model to evaluate the environmental and economic impacts of a biochar production system. We specifically choose wheat straw as the feedstock for biochar production, which is a byproduct of one of the most widely cultivated crops in the UK [30]. The research areas are selected as the East of England and the East Midlands, which are the main wheat-growing areas in England [31]. The functional unit of analysis is a one-year operation for the research area. The system boundary is from cradle to gate (Fig. 1), including feedstock supply, transportation, and biochar production.

However, due to the uneven distribution of feedstock within the research area, a spatial model is needed to determine the number, scale, and location of processing sites to minimise the overall transportation mass-distance between a set of feedstock supply locations and a set of processing sites location. The model is spatially explicit in terms of feedstock availability, road conditions, and land use conditions. Optimisation parameters include production scale, transportation distance and processing site location. To access the impact of factory strategies, we determine the optimal locations for the number of processing sites from 1 to 10 respectively. Benefits with regard to net GHG emission reduction benefits, GGR benefits, as well as costs associated with feedstock, capital, transportation, and operation and maintenance (O&M) are analysed by the integrated LCA and TEA method.

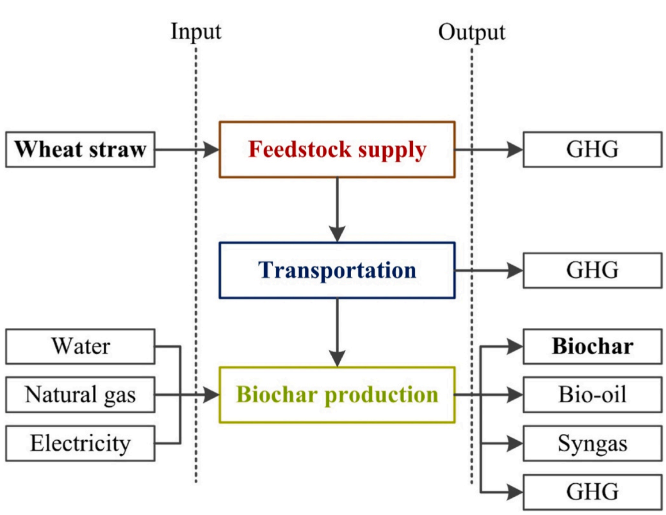

Fig. 1. System boundary of biochar production.

The inputs to the model are divided into three categories: GIS datasets, TEA specifications, and LCA datasets (Fig. 2). GIS datasets are used to capture aspects of the research area that vary spatially, such as the cost of collecting feedstock and the size of the processing site. The geographical approach can provide insight into factors that may particularly hinder or facilitate the adoption of biochar production in specific locations, such as feedstock availability, land use conditions, and the lack of specific transportation infrastructure.

Based on the spatial model and crop map dataset [32], we can obtain the distribution and planting area of wheat in these two regions (as shown in Fig. 3). Specific wheat straw yields can be obtained by planting area of wheat and straw yields (which is 4.0 tonnes per hectare [33]), with the overall wheat yields being 1.45 million tonnes and 0.947 million tonnes in the East of England and the East Midlands respectively. However, significant amounts of straw cannot be commercially utilised due to the factors like soil health maintenance and on-farm use [34]. Therefore, we compare two feedstock supply strategies of wheat straw based on the utilisation status of wheat straw on farms and the potential supply described in Townsend's research [35]. These situations are as follows: Situation 1 represents the baseline situation, where we assume the utilisation of the proportion of all currently available sold straw and the existing market prices (£50/tonne [36]) as feedstock for biochar production. Situation 2 represents the maximisation of feedstock supply. Based on Townsend's research [35], with the sold price of wheat straw of £100/tonne, 71.5% of respondents are likely to sell the chopped and incorporated straw. This situation assumes that given a wheat straw price of £100 per tonne, the straw supply proportion comprises the current straw supply proportion combined with 71.5% of the chopped and integrated straw proportion. The four scenarios of two regions and two supply situations are shown in Table 1. The study assumes that all available feedstock in each scenario is used to produce biochar. Based on the feedstock supply situation for each scenario, the best number of processing sites can be determined separately by the cost and environmental results.

2.1. Spatial analysis model

QGIS 3.34 software is adopted to process the GIS work, which has been widely used in spatial analysis [37,38]. All calculations described in this work are based on square grids, assuming that the entire area enclosed by the grid is characterised by a single cell value. The grid size of the feedstock layer is set to 1 km^2, and the grid size of the processing site location layer is set to 3 km^2. Cell-to-cell analysis is performed using the PyQGIS toolbox [39]. See Supplementary Information for detailed GIS processing in the analysis. Table 2 provides a list of the GIS datasets used in the analysis and their purpose (including information on their spatial aggregation levels). Alternative datasets can be used in place of the dataset used in this analysis, as the model is independent of the source of the geospatial data. Particle swarm optimisation is adopted to find the best location of the processing location with the shortest overall transportation mass-distance [40].

2.2. Life cycle assessment

Based on the spatial model results, we can obtain the location of the processing sites with the minimised total transportation mass-distance and the corresponding feedstock consumption under specific number of processing locations. It is essential to assess the optimal number of processing sites to calculate the GHG sequestration potential and minimise the unit cost of GGR benefits. Therefore, LCA is used for life cycle GHG emissions accounting.

In terms of life cycle inventory collection, the quantity and transportation mass-distance of wheat straw can be calculated by the spatial

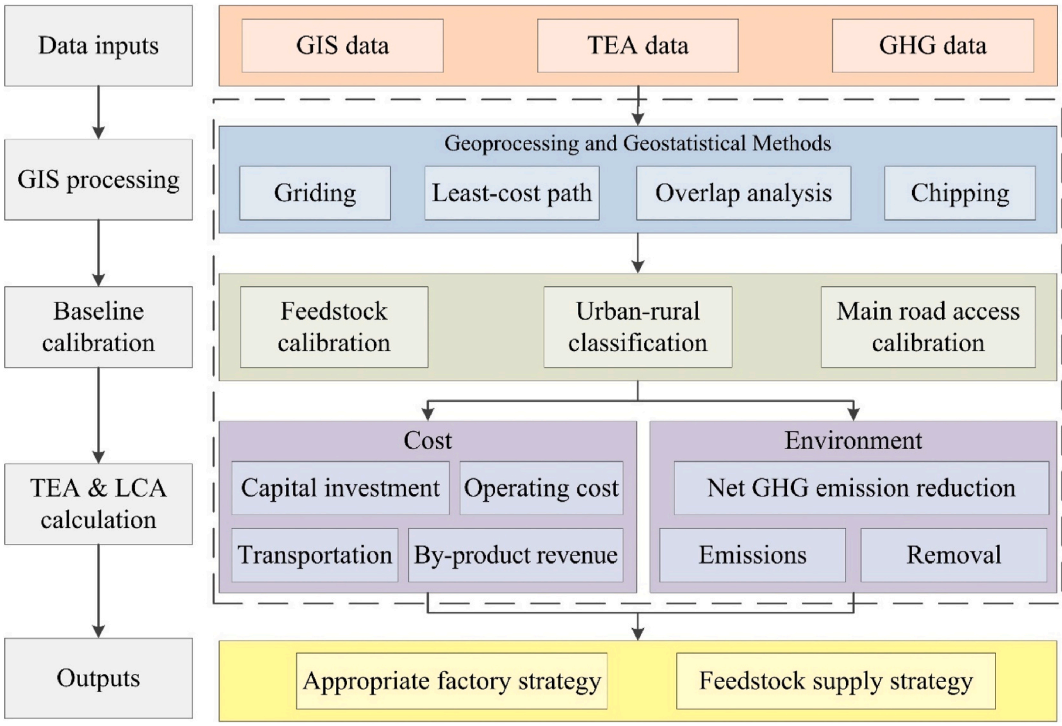

Fig. 2. Simplified optimisation model schematic describing the input data, processes, and outputs.

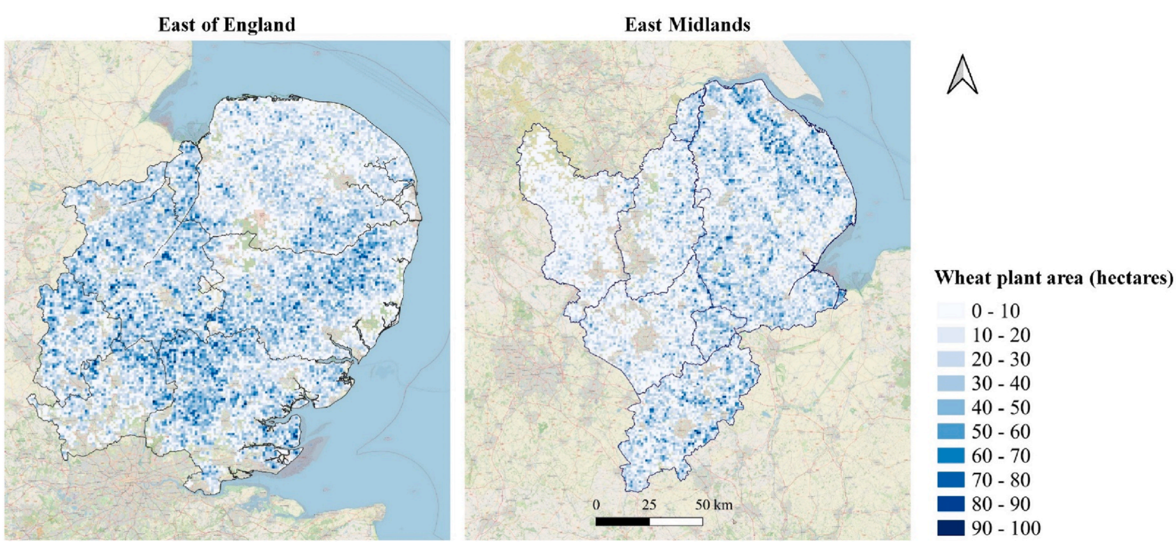

Fig. 3. Distribution of wheat plant area in the two research areas.

Table 1
Four scenarios of the biochar production.

Scenarios	Details
EE1	Research area is East of England, assuming that 28% of the total wheat straw is used for biochar production; the straw price is £50/tonne.
EE2	Research area is East of England, assuming that 74% of the total wheat straw is used for biochar production; the straw price is £100/tonne.
EM1	Research area is East Midlands, assuming that 34% of the total wheat straw is used for biochar production; the straw price is £50/tonne.
EM2	Research area is East Midlands, assuming that 69% of the total wheat straw is used for biochar production; the straw price is £100/tonne.

mode. The business quotation of Beston Company's equipment with a feedstock consumption of 5 tonne/hour is applied to estimate energy consumption and equipment purchase costs [45]. The raw materials consumed in the biochar production process include electricity, natural gas, and water, which are converted according to the scale of the processing site and the scale factor [46]. The maximum operating temperature of the application equipment (400 °C) is assumed as the pyrolysis temperature for the system. Based on Sedmihradská's experimental research [47], this pyrolysis process produces a biochar yield of 32.9%, bio-oil yield of 49.9%, and syngas yield of 15.6%. The calorific value of bio-oil and syngas is calculated by the thermochemical characteristics [47]. Bio-oil is considered as the substitution to fossil fuels, and syngas is assumed to produce heat.

The 100-year global warming potential (GWP100) values and the

Table 2
List of the GIS datasets.

	Dataset	Use	Resolution	Source
1	Crop Map of England (CROME) 2019	Base layer of the analysis. Used to represent crop types spatially. This is used as a proxy for demand of cooking. This case just considers three types of crops, which are barley, wheat, and oats. The crop dataset is converted to a geodata frame, where each grid cell becomes a row.	Original dataset available with the hexagonal cell which covers an area of 4156m^2. For this application the datasets have been resampled to the square grid of 1 km^2.	[32]
2	OS OpenMap - Local	Land use situation of Great Britain, used to remove grids with many areas (over 30%) that are not suitable for building factories. In this case, we just consider the building, functional site, and surface water area.	Vector layer	[41]
3	OS Open Roads	High-level view of the road network, used to identify the grid with path to the feedstock and calculate the transportation mass-distance. In this case, we just consider the road type of A Road, B Road, and Minor Road to simplify the simulation.	Vector layer	[42]
4	Rural Urban Classification	Rural-Urban classification for local enterprise partnership (LEP) areas based on census output areas, used to excludes grids within urban areas when calculating feedstock sources.	Original dataset available with the irregular area cell. For this application, the datasets have been resampled to the square grid of 1 km^2.	[43]
5	Google satellite map	Satellite view of England, used to validate the grid data.	Vector layer	[44]

Ecoinvent Database from SimaPro (2022) are adopted to evaluate the life cycle GHG emission. The GWP100 value is provided by the IPCC to evaluate the greenhouse effect of various gases over a 100-year time horizon [48]. This study considers the GHG emissions, net GHG emission reduction, and GGR benefits from biochar production. The GHG emissions are calculated by the life cycle inventory (LCI) and GWP100 values. The average emissions factors for GB electricity in 2023 as given in the Greenhouse Gas Reporting are used to calculate the GHG emissions of electricity consumption in the system [49]. GHG emissions from wheat straw pyrolysis are considered biogenic carbon emissions due to their origins in biological [50]. These biogenic carbon emissions are excluded from GHG accounting [51] and are believed to be absorbed from the atmosphere by the next natural cycle [52]. Natural gas is assumed to be pure methane and to undergo complete combustion. Given that the molecular weights of methane and CO_2 are 16 and 44 respectively, the GHG emissions resulting from natural gas combustion are calculated as 11/4 of the mass of natural gas.

The stable carbon content in biochar after 100 years is used to determine its GGR benefit. The carbon content of biochar is assumed to be 63% [47]. The molar ratio of hydrogen to carbon (H:C) at 400 °C is 0.6 [47]. It is expected that at least 60% of the biochar carbon will remain stable after 100 years with a 95% confidence level [53]. Apart from the GHG emissions and GGR benefits, the calculation of the net reduction GHG emissions also conclude the displacement of GHG emissions by the substitution of fossil fuel for bio-oil and the benefits from syngas, referring to Brassard's method [54].

2.3. Techno-economic analysis

A detailed spreadsheet-based model is used to evaluate the economic performance of the biochar production system. Specifically, we estimate the impact of the number and location for the processing sites on capital cost (CAPEX), operational cost (OPEX) and transportation cost. Overall, the methodology described in Perry's chemical engineers' handbook [55] served as the technical economic analysis guideline for this research. The equipment purchase cost is calculated by the cost of the equipment from Beston company, whose annual feedstock consumption is 36 thousand tonnes [45]. The scale factor is assumed as 0.6 for the scaling calculation [56]. Then the Lang method is used to calculate total investment cost (TIC). The OPEX is calculated based on the CAPEX and the product sales. Finally, the annual CAPEX is estimated based on the 8-year plant lifespan and the discount rate of 5%. The main assumptions adopted to perform the TEA are compiled in Table 3. The raw material consumption and the corresponding cost is shown in Table 4. The transportation cost for delivery is assumed as £0.22/tonne.km based on Phase 1 of the Biochar demonstrator project [5]. The revenue of bio-oil is assumed as £10/GJ [57]. The cost benefits of syngas and extra heat from pyrolysis system is disregarded.

2.4. Sensitivity analysis

The model enables to assessment of the impact of specific categories on facility strategy and feedstock supply strategy, allowing the assessment of net benefits from different perspectives. In detail, the sensitivity analysis is adopted to understand the importance of mass yield of pyrolysis, straw price, by-product price, infrastructure costs, unit transportation cost, and energy consumption efficiency on the unit cost of GGR benefits. We carry out sensitivity analysis based on the principle of only changing one parameter by 5% at a time [58]. The representative case for each scenario is the case has the number of processing sites with the lowest unit cost of GGR benefits. The variation in situations, ranging from 1 to 10 processing sites, is considered for sensitivity analysis to assess the error range in the results.

Table 3
Parameters and assumptions considered in the cost assessment.

Parameter	Value/Comment
Base year	2023 (Jul) CEPCI = 821.1 GBP/USD = 1.28
Currency	GBP
Plant lifespan (year)	20
UK location factor	1.02
Capital cost	
Equipment purchase cost (C_e)	£195,313 [45]
ISBL	ISBL = 3.2*C_e
OSBL	OSBL = 0.4*ISBL
Fixed capital cost (CAPEX)	CAPEX = 5.0*C_e
Fixed operating cost	
Labour (OL)	4 operators for the input capacity of 5 tonne/hr Average annual pay for operator = £25,350
Supervision	25% OL
Direct Ovhd.	45% OL&Superv
Maintenance	3% of CAPEX
General plant overhead	65% OL&Maint
Land	2% of (ISBL + OSBL)
Insurance	1% of (ISBL + OSBL)

Table 4
Operating material consumption and the cost for 5 tonne/hr equipment [45].

	Unit	Unit/GBP	Amount
Water	m^3	0.84	3
Electricity	kWh	0.31	2922
Natural gas	m^3	0.46	270

3. Results

3.1. Life cycle GHG emissions assessment

In our analysis, life cycle GHG emissions associated with biochar production can be divided into three components: emissions present within the system boundary, replacement of GHG emissions associated with biooil and syngas alternative fuels, and the GGR benefits of the biochar (Fig. 4). We focus on four scenarios for GHG outcomes and compare the impact of transportation strategies. Biochar production systems provide significant net reductions in GHG emissions in all cases. If biochar is produced from all locally available wheat straw in the East of England and the East Midlands, a net reduction of 300 thousand tonnes of CO_2e could be achieved annually. By optimising supply by increasing straw prices, the net emission reduction benefits in these two regions can be increased to 560 and 930 thousand tonnes of CO_2e, respectively.

Emissions from the system are classified into three stages: feedstock supply, transportation and biochar production. In different scenarios, emissions are positively correlated with the amount of feedstock consumption. Sorted by feedstock consumption from small to large, the emissions from the biochar production for scenarios EM1, EE1, EM2, and EE2 are approximately 17, 21, 32, and 52 thousand tonnes CO_2e, respectively. In terms of the scenario itself, as the number of processing sites increases, the total emissions initially decrease before stabilising. The underlying reason is that an increase in the number of processing sites initially leads to a notably reduction in GHG emissions due to an associated reduction in the transportation mass-distances, followed by a relatively modest change. As the number of processing sites increases, the reduction in the size of individual processing sites leads to a decrease in efficiency and an increase in production emissions, offsetting the reduction in transportation emissions.

The reduction in GHG emissions from the biochar production system greatly exceeds the GHG emissions generated during the process. The net reduction in GHG emissions includes the GGR benefits of biochar and the benefits of biooil and syngas displacing fossil fuels. This study focuses on the GGR benefits of biochar. It is evident that the GGR benefit of biochar is primarily positively related to the availability of feedstock. This finding is consistent with previous studies [54,59]. The achievable GGR benefits from biochar are 185, 490, 146 and 298 thousand tonnes CO_2e in the EE1, EE2, EM1 and EM2 scenarios, respectively, accounting for approximately 53% of the total emissions avoided in each scenario. The GHG emission reduction potential of fossil fuel substitution with bio-oil and syngas is similar to the GGR benefit of biochar, also constituting around 53% of total emissions avoided in each scenario.

3.2. Techno-economic analysis

The TEA results for biochar production (Fig. 5) show that the economic expenditure of the system exceeds the revenue from by-products without considering the economic value of biochar. The TEA results for the small feedstock supply scenarios (EE1, EM1) are 3 million GBP/year, while the TEA results for the large feedstock supply scenarios (EE2, EM2) are 57 and 36 million GBP/year respectively. From the perspective of production costs, feedstock supply accounts for the highest proportion, exceeding 70%, followed by transportation costs and OPEX, each accounting for approximately 10%. Energy consumption in the production process and annual CAPEX represent the smallest proportions, both less than 5%. In terms of revenue, bio-oil improves the economic viability of biochar production systems as an effective fuel alternative [60]. For the EE1 and EM1 scenarios, the revenue achieved by bio-oil is approximately 1.3 times the feedstock supply cost. For the EE2 and EM2 scenarios, bio-oil revenue is about 64% of the wheat straw cost.

Variations in the number of processing sites can result in nearly a

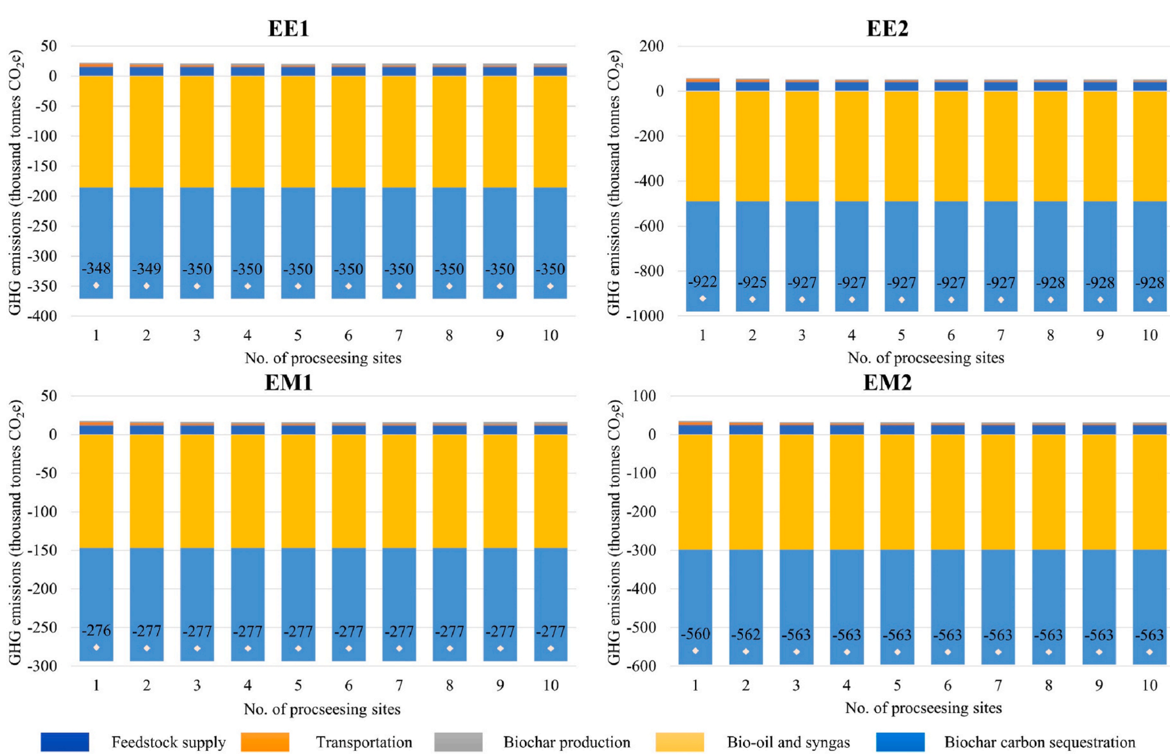

Fig. 4. Life cycle GHG emissions for biochar production.

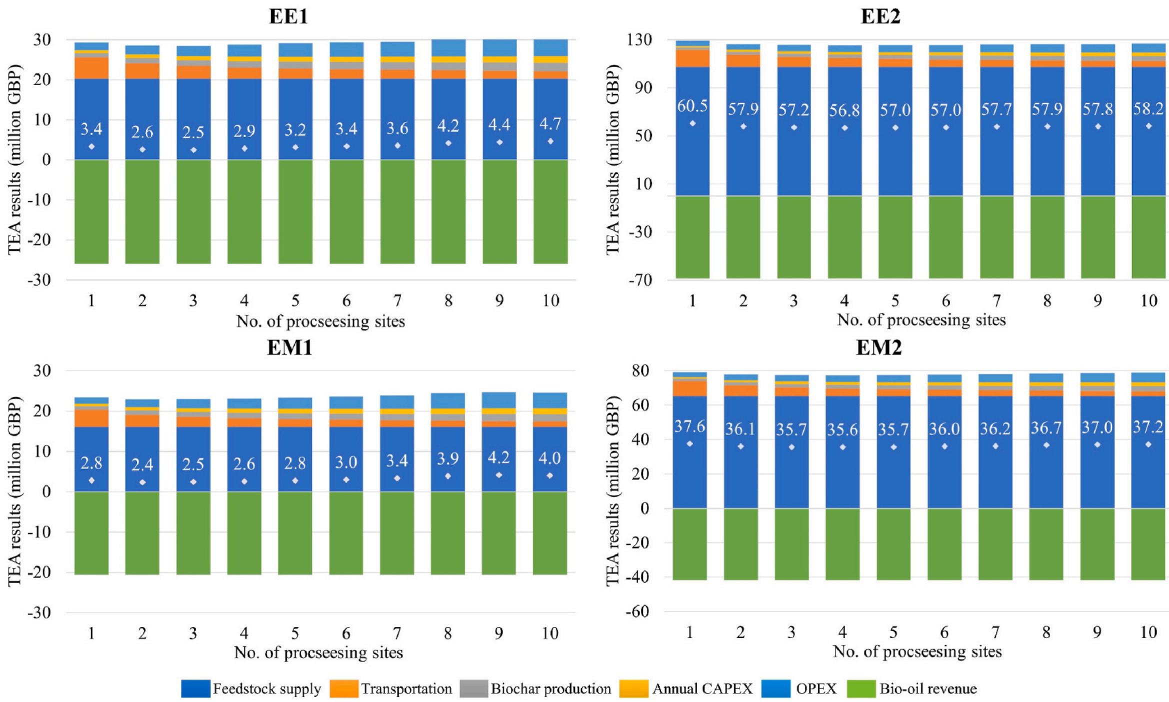

Fig. 5. Techno-economic cost of biochar production.

twofold difference in costs. Specifically, in all scenarios, the TEA results show an initial decrease followed by an increase as the number of processing sites increases. When the feedstock supply is constant, the total transportation costs decrease rapidly initially with an increase in the number of processing sites and then exhibit a slowing decreasing trend. Meanwhile, costs associated with OPEX, annual CAPEX, and energy consumption all increase. For scenarios EE1, EE2, EM1, and EM2, the optimal number of processing sites with the lowest costs are 3, 4, 1, and

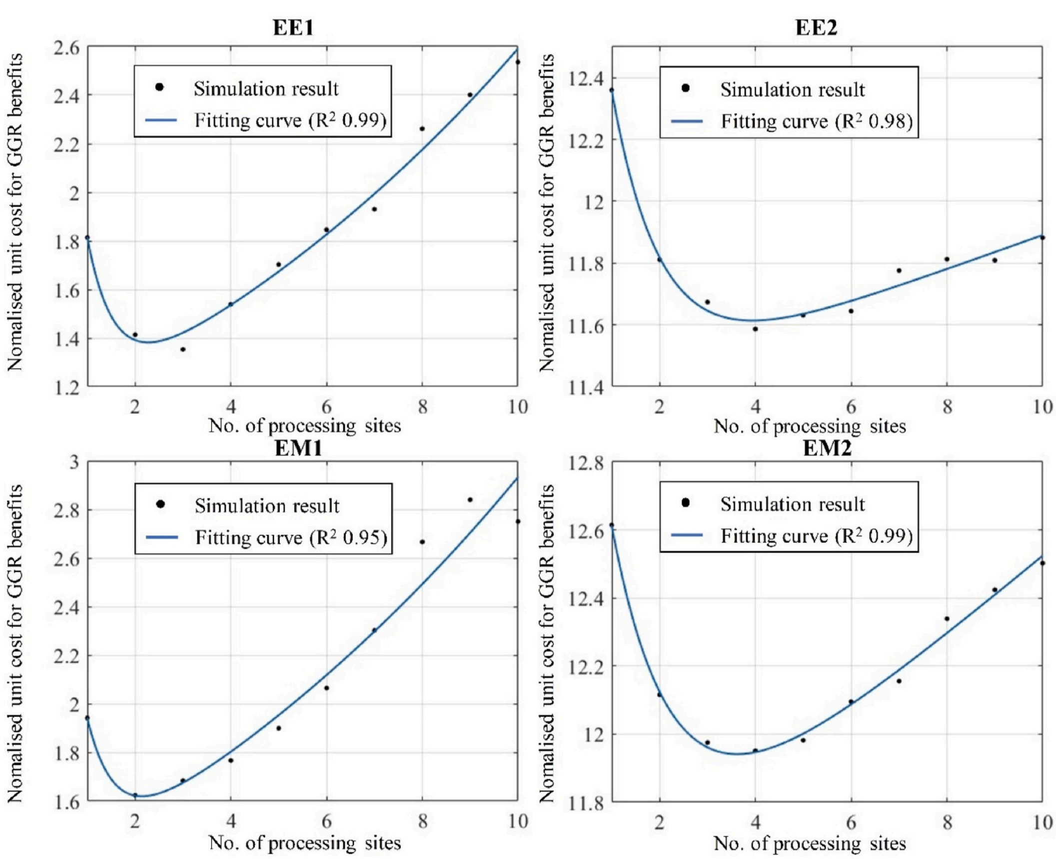

Fig. 6. Normalised unit cost for GGR benefits.

4, respectively. The corresponding TEA results are 2.5, 56.8, 2.4, and 35.6 million GBP.

3.3. Economic performance for GGR

This section focusses solely on the GGR benefits achieved by biochar. Fig. 6 summarises the unit cost of achieving GGR through wheat straw biochar production in four scenarios. The costs have been normalised based on a price of £10/tonne CO_2e. The study indicates that scenarios with lower feedstock supply cost tend to have lower unit costs for GGR benefits. Within the same research area, the unit cost of GGR benefits for the maximised feedstock supply scenarios is approximately six times that of the basic feedstock supply scenario. The relationship between unit cost and the number of processing sites is investigated when the amount of feedstock (biochar production amount) is constant. The results demonstrate that unit costs initially increase and then decrease with an increase in the number of processing sites, with a trend line. For scenarios EE1, EE2, EM1, and EM2, the lowest normalised unit cost of GGR occurs when the number of processing sites is 3, 4, 2, and 4, respectively, resulting in unit costs of 1.4, 11.6, 1.6, and 12, respectively. This outcome suggests that, with a fixed amount of feedstock supply, selecting an appropriate factory strategy and feedstock supply strategy is crucial for the large-scale application of biochar.

Fig. 7 shows the comparison results of the spatial changes in production costs at each processing point under the minimum unit cost condition for the four scenarios. When all currently available sold straw is used for biochar production, the number of processing sites is relatively low, with EE1 and EM1 having 3 and 2 sites, respectively. Upon the maximisation of feedstock supply, the number of processing sites in the study area increases to 4, which are distributed more widely to mitigate the cost increase associated with transportation. Due to the uneven distribution of feedstock spatially, the locations of processing sites often coincide with areas of high feedstock supply, resulting in varying unit costs with the changing positions of processing sites.

In the East of England, where the feedstock is concentrated in the south, processing sites in the south generally incur lower production costs compared to those in the north. In EE1, the unit cost for processing site 3 in the south is 1.31, while the costs for processing sites 1 and 2 in the north are 1.36 and 1.38, separately. In EE2, the unit costs for processing site 1 in the north is 11.8, while the unit costs for other processing sites 2, 3 and 4 are 11.6, 11.5 and 11.5, respectively. In the East Midlands, where feedstock is concentrated in the northeast and east, and the supply is low in the south and northwest. In EM1, the two processing sites are both to the east. The unit cost for processing site 1 in the southeast is 1.47, and for processing site 2 in the northeast is 1.81. In EM2, the lowest unit costs are for processing site 1 in the southeast corner and processing site 3 in the east, with costs of 11.7. The cost for processing site 4 in the south is 12.0. Due to the lowest feedstock supply density, processing site 3 in the northwest handles the least feedstock but incurs the highest unit cost at 12.6.

A comprehensive analysis of the optimal processing site scenarios of these four scenarios is conducted to understand how much we should pay for the increased GGR benefits from biochar (Fig. 8). The results indicate that in both study areas, the maximisation of feedstock supply

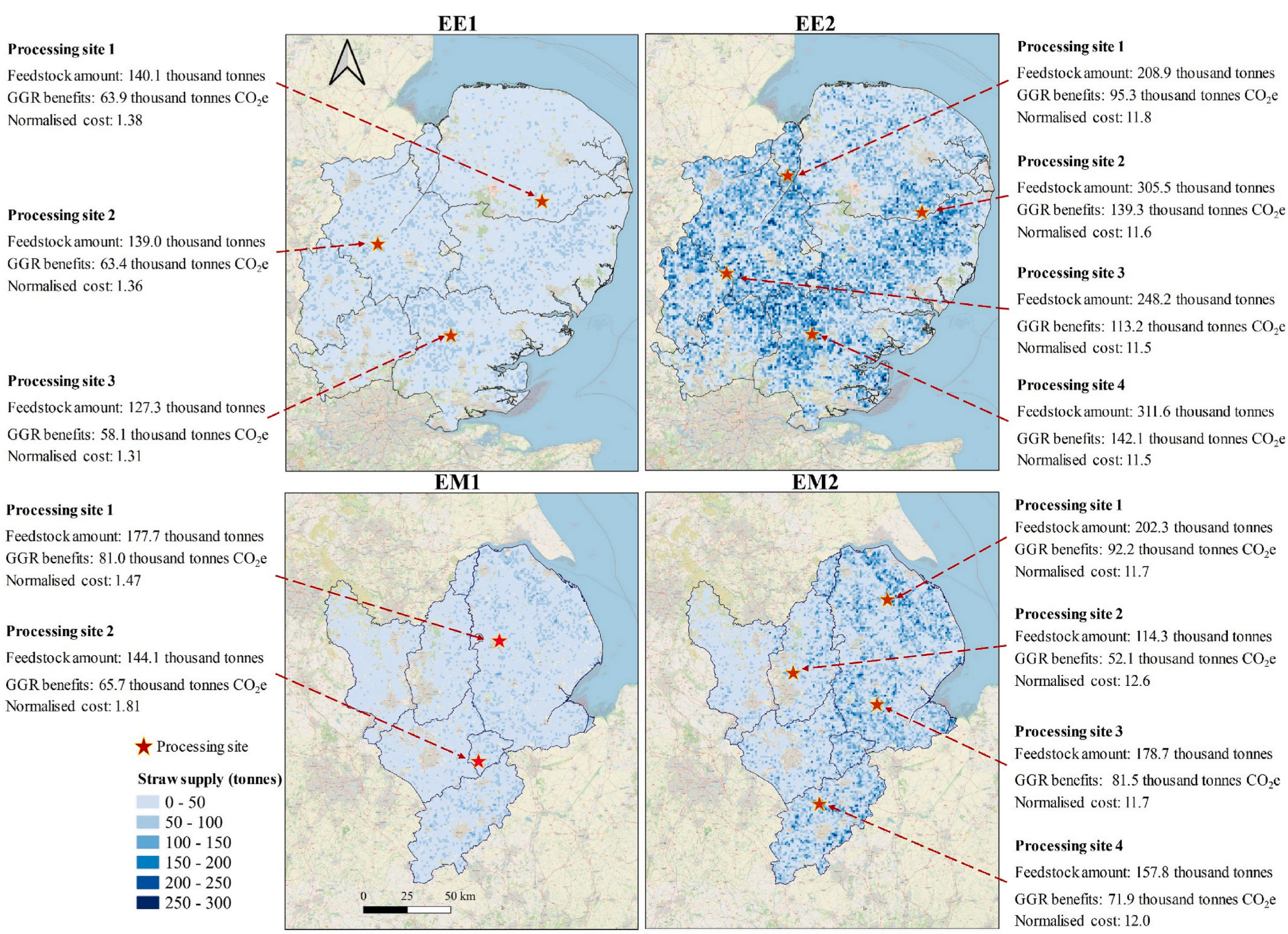

Fig. 7. Details of the processing sites for the representative situation of each scenario.

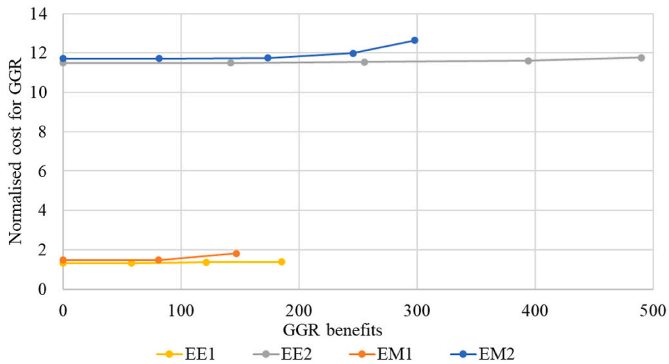

Fig. 8. Integrated analysis of GGR benefits and normalised unit cost for biochar production.

will lead to greater GGR benefits and higher unit costs corresponding to GGR benefits compared to the scenario involving all currently available sold straws. Additionally, the marginal cost increases with the amount of GGR benefits, and it is noteworthy that the varying trends among scenarios are significantly influenced by differences in feedstock supply density.

In the East of England, where feedstock distribution is relatively even, the increase in unit costs is relatively gradual with the rise in GGR benefits. In EE1, achieving 185 thousand tonnes of GGR benefits sees the unit cost increase from 1.3 to 1.4. In EE2, the unit cost corresponding to achieving the GGR benefit of 490 thousand tonnes CO_2e increases from 11.5 to 11.8. In the East Midlands, where feedstock distribution is concentrated mainly in the east and southeast, the increase in marginal costs becomes more pronounced with the increase in GGR benefits than that in the East of England, particularly evident when the feedstock supply is abundant. In EM1, realising 81 thousand tonnes CO_2e of GGR benefits can be achieved at a unit cost of 1.5, while achieving extra 66 thousand tonnes CO_2e of GGR benefits requires a unit cost of 1.8. In EM2, obtaining 246 thousand tonnes CO_2e of GGR benefits can be achieved at a unit cost of around 12, while 52 thousand tonnes CO_2e more of GGR benefits could require a unit cost of 12.6.

4. Discussion

4.1. Life cycle interpretation

The LCA and TEA results indicate the impacts of each stage in biochar production. Most of the system's emissions and production costs come from feedstock supply, constituting approximately 70%. Biochar production demonstrates a significant net reduction in GHG emissions, far surpassing the emissions generated during the production process. The bio-oil contributes a notable revenue, more than 50% of the total cost. If all current on-sale straw can be utilised for biochar production, GGR benefits from biochar in the East of England and the East Midlands could account for 4% and 3% respectively of the annual removal targets of the Net Zero Strategy by 2030 [61]. If we maximise the straw supply by increasing the straw price, the biochar production in these two regions can meet 10% and 6% of the GGR requirement of the UK net-zero target by 2030.

A comprehensive evaluation of the unit cost of the GGR benefits brought about by biochar reveals that, compared to the scenario where all currently available sold straw is used for biochar production, maximising feedstock supply at nearly double the price results in a doubling of achievable GGR benefits and a tenfold of unit costs. The finding suggests that increasing the quantity of feedstock and scaling up biochar production can significantly enhance the environmental benefits of biochar. However, it is noteworthy that the cost of feedstock emerges as a primary financial burden in scaling up biochar production. Besides, considering straw as a feedstock supply necessitates considerations of soil sustainability [62] and farmer willingness [63]. The current uncertainty regarding the impact of straw removal on soil is a primary concern for farmers [34], leading them to be hesitant to supply straw even with an increase in straw prices. Therefore, policymakers should prioritise sustainability and promote straw as a feedstock supply with an understanding of farmer needs to ensure that relevant policies are aligned with sustainable practices.

The study employs a spatial model to analyse the impact of factory strategy and feedstock supply strategy on the benefits of biochar production. Earlier regionalised LCA studies indicated that spatial analyses provide precise insights into the impact of feedstock supply and regional characteristics on the environmental and economic benefits of biomass utilisation [64,65]. In regional comparisons, the East of England region, with higher feedstock supply density and quantity than the East Midlands region, has more significant net reduction of GHG emissions and GGR benefits, with lower unit costs for GGR benefits. Within each region, variations in factory strategy have a negligible impact on the system's net reduction of GHG emissions. However, variations in factory strategy significantly influence the system costs and the unit costs of GGR benefits, which decrease initially before increasing with an increase in the number of processing sites. Additionally, there exist substantial differences in the quantity of GGR benefits and corresponding unit costs among processing sites.

4.2. Sensitivity analysis

The cost associated with the carbon sequestration benefits is most sensitive to the bio-oil price and straw price (see Fig. 9). Transportation costs and biomass yield have some impact on the carbon sequestration cost. The production efficiency and CAPEX does not significantly affect it. Under a baseline feedstock supply situation, a 5% change in both bio-oil and straw prices can result in a minimum 40% and 30% variation in the unit cost of GGR benefits, respectively. In contrast, under a maximisation feedstock supply situation, corresponding variations within the same percentage range (±5%) for bio-oil and straw prices lead to approximately 10% and 6% changes in the unit cost of GGR benefits, respectively. The sensitivity of these changes varies with the number of processing sites. Some studies have similar results, which indicate that feedstock prices significantly impact production costs, and the revenue from pyrolysis by-products significantly influences the revenue of processing sites [18,57,66]. Calling for farmers to contribute more straws for biochar production and reducing the straw price could enhance the feasibility of large-scale biochar production for achieving GGR.

Increasing the biochar yield has a positive impact on the overall GGR benefits of the system. Research indicates that biochar yield is affected by factors such as production conditions (temperature and pressure), feedstock types, and production scale [67,68]. Hence, it is necessary to find the optimal production conditions to maximise the biochar yield on the premise of stability. Additionally, reducing transportation costs can decrease the cost of GGR benefits, with a more pronounced effect when the available feedstock quantity is substantial. Therefore, selecting appropriate factory and feedstock supply strategies to reduce transportation costs can enhance the scalability and economic feasibility of large-scale biochar production [69].

4.3. Implications and limitations

The results of the study estimate the biochar production potential in two UK regions with particular feedstocks, as well as the corresponding minimum break-even biochar price, as shown in Table 5. If all currently available wheat straw in the market is used for biochar production, a substantial annual biochar yield can be achieved. In the East of England and the East Midlands, biochar production could reach 130 and 110 thousand tonnes, respectively, with corresponding minimum break-even costs of £18.8/tonne and £22.5/tonne. Increasing the feedstock price to £100/tonne could double the amount of straw supply. In this scenario,

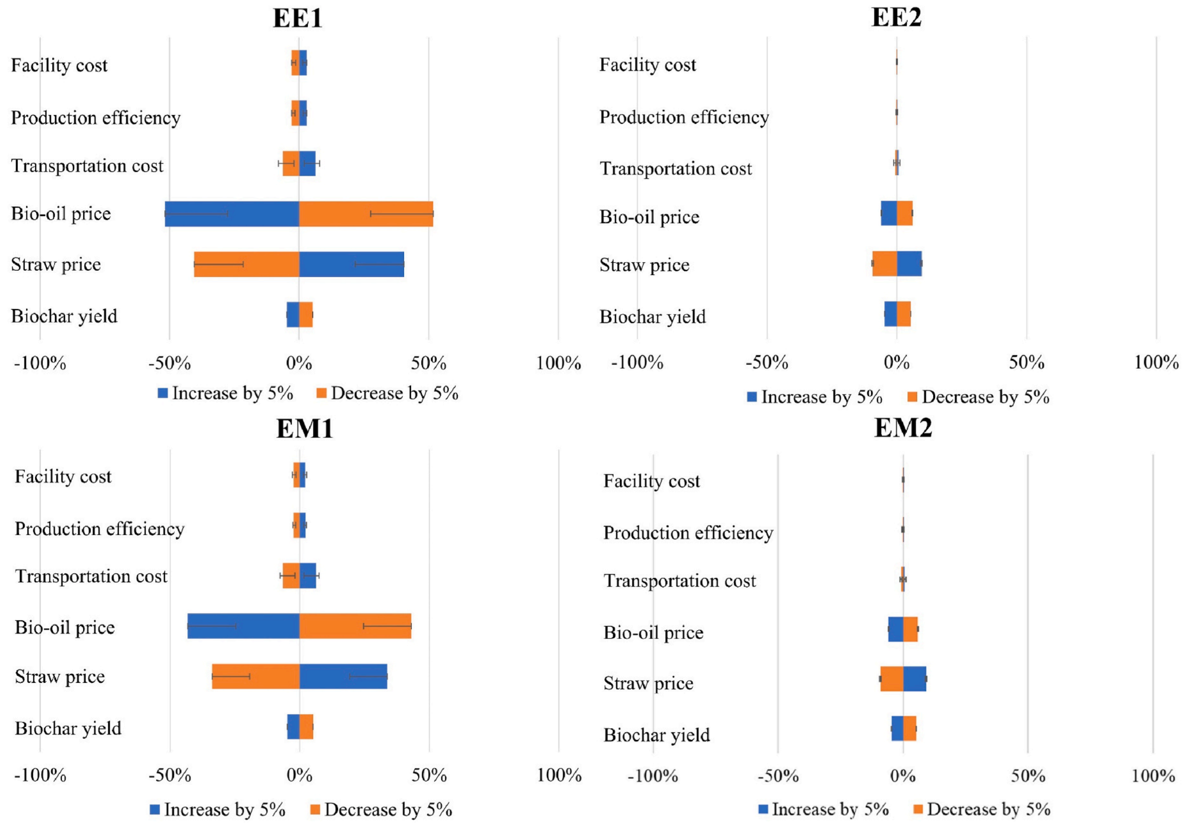

Fig. 9. Sensitivity results.

Table 5
Biochar quantity potential and corresponding minimum break-even biochar price.

	Biochar (tonne)	Biochar cost (GBP/tonne)
EE1	1.3E+05	18.8
EE2	3.5E+05	160.6
EM1	1.1E+05	22.5
EM2	2.1E+05	165.6

the two regions could produce 350 and 210 thousand tonnes of biochar, with the corresponding minimum break-even costs rising to £160.6/tonne and £165.6/tonne.

Due to the denser distribution of feedstock in East of England compared to East Midlands, a higher biochar yield can be achieved at a lower unit cost. Moreover, in the event of rising feedstock prices, farmers in East of England are more inclined to sell chopped and incorporated straw compared to their East Midlands counterparts, resulting in a higher potential for biochar production. Additionally, within two regions of UK, substantial variations in feedstock distribution density lead to significant differences in production scale and unit production costs among processing sites. Results indicate that geographical variability in feedstock distribution, coupled with variations in feedstock prices and selling preferences across regions, have important implications in determining factory strategies and feedstock supply strategies for biochar production.

The production of biochar is highly contingent on the feedstock supply, although specific issues regarding the feedstock availability are not extensively addressed in this work. Currently, a significant portion of wheat straw is chopped and incorporated [35] and meaning there is the competition for use of straw [70]. The framework here assumes that all available straws are utilised for biochar production, providing an upper limit for environmental benefits. Despite various constraints, the results obtained in this study remain valuable for several reasons. Firstly, there is a lack of large-scale biochar production in the UK [6,7]. The research explores the potential for scaling up biochar production and the associated costs to achieve these environmental benefits. This offers insights into the expectations and policy support required for achieving GGR goals through biochar. Secondly, the study considers the impact of spatial diversity, facilitating the identification of advantageous regions and understanding the policy needs of different regions. The results indicate that, based on the current prices of on-sold feedstock, biochar production system requires additional revenue to meet the break-even. Furthermore, the research finds that maximising feedstock availability by increasing feedstock prices does enhance the potential for biochar production, but it comes with a significant increase in costs.

5. Conclusion

Through this work, we have developed a spatial framework for analysing biochar production systems that integrate life cycle assessment and techno-economic analysis. Our findings demonstrate that biochar production can yield substantial net reductions in greenhouse gas emissions (GHG) and provide significant greenhouse gas removal (GGR) benefits.

In the East of England and the East Midlands, utilising all currently sold wheat straw for biochar production could result in net GHG reductions of 350 and 277 thousand tonnes, producing 130 and 110 thousand tonnes of biochar, respectively. Maximising feedstock supply by doubling feedstock prices in these regions could achieve net GHG reductions of 560 and 930 thousand tonnes, yielding 350 and 210 thousand tonnes of biochar, respectively. Feedstock supply constitutes 70% of system emissions and production costs, with bio-oil contributing to 53% net GHG reduction and substantial revenue, constituting 50% of total costs. According to the baseline feedstock supply situation, GGR benefits from biochar production in the East of England and the East

Midlands could constitute 4% and 3% respectively of the annual removal targets of the Net Zero Strategy by 2030. If maximisation the feedstock supply, the proportions for these two regions are increased to 10% and 6%.

An integrated assessment of the unit cost for the GGR benefits of biochar reveals that maximising feedstock supply at nearly double the current price results in a tenfold increase in the unit cost compared to the scenario where all available wheat straw is used for biochar production. The cost associated with GGR benefits is most sensitive to bio-oil and straw prices, while transportation costs and biomass yield have a moderate impact on the unit costs. Spatial heterogeneity significantly influences the unit cost of GGR benefits, with higher feedstock supply density and quantity in the East of England leading to lower unit costs. Changes in the number of processing sites can result in cost variations exceeding 100% in each region, demonstrating substantial differences in GGR benefits and corresponding unit costs among different processing locations.

The scalability of biochar production is heavily dependent on feedstock supply and pricing, requiring the identification of additional revenue sources. This study facilitates the calculation of the potential for biochar production and associated costs, allowing for the identification of regions with lower unit costs and an understanding of the policy requirements of different regions. Further research is needed to explore the competition for feedstock and strategies to enhance farmer acceptance, promoting biochar production. These offer opportunities for future research.

CRediT authorship contribution statement

Yuzhou Tang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Yue Li:** Validation, Methodology. **Tim T. Cockerill:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2024.107187.

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