Applied Energy 279 (2020) 115782

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Techno-economic and environmental assessments for nutrient-rich biochar production from cattle manure: A case study in Idaho, USA

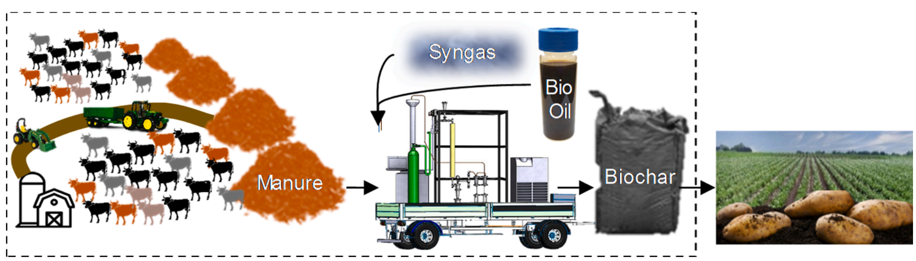
Ethan Struhs[a,*], Amin Mirkouei[a,b,*], Yaqi You[c], Amir Mohajeri[b]

[a] Department of Mechanical Engineering, University of Idaho, Idaho Falls, ID 83402, USA
[b] Industrial Technology and Technology Management Programs, University of Idaho, Idaho Falls, ID 83402, USA
[c] Department of Environmental Resources Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, USA

HIGHLIGHTS

- This study integrates technological and sustainability aspects of biochar production.
- A portable refinery unit is proposed for converting manure to value-added products.
- A multi-criteria evaluation method is developed to facilitate decision making analysis.
- Uncertainty effects are investigated through a stochastic optimization model.
- Manure-based biochar can promote carbon management and GHG emission mitigation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Cattle manure
Biochar
Techno-economic analysis
Optimization
Environmental assessment
Portable refinery

ABSTRACT

Bioproducts from biomass feedstocks and organic wastes have shown great potential to address challenges across food-energy-water systems. However, bioproducts production is at an early, nascent stage that requires new inventions and cost-reducing approaches to meet market needs. Biochar, a byproduct of the pyrolysis process, derived from nutrient-rich biomass feedstocks (e.g., cattle manure and poultry litter) is one of these bioproducts that has numerous applications, such as improving soil fertility and crop productivity. This study investigates the market opportunity and sustainability benefits of converting manure to biochar on-site, using a portable refinery unit. Techno-economic and environmental impact assessments are conducted on a real case study in Twin Falls, Idaho, USA. The techno-economic analysis includes a stochastic optimization model to calculate the total cost of biochar production and distribution. The environmental study employs a life cycle assessment method to evaluate the global warming potential of manure-to-biochar production and distribution network. The total cost of biochar production from cattle manure near the feedlots is approximately $237 per metric ton, and total emission is 951 kg CO_2 eq. per metric ton. The on-site operation and manure moisture content are two key parameters that can reduce biochar unit price and carbon footprint of manure management. It is concluded that converting cattle manure, using the presented strategy and process near the collection sites can address upstream and midstream sustainability challenges and stimulate the biochar industry.

* Corresponding authors at: Tingey Administration Building, Suite 310, University of Idaho, Idaho Falls 83402, USA.
E-mail addresses: stru4589@vandals.uidaho.edu (E. Struhs), amirkouei@uidaho.edu (A. Mirkouei).

https://doi.org/10.1016/j.apenergy.2020.115782
Received 11 February 2020; Received in revised form 2 July 2020; Accepted 22 August 2020
Available online 2 September 2020

1. Introduction

Challenges and Motivation. Based on the U.S. National Oceanic and Atmospheric Administration (NOAA), atmospheric CO_2 concentration increases every year and it reached 414.7 parts per million (ppm) in 2019, which is 3.5 and 14.7 ppm higher than the 2018 and 2014 recorded level, respectively [1]. Carbon sequestration should be deployed to stabilize the concentration of CO_2 in the atmosphere. Biochar-based carbon sequestration is considered a negative emission strategy for reliable carbon management because of its ability to lock black carbon in the soil, which will remain there for multiple centuries [2]. Biochar produced from nutrient-rich agricultural leftovers and waste streams has multiple environmental benefits and can be used as a soil amendment explicitly for organic crop production [3,4]. It can significantly enhance soil fertility and crop yield while reducing greenhouse gas (GHG) emissions and leaching of nutrients, heavy metals, and pesticides to surface and groundwater [5]. Specifically, slow pyrolysis (SP) condition is more favorable than fast pyrolysis for the

Nomenclature

Indices

a	Set of collection sites
b	Set of conversion sites
c	Set of biochar storage sites
co	Collection
cs	Biochar storage
d	Set of bio-oil storage sites
dr	Dryer
e	Set of biochar distribution centers
gr	Grinding
os	Bio-oil storage
py	Pyrolysis
tr	Truck
u	Utilization
t	Set of time

Parameters

AMN_t	Annual available cattle manure (metric ton/yr)
BQ_t	Average biochar quality rate (%)
CAP_b	Annual capacity of a conversion refinery unit (metric ton/yr)
C_{C-co}	Annual capital cost of collection ($/yr)
C_{C-cs}	Annual capital cost of biochar storage ($/yr)
C_{C-dr}	Annual capital cost of drying ($/yr)
C_{C-gr}	Annual capital cost of grinding ($/yr)
C_{C-os}	Annual capital cost of bio-oil storage ($/yr)
C_{C-py}	Annual capital cost of pyrolysis ($/yr)
C_{C-tr}	Annual capital cost of double-trailer truck ($/yr)
CO_u	Annual handling equipment (loader) utilization (metric ton/yr)
CS_u	Annual biochar storage equipment utilization (metric ton/yr)
C_{V-co}	Annual variable cost of collection ($/yr)
C_{V-cs}	Annual variable (labor and operational) cost of biochar storage ($/yr)
C_{V-dr}	Annual variable cost of drying ($/yr)
C_{V-gr}	Annual variable cost of grinding ($/yr)
C_{V-os}	Annual variable cost of bio-oil storage ($/yr)
C_{V-py}	Annual variable cost of pyrolysis ($/yr)
C_{V-tr}	Annual variable cost of double-trailer truck ($/yr)
CY_{char}	Conversion yield (%)
D	Distance (miles)
DR_u	Annual drying equipment utilization (metric ton/yr)
GR_u	Annual grinder utilization (metric ton/yr)
M	A large number
M_{char}	Mass of produced biochar (metric ton)
M_{manure}	Mass of raw manure (metric ton)
MQ_t	Average manure quality rate (%)
NCS_t	Number of selected collection sites
NR	Biochar nutrient content range (%)
OS_u	Annual bio-oil storage equipment utilization
P_{char}	Biochar production GWP (kg CO_2 eq.)
P_{trans}	Biochar transportation GWP (kg CO_2 eq.)
P_{up}	Upstream processes GWP (kg CO_2 eq.)
PR	Manure pre-treatment range, depends on moisture content (%)
PY_u	Annual pyrolysis utilization (metric ton/yr)
RCH4	Emissions rate of CH_4 (kg CO_2 eq./kg CH_4)
RCO2	Emissions rate of CO_2 (kg CO_2 eq./kg CO_2)
RN2O	Emissions rate of N_2O (kg CO_2 eq./kg N_2O)
TR_u	Annual truck utilization (metric ton/yr)
W	SVM weight
η_{char}	GHG emissions factor for biochar production process (kg CO_2 eq. per ton)
$\eta_{char,CH4}$	CH_4 emission factor of biochar production processes (kg CH_4 per ton)
$\eta_{char,CO2}$	CO_2 emission factor of biochar production processes (kg CO_2 per ton)
$\eta_{char,N2O}$	N_2O emission factor of biochar production processes (kg N_2O per ton)
η_{trans}	GHG emissions factor for biochar transportation (kg CO_2 eq. per ton-mile)
$\eta_{trans,CH4}$	CH_4 emission factor of biochar transportation (kg CH_4 per ton-mile)
$\eta_{trans,CO2}$	CO_2 emission factor of biochar transportation (kg CO_2 per ton-mile)
$\eta_{trans,N2O}$	N_2O emission factor of biochar transportation (kg N_2O per ton-mile)
η_{up}	GHG emissions factor for upstream processes (kg CO_2 eq. per ton)
$\eta_{up,CH4}$	CH_4 emission factor of upstream processes (kg CH_4 per ton)
$\eta_{up,CO2}$	CO_2 emission factor of upstream processes (kg CO_2 per ton)
$\eta_{up,N2O}$	N_2O emission factor of upstream processes (kg N_2O per ton)
φ	Phi
μ	Mean value
σ^2	Variance value

Decision variables

$Char_{bct}$	Integer variable for biochar mass from conversion site *b* to storage site *c* during time period *t* (metric ton)
$Char_{cet}$	Integer variable for biochar mass from storage site *c* to distribution center *e* during time period *t* (metric ton)
MN_{abt}	Continuous variable for manure mass from collection site *a* to conversion site *b* during time period *t* (metric ton)
Oil_{bdt}	Integer variable for bio-oil mass from conversion site *b* to storage site *d* during time period *t* (metric ton)
Z_{abt}	Binary variable for manure from collection site *a* to conversion site *b* during time period *t*

production of biochar and generates biochar with higher stability that allows long-term carbon sequestration in soils [6–8].

Biochar can retain nutrients in the soil and release macronutrients, e.g., nitrogen, phosphorus, and potassium (NPK), for plant growth [9]. Biochar can, thus, reduce the need for soil fertilization and work as a slow-release fertilizer [10]. Moreover, the enhanced water-holding capacity in biochar-amended soils will increase crop yield per drop of water applied [11]. Its porous nature enables biochar to adsorb heavy metals and thus reduce their uptake by plants and subsequent ingestion by humans and animals [12]. Apart from agronomic applications, unblended biochar and biochar blended with other compositions have broad applications, such as nutrient recovery and reuse [13], livestock farming [14], and pharmaceutical [15]. Biochar also has large potential in the treatment of water [16], a quintessential resource for the future of the population and the standard of living [17]. Despite considerable empirical evidence of agronomic and environmental benefits of biochar from laboratory and field studies [18], systems-level assessment of biochar effects is still limited, impeding translation into large-scale management practices [19,20].

Background. The future of resources (e.g., food, water, and energy) sustainability is an ever-increasing global concern due to the rapidly growing population and the doubling of global demands in the next 25 years [21–23]. Particularly, a global increase in the demand for food requires substantial land, energy, and water resources while mitigating negative environmental impacts of food systems. Reusing or recycling resources is one promising approach to reduce the negative impacts of the food system on agro-ecosystems. Delaney (2015) reported that the U.S. national market potential of biochar is projected to reach over $5 billion across various sectors (e.g., aquaculture, agriculture, and horticulture) [24]. Existing biochar on the market is mainly from wood-based feedstocks that can increase forest restoration and employment [25]. Wrobel-Tobiszewska et al. (2015) developed an economic analysis for on-site biochar production in Tasmania, using eucalypt plantations residue wood as feedstock [26]. They used the biochar within the system or sold it as a product, and their cost model revealed an annual income of $179,000, with benefit depending mainly on biochar unit price and distribution.

A comprehensive classification of research related to this study based on the characteristics of biochar problems is provided in Table 1. This classification is based on the following distinguishing factors:

Production strategies. Several studies have conducted cost analysis for biochar and bio-oil production from different feedstocks (e.g., rice husk, pinewood, wheat straw, maize straw, poplar wood, and rice straw) in various regions (e.g., USA, China, Vietnam, and Australia), using various thermochemical conversion technologies [27–29]. Among thermochemical technologies, SP technology can produce biochar with higher stability and carbon content. SP is expected to grow rapidly due to high process yield (around 35%) and end-product quality (over 55% carbon content) in comparison to other conversion pathways (e.g., fast pyrolysis and gasification) [30]. A comprehensive overview of biochar production and utilization has been given by Panwar et al. (2019) [31].

Techno-economic analysis (TEA). Recent studies reported varying biochar selling prices, such as $231-$283 per ton using pyrolysis and gasification processes as modeled with ECLIPSE software [32], $474-$704 per ton using pyrolysis with a case study developed around the Upper Klamath Basin [25], and $220-$280 per ton, using SP [33]. TEA shows that capital and operating costs of a pyrolysis unit have the lowest sensitivity impact, while the biochar selling price and biomass management cost have the highest impact [34]. Similar studies also show that capital investment, feedstock costs, and labor costs are the greatest influencing factors of biochar and bio-oil minimum selling price [20,35,36].

Environmental impact assessment. Biochar has greater agronomic benefits and is generally more environmentally beneficial than mineral fertilizers in terms of global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) [37]. Several studies used life cycle assessment (LCA) for evaluating biochar and bio-oil production by pyrolysis technology in different countries (e.g., Spain, Brazil, and USA) [27,38]. A Monte Carlo simulation of biochar climate impact on harmful emissions in Stockholm, Sweden showed a near-linear correlation between the concentration of biochar used and its effects [39]. LCA suggested biochar made from the main crop for biodiesel in the EU, winter oilseed rape, may decrease GHG emissions by 73% and 83% [40].

Multi-objective studies. Belmonte et al. (2018) developed an optimization model with both economic (profit) and environmental (carbon sequestration) objectives and conducted a Philippine case study to explore the trade-off between these two objectives. Li et al. (2019) performed regional TEA and LCA of biochar production for an integrated pyrolysis-bioenergy-biochar platform in three U.S. states, considering different feedstocks (wood, straw, grass) in each state [41]. Their TEA concluded that farmer's willingness-to-pay ranged from $75 to $1272 per metric ton of biochar, LCA proved that higher ash content of the feedstocks led to higher biochar yield, resulting in a larger reduction of GHG emissions. Case studies performed in Belgium attempted to monetize the environmental impacts of biochar production from willow and pig manure. Wood-based biochar outperformed manure in all categories of environmental impact and

Table 1
A summary of recent biochar studies, focusing on economic and environmental aspects.

References	Objectives		Pyrolysis	Uncertainties	Sources	Solution Method	Case Study
	Economic	Environmental					
[2]	✓	✓	✓	x	Coconut	ε-Constraint	✓
[27]	✓	x	✓	x	Rice	LCA	✓
[30]	x	✓	✓	x	Vines	LCA	✓
[32]	✓	x	✓	x	Poultry Litter	TEA	✓
[33]	✓	x	✓	x	Pine	TEA	x
[34]	✓	x	✓	x	Biosolid	TEA	✓
[35]	✓	x	✓	x	Forest	TEA	x
[37]	x	✓	✓	x	Oak residue	LCA	✓
[39]	x	✓	✓	x	Woodchip	LCA	✓
[40]	x	✓	✓	x	Oilseed	LCA	✓
[41]	✓	✓	✓	x	Rice; corn; peanut	TEA, LCA	✓
[42]	x	✓	✓	x	Willow; pig manure	LCA	✓
[43]	✓	x	✓	✓	Forest	TEA, Monte Carlo	✓
[44]	x	✓	✓	✓	Olive husk	LCA, Monte Carlo	✓
[45]	✓	x	✓	✓	Pine pulpwood	TEA, Monte Carlo	✓
This study	✓	✓	✓	✓	Cattle manure	TEA, LCA, GA	x

LCA: life cycle assessment; TEA: techno-economic assessment; GA: genetic algorithm.

cost due to the high energy demand for pretreatment, especially dewatering manure [42].

Uncertainties incorporation. Campbell et al. (2018) conducted a comparative TEA for biofuel and biochar production, using two different conversion pathways [43]. They also incorporated the effects of uncertainty and volatility often critical variables. A study involving four scenarios, using different pyrolysis technologies and end-use of products, was performed to calculate carbon emission abatement [44]. Monte Carlo analysis was used to model 16 uncertainty parameters. In another study, techno-economic uncertainties of two pathways for catalytic pyrolysis were assessed [45]. Uncertainty of variables, such as internal rate of return, feedstock price, total project investment, electricity price, biochar yield, and bio-oil yield was evaluated.

Biochar from nutrient-rich sources. Animal manure and poultry litter are sources, containing phosphorus and nitrogen, which are mainly used as a fertilizer and soil conditioner [47,47]. Biochar-based products derived from nutrient-rich organic resources (e.g., manure) have been suggested as sustainable materials for addressing environmental issues, such as nutrient leaching and chemical fertilizer runoff, which lead to eutrophication (oversupply nutrients) in surface waters. It is essential to supply enough nutrients for healthy crop growth and yields, while not polluting the environment. Earlier studies estimated that eutrophication could cause approximately $2 billion per year in the U.S. [48]. These environmental challenges require new solutions and biochar products derived from nutrient-rich organic biomass hold the promise of replacing synthetic fertilizers. Raw manure has high levels of pollutants and pathogens, however, it is a valuable resource given high content of NPK for farming and cropping [46]. In the U.S., manure transportation costs vary and depend on the state. For example, the average management cost is $1.05 per cow per month ($12.6 per cow per year) in California [46], which is over $50,000 annually for a dairy with around 4,000 cows. This amount of manure management cost can be used for building a portable refinery unit that can convert manure to value-added products on-site, subsequently reducing the carbon footprint of manure management operation and livestock GHG emissions (roughly 80 MMT CO_2 eq.) [46].

The novelty of this study lies in (i) the proposed multi-criteria decision making, including TEA and LCA for sustainable nutrient-rich biochar production from cattle manure, (ii) the proposed stochastic optimization model to incorporate the effects of uncertainty parameters and explore the commercial feasibility of biochar production, and (iii) the presented case study in Twin Falls, Idaho, USA for verifying the proposed methods and models. Additionally, this study contributes to techno-economic and environmental dimensions of biochar production, highlighting the feasible use of portable refinery units to convert cattle manure to biochar near the collection sites and reduce the environmental footprint of dairy manure management. The TEA investigates a mixed conversion pathway for producing nutrient-rich biochar and high yield bio-oil, and a stochastic optimization model to minimize the total cost of biochar production and distribution (i.e., collection, grinding, drying, conversion, storage, and transportation). The stochastic model has two constraints that investigate the uncertainty of manure moisture and biochar nutrients on the total cost and biochar quality. The environmental assessment evaluates GWP of manure-to-biochar production systems and distribution networks, using the LCA method, including four phases (i.e., goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation). Finally, a case study in Twin Falls, Idaho, USA investigates the sustainability benefits of the proposed conversion process in regions with a high density of dairy feedlots and demonstrates the applicability of the optimization model in energy and agricultural areas.

2. Methods and materials

The portable refinery unit in this study employs mixed fast and slow pyrolysis reactors to produce nutrient-rich biochar and high-yield bio-oil (Fig. 1). Pyrolysis oil and gas are fed for heat and electricity production for pretreatment purposes, such as dewatering manure and particle size reduction. Fresh cattle manure generally has a moisture content between 80 and 90% and is ideally reduced to 50% by composting processes [49,50]. Typically, biomass moisture content should range below 5% in order to produce quality products [51]. Moisture content in the composted manure was assumed to be 50% and was decreased to around 5%, utilizing a Roto-Louvre rotary dryer along with produced bio-oil and pyrolysis gas as sources of heat. Grinding cost was simulated for a Peterson 5710C horizontal grinder. The required storage facilities and equipment are 0.5 tons (over 1000 lbs) bulk bags for biochar and a tanker with 50 gallons capacity for bio-oil storage, connected to the refinery unit. Besides, a double-trailer truck is considered for transferring biochar from the production site to storage facilities. The capital and variable costs are estimated using an approach reported in the earlier study [52] and adjusted for inflation to 2019, using the Producer Price Index [53].

The portable refinery unit in this study is a simulated, scaled-up model of ourdesigned and built in-house portable refinery, which was used to perform manure pyrolysis experiments to determine relative yield, generate products for physicochemical analysis, and provide a basis for simulation. Pretreatment for the experimental smaller unit was carried out by drying the manure in a laboratory oven, running at a setpoint of 100 °C for several hours. Grinding of the dried manure was performed, using an electric coffee grinder. Products produced by the unit were stored in storage vessels connected directly to the setup. The produced biochar samples were analyzed in two analytical laboratories (i.e., Environmental Analytical Laboratory at Brigham Young University, UT and Huffman Hazen Laboratories, CO). For simulation purposes, the pyrolysis reactor was modeled in Aspen HYSYS (a chemical process modeling simulator), using a continuously stirred-tank reactor (CSTR) because of their ability to model kinetic reactions (Fig. 2). The CSTR was used to simulate the primary decomposition reactions of pyrolysis as well as some of the secondary reactions. Nitrogen was used as an inert gas to control reactor residence time and promote the decomposition of biomass within the reactor. Nitrogen and biomass enter the unit at ambient temperature, and the pyrolysis unit operates between 0 and 15 psi [54]. The refinery capacity is approximately 50 metric tons of biomass per day. Nitrogen mixes with biomass and pushes it through the pipeline. Mixed inlet streams enter the primary pyrolysis reactor and are heated by the core heater, making sure that biomass reaches 550 °C while in the primary reactor [54,55]. Upon entering the primary reactor, biomass decomposes and solid carbonaceous residue (biochar) exits

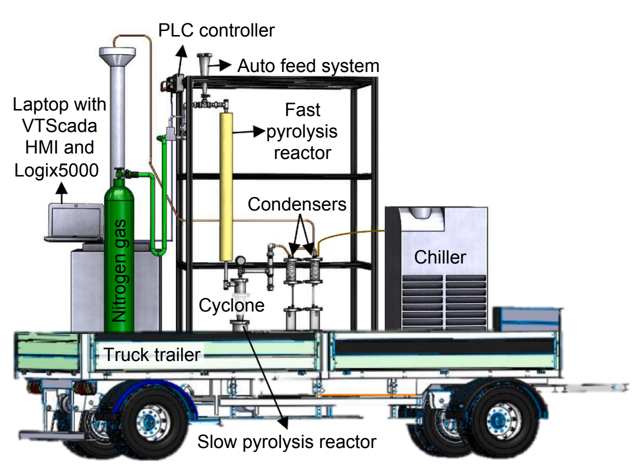


Fig. 1. Schematic of mixed fast and slow pyrolysis portable refinery unit.

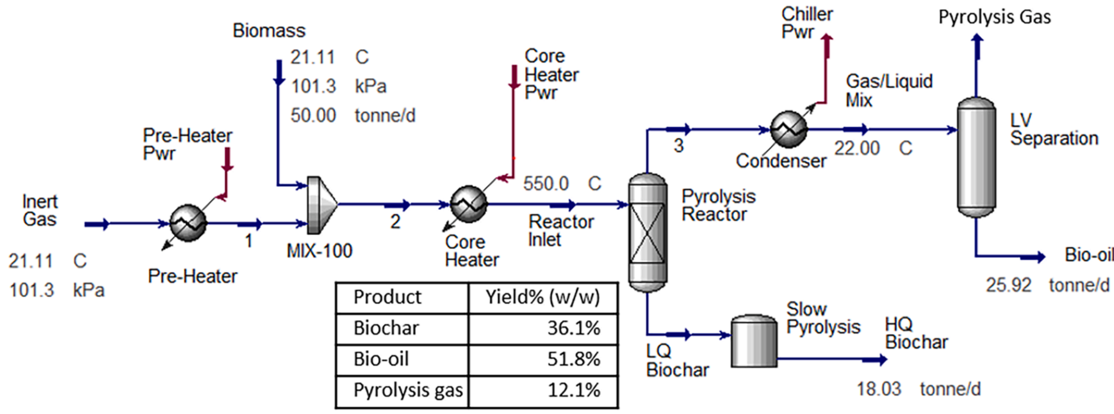


Fig. 2. Aspen HYSYS simulation of biochar production.

through the bottom stream. The biochar stream then enters a fixed-bed reactor where it undergoes slow pyrolysis to produce nutrient-rich biochar. The reactor is heated to 350 °C, and biochar has a residence time of one hour [56]. The vapor phase exits through the top stream, which enters the secondary reactor. Secondary pyrolysis reactions take place to further break down the products of the primary reactor. From the secondary reactor, products exit to a condenser, bringing down the stream temperature to 21 °C and proceeding to be separated into gas product and bio-oil streams. The simulation was used to estimate biochar yield and emissions released as gas, as well as energy required to heat and cool the material streams. Details on process flow parameters simulated in Aspen HYSYS are provided in Supplementary Materials, Appendix A. The HYSYS simulation was used to simulate a scaled-up version of the small portable refinery unit designed and built in-house, allowing for predictions of biochar yield, unit emissions, and power requirement.

The developed evaluation procedure for multi-criteria decision making encompasses two main steps (i.e., techno-economic modeling and environmental impact assessment) to explore manure-based biochar production (Fig. 3).

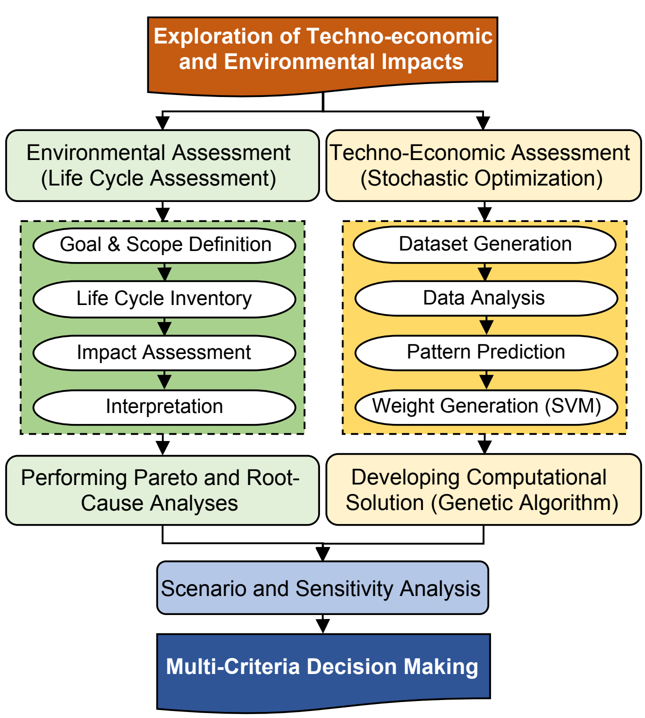


Fig. 3. Evaluation procedure for multi-criteria decision making.

2.1. Techno-economic assessment

A stochastic optimization model is formulated to explore the potential for biochar commercialization, using the proposed portable refinery unit. The main operational and capital cost elements of the mathematical model include collection, pretreatment (i.e., grinding and dewatering), refinery or conversion, storage, and distribution costs. The presented model has two stochastic constraints to incorporate the uncertainties and investigate the economic feasibility of nutrient-rich biochar production, using the mixed conversion pathway. The support vector machine (SVM) method is utilized to predict the pattern of uncertainty variables (i.e., biomass and biochar quality), which are highly influential in terms of biochar commercialization and sustainability performance. Based on the data collected using methods detailed below, the stochastic constraints manage uncertainties by considering probability distributions of the defined parameters.

Particularly, biomass quality in this study is determined by manure water content and carbon content (wt%). Manure with high water (H_2O) content is considered as low-quality biomass because it requires more energy for dewatering that subsequently increases the pretreatment cost. Cattle manure typically has a high water content of around 70–80% and a carbon content around 7–9%. Additionally, biochar quality is determined through pH and nutrient (NPK) content (wt%). In this study, the manure water content before and after drying procedure is measured, using a moisture meter. For produced biochar, carbon content, nutrient content, and pH are measured with standard methods at analytical chemical laboratories. Due to the lack of large datasets for the SVM approach, we randomly generated a dataset, using a uniform distribution within the defined ranges reported in the literature (Table 2) for each parameter [57–60].

The developed dataset forms the training and testing datasets (provided in Supplementary Materials, Appendix B) used by the SVM model, including input and output data. The inputs are raw manure water and carbon content, and biochar pH, and carbon and nutrient (N, P, and K) content. The outputs are manure and biochar quality in terms of percentages. Training and testing datasets have 30 and 10 sample values,

Table 2
Cattle manure and biochar property values [58–60].

Parameters	Cattle Manure (min–max wt %)	Manure-based Biochar (min–max wt%)
Water content	70–80	< 10
pH	7.4–8.9	8.3–9.5
C	11.2–19.7	61.5–75.2
N	0.8–1.5	1.3–1.8
P	0.003–0.007	0.000–0.002
K	0.008–0.011	0.004–0.013

respectively. These datasets are used to recognize the pattern of uncertainty variables (manure and biochar quality) through the SVM supervised learning algorithm. SVM learning algorithms (i) analyze and classify the data, (ii) predict the pattern of parameters and variables, using regression analysis, and (iii) generate the weight for uncertainty parameters, using the training dataset.

The stochastic optimization model used herein targets the commercial feasibility of biochar production. The objective function (Eq. (1)) aims to minimize the total manure-to-biochar cost over a specific time horizon. Total cost includes both capital (fixed) and operational (variable and labor) costs. Notations of model parameters and variables are provided in the Nomenclature section.

$$\boldsymbol{MinZ} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{1}$$

Each of the terms (C_1-C_6) in Eq. (1) is defined in the sequence below. The collection cost (C_1) is calculated (Eq. (1a)) as follows:

$$C_1 = \sum_a \sum_b \sum_t C_{C-co} \times Z_{abt} + (C_{V-co}) \times \frac{MN_{abt}}{CO_u} \tag{1a}$$

The grinding cost (C_2) is calculated (Eq. (1b)) as follows:

$$C_2 = \sum_a \sum_b \sum_t (C_{C-gr} + C_{V-gr}) \times \frac{MN_{abt}}{GR_u} \tag{1b}$$

The drying cost (C_3) is calculated (Eq. (1c)) as follows:

$$C_3 = \sum_a \sum_b \sum_t (C_{C-dr} + C_{V-dr}) \times \frac{MN_{abt}}{DR_u} \tag{1c}$$

The conversion cost (C_4) is calculated (Eq. (1-d)) as follows:

$$C_4 = \sum_a \sum_b \sum_t (C_{C-py} + C_{V-py}) \times \frac{MN_{abt}}{PY_u} \tag{1d}$$

The storage cost (C_5) is calculated (Eq. (1-e)) as follows:

$$C_5 = \sum_b \sum_c \sum_t (C_{C-cs} + C_{V-cs}) \times \frac{Char_{bct}}{CS_u} + \sum_b \sum_d \sum_t (C_{C-os} + C_{V-os}) \times \frac{Oil_{bdt}}{OS_u} \tag{1e}$$

The distribution cost (C_6) is calculated (Eq. (1f)) as follows:

$$C_6 = \sum_c \sum_e \sum_t (C_{C-tr} + C_{V-tr}) \times \frac{Char_{cet}}{TR_u} \tag{1f}$$

The model includes several constraints that include capacity, linking-shipping, structure, flow conservation, balance, and uncertainty, as well as non-negativity, binary, and integer constraints. Capacity constraint (Eq. (2)) ensures that the sum of the flow exiting from all collection sites to each conversion site does not exceed the annual capacity of a conversion refinery unit. Eq. (3) presents the annual available amount of processed cattle manure (*AMN*) in each collection area, and the sum of the manure flow in the whole system does not exceed the total amount available annually in the region.

$$\sum_{a \in A} MN_{abt} \le CAP_b \quad \forall_b \in B, \forall_t \in T \tag{2}$$

$$\sum_{a \in A} \sum_{b \in B} MN_{abt} \ge AMN_t \quad \forall_t \in T \tag{3}$$

Linking-shipping constraint (Eq. (4)) ensures that there are no links between any collection site and conversion site without actual shipments, and there is no shipping between any non-linked collection site and conversion site.

$$MN_{abt} \ge 1 - M(1 - Z_{abt}) \quad \forall_a \in A, \forall_b \in B, \forall_t \in T \tag{4}$$

Structure constraint (Eq. (5)) ensures that the sum of the connection links from collection sites to each conversion site does not exceed the maximum limit of selected collection sites.

$$\sum_{a \in A} Z_{abt} \le NCS_t \quad \forall_b \in B, \forall_t \in T \tag{5}$$

Flow conservation constraints (Eqs. (6) and (7)) ensure that the sum of the exiting biochar flow from each conversion site to biochar storage sites does not exceed the conversion rate of manure-to-biochar at each conversion site, and the sum of the exiting biochar and bio-oil flow from each conversion site to storage sites does not exceed the flow of manure mass entering each conservation site from all collection sites, respectively. Conversion yield (*CY*) that can be obtained multiplying the average manure quality rate (*MQ*) by the calculated weight, using SVM method.

$$\sum_{c \in C} Char_{bct} \le CY_{char} \times \sum_{a \in A} MN_{abt} \quad \forall_b \in B, \forall_t \in T \tag{6}$$

$$\sum_{c \in C} Char_{bct} + \sum_{d \in D} Oil_{bdt} \le \sum_{a \in A} MN_{abt} \quad \forall_b \in B, \forall_t \in T \tag{7}$$

Balance constraint (Eq. (8)) ensures that the flow of biochar entering each storage site from all conversion sites is equal to the sum of the exiting biochar flow from this storage site to distribution centers.

$$\sum_{b \in B} Char_{bct} - \sum_{e \in E} Char_{cet} = 0 \quad \forall_c \in C, \forall_t \in T \tag{8}$$

Uncertainty constraints (Eqs. (9) and (10)) ensure that quality rate of manure flow entering each conversion site from all collection sites at least meet the average manure quality rate, and quality rate of manure-based biochar at each conversion site at least meet the average biochar quality rate, respectively.

$$\sum_{a \in A} \mu_{abt} \times Z_{abt} + \sqrt[2]{\left(\sum_{a \in A} \sigma^2_{abt} \times Z_{abt}\right)} \times \frac{(1 - PR)}{\varphi} \le MQ_t \quad \forall_b \in B, \forall_t \in TPR \in [0,1] \tag{9}$$

$$\sum_{a \in A} \mu_{abt} \times Z_{abt} + \sqrt[2]{\left(\sum_{a \in A} \sigma^2_{abt} \times Z_{abt}\right)} \times \frac{(1 - NR)}{\varphi} \le BQ_t \quad \forall_b \in B, \forall_t \in TNR \in [0,1] \tag{10}$$

Other constraints (Eqs. (11)–(13)) are non-negative, integer, and binary variables, respectively.

$$MN_{abt} \ge 0 \quad \forall_a \in A, \forall_b \in B, \forall_t \in T \tag{11}$$

$$Char_{bct}, Char_{cet}, \text{ and } Oil_{bdt} \text{ are integers} \quad \forall_b \in B, \forall_c \in C, \forall_d \in D, \forall_e \in E, \forall_t \in T \tag{12}$$

$$Z_{abt} = \{0, 1\} \ fora \quad \forall_a \in A, \forall_b \in B, \forall_t \in T \tag{13}$$

The weight of each uncertainty parameter represents the coordinate where the vector of the SVM model is perpendicular to the hyperplane (or decision surface). We utilized R (version 3.6.2), a programming language for statistical computing and graphics, to determine each uncertainty parameter's weight (Table 3). R codes can be found in Supplementary Materials, Appendix D. The failure rates were calculated by comparing the weight determined from the training data with the weight determined from the testing data, which is very low for all parameters. The manure and biochar quality rates (MQ_t and BQ_t) for each refinery site can be estimated, using the defined weight for each parameter. In this study, MQ_t and BQ_t are estimated at 60% and 70%, respectively. Additionally, the manure quality rate (higher rate indicating lower water content and higher carbon content) can help decision makers to select collection sites for better economic and environmental outcomes.

Due to the complexity of the proposed techno-economic optimization model, we utilized the metaheuristic approach, Genetic Algorithm

Table 3
Calculated weights for uncertainty parameters in training and testing datasets, using SVM technique.

	Carbon	Moisture	Manure Quality Rate	pH	Carbon	Nutrient	Biochar Quality Rate
Trainging Weight	0.81	3.73	2.18	43.30	3.22	0.05	2.14
Testing Weight	0.89	3.68	2.23	43.60	3.21	0.10	2.15

implemented in MATLAB (version R2017a) to solve the model with 10 collection sites (MATLAB codes are provided in Supplementary Materials, Appendix D). The applied computer system to solve the model has 32 GB RAM, 64-bit OS, Intel Xeon CPU with Windows 10.

2.2. Environmental assessment

An LCA method is applied using OpenLCA, along with information from previous studies to evaluate the environmental impacts of the manure-to-bioproducts life cycle [61–63]. LCA study includes four parts, which are the definition of goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation.

Goal and Scope Definition. Environmental and economic impacts of bioenergy production from biomass conversion methods need to be assessed in comparison with the impacts of established fossil energy methods. LCA performed herein evaluates GWP for the manure to value-added products life cycle. GHG emission factors are used to calculate the GWP (in kg CO_2 equivalent) with the key factors being 28 kg CO_2 eq./kg CH_4 and 265 kg CO_2 eq./kg N_2O, which are acquired from the Intergovernmental Panel on Climate Change for a 100-year time horizon [64]. The scope of this study includes four distinct stages that can be categorized into two processes: (i) upstream processes, including raw material (cattle manure) collection, and (ii) midstream processes, involving on-site pretreatment (dewatering and size reduction), on-site converting manure to intermediate products (biochar, bio-oil, and pyrolysis gas), on-site reusing intermediate products (e.g., bio-oil and pyrolysis gas) for pretreatment purposes (i.e., heat and electricity), and biochar distribution. This scope considers a cradle-to-gate system boundary (Fig. 4). The functional unit in this study is one kilogram of biochar, using the identified scope.

Life Cycle Inventory Analysis. In order to accurately evaluate the manure-based bioproducts production and distribution system, data was obtained from the AGRIBALYSE and OpenLCA databases for the input and output parameters [65]. Equipment used for the upstream collection of raw manure generally includes a forwarder and loader. Input into the dairy farm stage is cattle manure and fossil-based energy and lubricants required by the machinery, and outputs comprise of methane emitted from manure, as well as equipment operation emissions. GHG emission factor for the upstream includes collecting and hauling of manure.

After collection, the midstream processes start by loading manure into an on-site grinder and then into a rotary dryer for biomass pretreatment. Midstream pretreatment inputs are raw cattle manure and diesel fuel, and the outputs are pretreated biomass and GHG emissions, including fuel combustion and water vapor released during biomass drying. GWP is directly affected by manure moisture content and biomass quality. During pretreatment, dry biomass is run through a portable pyrolysis unit, utilizing nitrogen (as an inert gas) and a heat source, powered by electricity. Midstream pyrolysis inputs are pretreated biomass, nitrogen, fuel to produce electricity, and cooling water, while outputs consist of biochar (the focus of this study), bio-oil, and gas as precursors to the final bioenergy products, as well as emissions. The emissions include biogenic GHGs produced in the conversion of biomass to biochar in addition to the gas and emissions from fuel combustion. The produced biochar will be transported by a tanker, using diesel fuel to the distribution center. The fuel and its impact depend largely on truck trips and distance between the dairy farm and distribution centers.

Life Cycle Impact Assessment. Impact analysis is performed using data from a case study in the region surrounding Twin Falls, Idaho. The above-described process is converted into a production system using OpenLCA, focusing on biochar-based soil health improvement as the principal product of significance. Life cycle impact assessment was conducted using the CML-IA baseline method, created by the University of Leiden (version 1.5.5). Total upstream emission factors and GWP are calculated, using Eqs. (14) and (15):

$$\eta_{up} = R_{CO2} \times \eta_{up,CO2} + R_{CH4} \times \eta_{up,CH4} + R_{N2O} \times \eta_{up,N2O} \tag{14}$$

$$P_{up} = M_{manure} \times \eta_{up} \tag{15}$$

Midstream emission factors and GWP for biochar production are calculated, using Eqs. (16) and (17):

$$\eta_{char} = R_{CO2} \times \eta_{char,CO2} + R_{CH4} \times \eta_{char,CH4} + R_{N2O} \times \eta_{char,N2O} \tag{16}$$

$$P_{char} = M_{char} \times \eta_{char} \tag{17}$$

Biochar transportation emission factors and GWP are calculated, using Eqs. (18) and (19):

$$\eta_{trans} = R_{CO2} \times \eta_{trans,CO2} + R_{CH4} \times \eta_{trans,CH4} + R_{N2O} \times \eta_{trans,N20} \tag{18}$$

$$P_{trans} = M_{char} \times \eta_{trans} \times D \tag{19}$$

Interpretation. The major environmental impacts that are concluded in this study comprise of GWP (100 years), photochemical oxidation, and human toxicity. This information will be useful in grasping the environmental impacts of the inputs and outputs of the defined system and, thereby, help determine future efforts in enhancing the system's sustainability benefits. Emissions from the products of the system (e.g.,

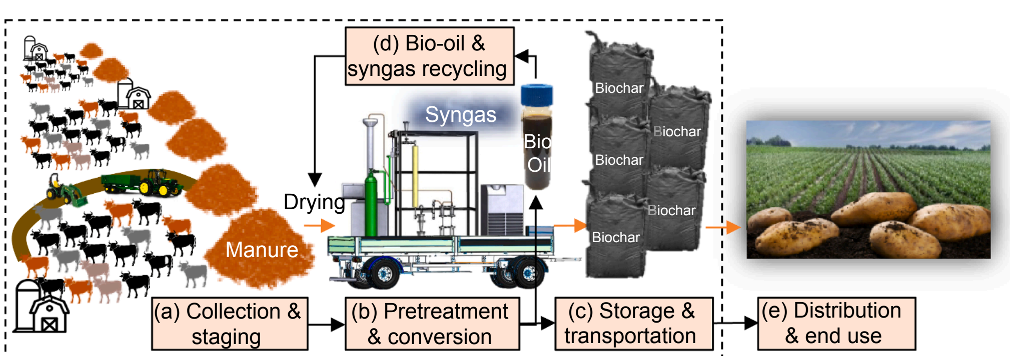


Fig. 4. The dotted line shows the cradle-to-gate system boundary for the LCA of manure-to-biochar production in this study.

bio-oil and biochar) are considered as biogenic and part of natural processes. The study also looks into each factor and its individual impact on the system as a whole. The largest contributor to GWP is methane emitted from cattle manure, which would decrease when manure is converted to other hydrocarbon compounds, such as high energy density bioproducts. Other GHGs are emitted from the dryer, grinder, pyrolysis unit, and trucks for transportation.

3. Case study

To assess the proposed techno-economic and environmental assessment framework, we conducted a case study in Magic Valley, South of Idaho that has over 1,212,500 cows, and can produce approximately 16 million metric tons of manure per year (Fig. 5) [66,67]. Idaho is the 3rd largest milk-producing state in the U.S., and dairy is Idaho's top agricultural industry [68,69]. From 2007 to 2017, the average farm size in Idaho has nearly doubled from 663 to 1240 cows per farm [70].

The total number of collection sites in this region are over 30 dairies with over 3000 cows per dairy farm. Actual dairy locations and cow counts data are obtained from ArcGIS and can be found in Supplementary Materials, Appendix C. The main case study considers ten large dairies, located in Lincoln, Gooding, and Cassia counties (Fig. 5B) that have different cattle types (e.g., dairy and beef farming/ranching cows). The main case study requires different equipment for manure collection, drying, and size reduction, including compact tractor with loader and wagon, grinder, and rotary dryer. Two portable refinery units are used. The portable refinery unit travels to near the feedlots and dry lots to convert raw manure to biochar and bioenergy products, which reduces transportation fuel consumption and logistical costs associated with handling raw, high-moisture-content manure, and mitigates environmental emissions associated with manure storage and land application. Additionally, the following assumptions are made from earlier published studies or reports.

1. The short-term bio-oil storage tanker is considered as part of the refinery unit, and associated costs are included in the refinery operational costs.
2. The loader utilization rate is 60,000 tons per year [71].
3. The grinder utilization rate is 37,500 per year [72].
4. The dryer utilization rate is 37,500 per year [73].
5. The effective lifetime of the portable refinery is assumed for ten years.
6. The portable refinery capacity is 50 dry metric tons of biomass per day.
7. The annual scheduled portable refinery process is 328 for 12 h per day.
8. Annual available cattle manure is at least 60,000 dry tons at ten large dairies in Magic Valley, Idaho [66,67].
9. The time horizon is one year.
10. Manure was received for free from the diaries in Twin Falls, ID.
11. The type of equipment and facilities are known.
12. The manure has between 70 and 80 wt% moisture content [50].
13. Conversion process yields for biochar, bio-oil, and pyroylsis gas are 35%, 45%, and 20%, respectively, using the proposed portable refinery unit.
14. The roundtrip distance from the production site to the storage facility is assumed 100 miles (160 km) (ArcGIS 2019).
15. The manure pretreatment rate (PR) ranges from 5 to 10%, depending on manure moisture content (70–80%) [50].
16. The biochar quality rate (NR) ranges from 5 to 10%, depending on nutrient content (NPK) of biochar (0–2%).
17. The setup and breakdown of the portable refinery unit is a day, and the mileage charge is \$1.6 per mile (\$1 per km) [71].

The distance between large dairies is defined, using the shortest path, calculated using ArcGIS software. For the main case study, two portable refinery units are deployed for dairies 1–3 (with over 45,000 cows) and dairies 4–10 (with around 70,000 cows), as shown in Fig. 6. The mean (μ) and variance (σ^2) for stochastic constraints (Eqs. (9) and (10)) in the techno-economic model are calculated for each dairy location, using the simulated datasets. The probability of manure and biochar quality rates (i.e., PR and NR) and average manure and biochar quality rates (i.e., *MQ* and *BQ*) are calculated, using datasets and SVM approach. PR and NR are probabilities, which are between 0 and 1. Dairy locations that have *MQ* and *BQ* below the defined average rate represent sites with low-quality manure or low-quality biochar that will be excluded from the final decision. Decision makers can simplify this setting by reducing the number of dairies and selecting qualified large dairies with a sufficient amount of low-moisture-content manure.

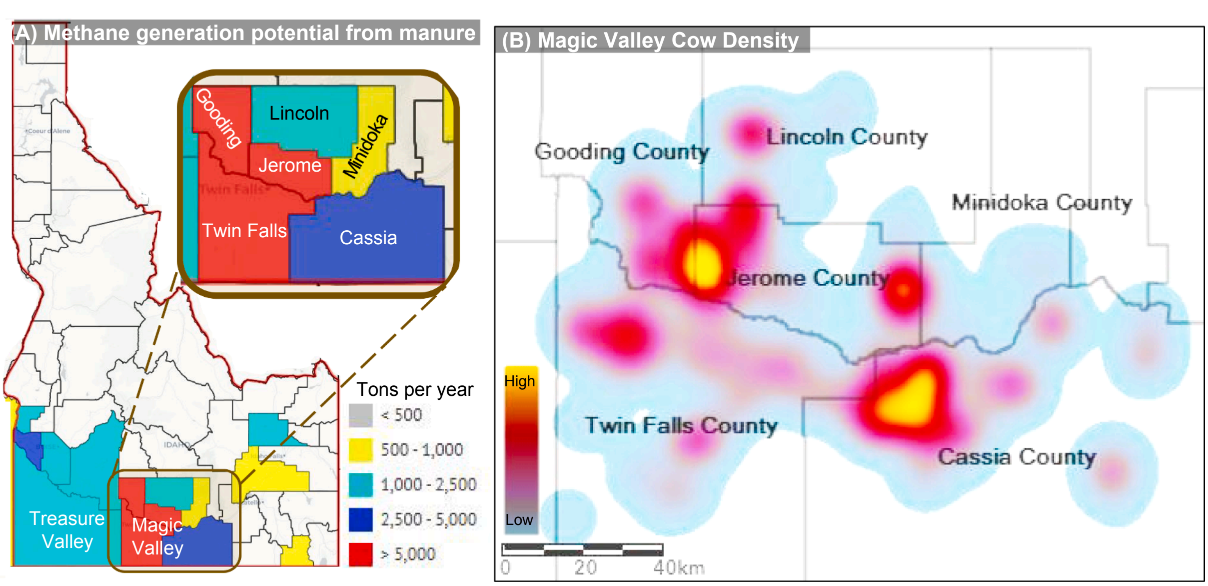


Fig. 5. (A) Methane generation potential from animal manure (tons per year) in Southern Idaho; (B) six Idaho counties considered in our case study (ArcGIS 2019) – the map uses cool (blue) and warm (yellow and red) colors for low (3–10k) and high (over 10k) cows, respectively.

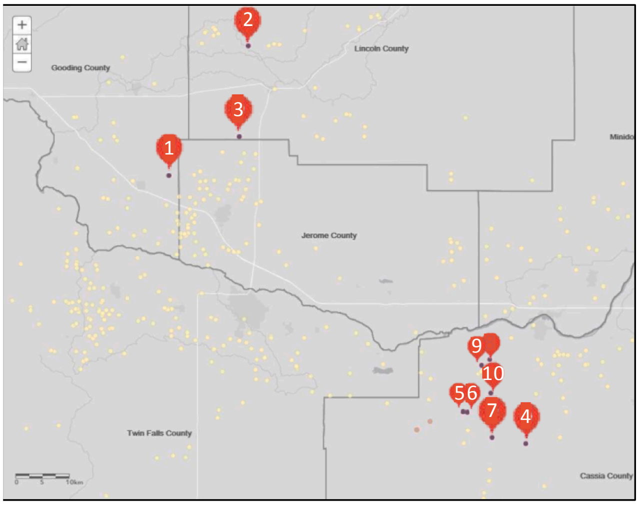


Fig. 6. Large dairies involved in the main case study with over 10,000 cows in each dairy (ArcGIS 2019).

4. Results

According to the International Biochar Initiative (IBI) and European Biochar Certificate (EBC), biochar above 50% carbon content classifies as high quality, and below 50% carbon content classifies as pyrogenic carbonaceous material [74,75]. The elemental analyses performed by two analytical laboratories (i.e., BYU Environmental Analytical Lab and Huffman Hazen) indicate that the carbon content is around 25% and ash content is over 58%, along with nutrients, such as 1.5% nitrogen, 0.4 phosphates, and 1.5% potassium. The main chemical component of ash is carbon, which is produced during incomplete combustion. Based on the IBI and EBC classification, the produced manure-based biochar in this study could be classified as nutrient-rich carbonized biomass or high-quality biochar.

Several studies investigated various feedstocks (e.g., livestock manure, poultry litter, and agriculture residues) and production process parameters (e.g., operation temperature and reactor type) for producing nutrient-rich biochar [76–78]. Atienza-Martinez et al. (2019) assessed various production parameters for producing nutrient-rich biochar from dairy manure [79]. Their results indicate that the properties of biochar mainly depended on pyrolysis process temperature, but the reactor type (e.g., fast or slow pyrolysis) did not have a significant effect. Tsai et al. (2019) performed experiments to produce highly porous, nutrient-rich biochar from dairy manure [80]. They concluded that the produced biochar is a promising soil amendment because of the high porosity and the abundance of nutrients. Lehmann et al. (2015) reviewed biochar nutrient concentrations for various feedstocks (e.g., agricultural residue, forest residue, and animal manure) and pyrolysis process parameters (e.g., reaction temperature) [76]. They concluded that manure-based biochars have noticeably higher nutrient content (e.g., nitrogen, phosphorous, and potassium) compared to biochar produced from other feedstock types, and pyrolysis process configurations can slightly affect the nutrient content of biochar.

Table 4 shows the results of proximate and ultimate analyses, including the properties of raw manure and produced biochar, and compares the empirical and Aspen HYSYS model results for validating the simulated model. Certain physicochemical properties (e.g., nutrient levels) were not able to be determined by the HYSYS simulation and have been left blank.

According to the HYSYS simulation, about 162 MW total energy was required to convert 50 metric tons of manure into biochar. Particularly, 26.57 MW was used for the preheater, 54.61 MW for the pyrolysis reactor, and 80.84 MW for the chiller. The required energy in the case study was provided by reusing intermediate products (e.g., bio-oil and gas) for pretreatment purposes (i.e., heat and electricity), as well as the combustion of fossil fuels. Biochar nutrient levels for carbon, nitrogen, phosphorous, and potassium in the empirical studies are in line with those found in the literature [76–78].

Table 4
Properties of raw manure and produced biochar.

	Empirical studies		Aspen HYSYS model	
	Manure	Biochar	Manure	Biochar
Proximate analysis				
Ash content (% w/w)	15.70	58.87	15.70	42.37
Volatile matter (% w/w)	56.4	26.8	–	–
pH	7.30	7.30	–	–
HHV (BTU/lb)	6455	3362	–	–
Ultimate analysis				
Fixed carbon (% w/w)	17.30	12.40	17.30	16.31
Carbon (% w/w)	38.38	23.21	39.38	23.17
Hydrogen (% w/w)	5.17	1.79	5.79	3.70
Nitrogen (% w/w)	2.50	1.51	2.12	0.08
Sulfur (% w/w)	0.45	0.29	–	–
Phosphorous (% w/w)	0.29	0.45	–	–
Potassium (% w/w)	1.41	1.58	–	–
Oxygen (% w/w)	37.80	14.33	37.52	18.91

4.1. Techno-economic results

The number of feasible and infeasible computational solution combinations are 2^{10} (1024). The optimal solution after 500 iterations reports that 32,800 tons of cattle manure in the selected ten dairies would be converted to 11,480 tons of biochar and 14,760 tons of bio-oil (about 3.25 million gallons) over a one-year time horizon. The total cost and unit biochar cost for the main case with two portable refinery units are estimated at $2,722,746 per year and $237 per metric ton, respectively. The total cost and unit biochar cost for a single portable refinery unit are predicted to be $1,576,615 per year and $274 per metric ton, respectively. Table 5 presents the capital and operational costs of each point and process. Approximately 80% of the total cost is due to operational cost and 20% due to capital cost. The major operational cost is drying during the pretreatment phase. It is possible to reduce the drying cost if the manure is allowed to dry naturally in the field before mechanical drying or if the other pyrolysis products (e.g., gas and bio-oil) are combusted to produce drying heat [81,82]. The cost of electricity used was the average retail price of $0.08/kWh as reported in the most recent U.S. Energy Information Administration for the Idaho state electricity profile (2018) [83].

While the cost per metric ton of biochar estimated in this study is lower than in some other biochar economic studies, there is considerable uncertainty and volatility in biochar prices that make the future of the biochar market difficult to predict [43,87]. Until a biochar market price

Table 5
Detailed capital and operational costs, as well as the annual utilization rate of each process.

Point to point[a]	Process	Capital Cost ($/yr)	Variable Cost ($/yr)	Annual utilization rate (metric ton/yr)	Reference
a to b	Collection	84,996	236,827	60,000	[85,85]
a to b	Grinding	164,044	582,656	37,500	[72]
a to b	Drying	81,337	862,686	37,500	[73]
a to b	Conversion	228,201	49,536	16,400	[86]
b to c	Char storage	80,798	167,034	11,480	[85]
b to d	Oil storage	182,653	–[b]	14,760	[85]
c to e	Transportation	71,455	285,846	50,000	[71]

[a] Points as shown in Fig. 4. a: Set of collection sites, b: Set of conversion sites, c: Set of biochar storage sites, d: Set of bio-oil storage sites, e: Set of biochar distribution centers.
[b] Considered in portable refinery variable cost.

is well established, it is complicated to predict the exact profitability for any biochar production technology.

4.2. Environmental assessment results

LCA was performed for the conversion of raw manure into energy, using the portable pyrolysis refinery unit to delve into sustainable approaches across the manure life cycle. The majority of GHG emissions is CO_2 (68% of GHGs) generated from the pyrolysis unit, transportation, and machinery operation (Table 6). While the amount of CO_2 is significantly greater than CH_4 and N_2O, the latter two gases have much larger GWP and significant contribution to the overall climate change impact of the process. Looking strictly at the conversion process, the major contributing factors to environmental impact are the combustion of fuels for powering the machinery (e.g., grinder, dryer, and transportation), the water vapor generated while running the manure through the dryer, and gas emission from the pyrolysis unit.

Table 7 shows the environmental impact of processing 50 metric tons of manure per day. Based on this analysis, C footprint, human toxicity, and photochemical oxidation would be the main environmental concerns, which could lead to adverse outcomes, such as climate change, detriment to respiratory health, and crop failure. Aguirre-Villegas et al. (2017) assessed dairy manure management practices in Wisconsin, USA, using LCA and survey data [88]. The results of the study showed GHG emissions per ton of manure range from 34 to 132 kg CO_2-eq for total manure management practices. GHG emissions from the manure-to-bioproducts pathway generate 172 kg CO_2-eq, having a similar level of impact on GWP as conventional manure management practices.

Pareto analysis was also performed for assessing the environmental impacts of process emissions (Fig. 7). This analysis presents a comparison of the impacts of each GHG emission on overall GWP. Each emission is converted into kg CO_2 eq. in order to accurately compare the impact. Pareto analysis follows the 80/20 rule, where 20% of the emissions cause 80% of the impact. While not always the case, this assumption and the corresponding analysis is extremely useful when determining potential processes requiring special attention.

Analyzing the pretreatment stage shows that the emissions from fuel combustion had little impact compared to the other emissions. Rather, water vapor emitted at the pretreatment stage had the highest environmental impact for drying the raw manure from 50% to <5% moisture content that contributes approximately 80% of total emission-related GWP. While reducing this component is not easy due to the need for drying manure prior to pyrolysis, condensing and coupling water vapor with other uses, such as on-site energy supply could be an option, although it may be commercially unfavorable. Emission from the pyrolysis stage mostly consists of incondensable gases. These byproducts are known collectively as pyrolysis gas, which is composed of nitrogen gas with noticeable amounts of carbon monoxide, carbon dioxide, and methane, as well as exiting N_2 gas that serves as an inert gas in the pyrolysis process. The produced gas has the potential to be captured and used as a heat or power source, as it is similar to natural gas in terms of composition but with a lower heating value [70].

According to the case study, 172.8 kg CO_2 eq. is emitted to produce one metric ton of biochar. Fig. 8 compares the GHG emissions (kg CO_2 eq. per ton and metric ton CO_2 eq. per year) from the proposed biochar production with traditional manure management practices [89]. It is shown that the proposed manure-to-bioproducts conversion produces significantly less emissions than other practices per ton of dry manure. This study does not consider GHG emissions from land application of manure, which has larger N_2O emissions than during manure storage [90]. Therefore, the overall environmental benefits of the proposed manure-to-bioproducts conversion could be even greater than the calculated results of this study. Besides carbon footprint, human toxicity impact of manure-to-bioproducts conversion is estimated as 0.18 kg 1,4-dichlorobenzene eq. for one metric ton of biochar. Methane is the sole contributor to photochemical oxidation impact. Manure can lead to environmental pollution when overapplied on cropland or when discharged to surface water with runoff [91]. Pathogens in manure affect soil and water quality with a consequent risk to human health through the food chain [92]. The manure-to-biochar conversion process is

Table 6
Manure-to-bioproducts total pathway emissions for 50 metric tons of manure.

Emissions	Amount	Unit
Water vapor	1.9E+4	kg
Nitrogen	2950	kg
CO_2	1333	kg
CO (biogenic)	1174	kg
Hydrogen	630	kg
Methane	261	kg
Nitrogen oxides	2.17	kg
CO	0.35	kg
NMVOC	0.20	kg
Particulates < 2.5 um	0.10	kg
Particulates, > 2.5 um < 10um	5.4E-3	kg
N_2O	1.9E-3	kg

NMVOC: non-methane volatile organic compounds.

Table 7
Life cycle impact assessment data, using CML baseline.

Impact Category	Result	Reference Unit
Acidification	1.08	kg SO_{-2} eq.
Eutrophication	0.28	kg PO_4 eq.
Freshwater Aquatic Ecotoxicity	0	kg 1,4-dichlorobenzene eq.
Climate Change (GWP 100)	8642	kg CO_2 eq.
Human Toxicity	2.68	kg 1,4-dichlorobenzene eq.
Marine Aquatic Ecotoxicity	0	kg 1,4-dichlorobenzene eq.
Ozone Layer Depletion	0	kg CFC-11 eq.
Photochemical Oxidation	1.57	kg C_2H_4 eq.
Terrestrial Ecotoxicity	0	kg 1,4-dichlorobenzene eq.

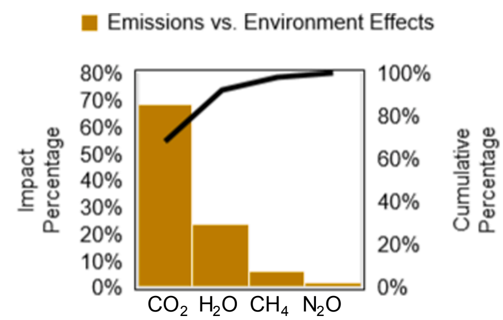


Fig. 7. Pareto analysis of the impact of each emission on the environment.

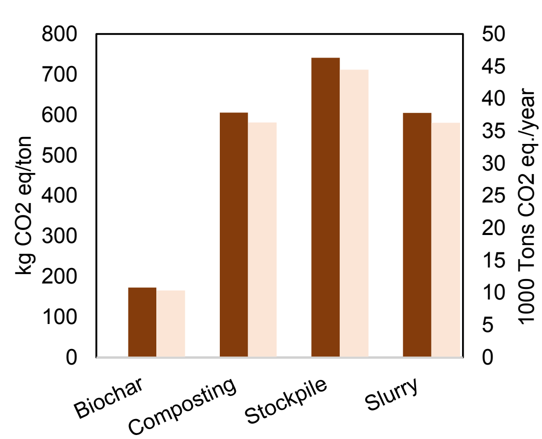


Fig. 8. Emissions produced from processing one ton of dry manure and emissions per year for the case study area.

suggested to have minimal acidification and eutrophication impacts, thus having advantages over conventional manure land application from the water quality perspective. Key contribution to these impacts was the combustion of diesel to run machinery and power transportation. Recycling gas and oil produced during operation to produce heat and power could help in alleviating the impact of GWP, as well as decreasing diesel consumption, subsequently lowering acidification and eutrophication impacts. In the future, more detailed post-processing data of pyrolysis products could be used to further refine environmental assessment results.

5. Sensitivity analysis and discussion

There are several major parameters that can affect the economic and environmental outcomes of the production process. Sensitivity analysis used herein explores the effect of the associated cost and GHG emission parameters as two major contributors to the economic and environmental performance. Key variables analyzed in this study include the number of portable refinery units and the refinery costs, as well as manure moisture content. Four scenarios are investigated and compared with the main case study, which provides insights into parameter tuning. Additionally, we conducted the cause and effect analysis to examine the key parameters that contribute to manure-to-biochar sustainability. The cause and effect (fishbone) diagram shows the facets of economic, environmental, and safety challenges, as well as the potential causes throughout the manure-to-biochar life cycle (Fig. 9).

5.1. Effect of raw manure moisture content

The pretreatment stage (i.e., size reduction and drying) is one of the main commercialization barriers for biochar production. Since the moisture content of raw manure can vary depending on conditions, we investigated the effect of this element on the commercial feasibility of biochar production. Two additional cases were considered, in Case 1, the manure moisture content is 15% less than in the main case study, and in Case 2, the manure moisture content is 15% more than in the main case study. GHG emissions and production costs are found to change monotonically with the moisture content of raw manure (Fig. 10). Compared to the main case study, Case 1 could decrease GHG emissions by 10 kg CO_2 eq. per metric ton of biochar (1.1%) while Case 2 could increase GHG emissions by 3.3 kg CO_2 eq. per metric ton of biochar (0.3%). The change in the cost would also mirror this trend due to the change in energy (e.g., diesel) required for drying. Compared to the main case study, Case 1 would decrease the biochar production cost by 5%, and Case 2 would increase the cost by ~ 8% (Table 8).

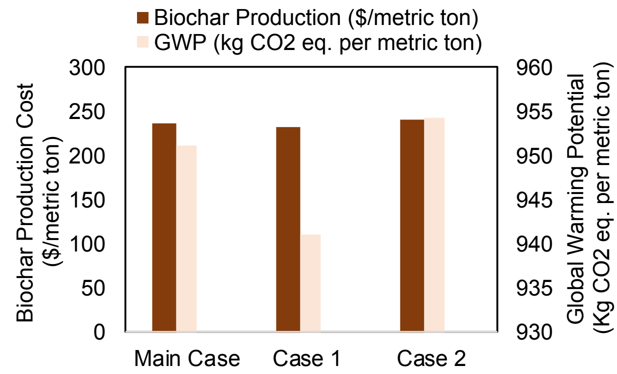


Fig. 10. Effect of raw manure moisture content on economic and environmental aspects (moisture content of Main Case, Case 1, and Case 2 are 80%, 65%, and 95%, respectively).

5.2. Effect of portable refinery units

In the main case, the total amount of manure (1,404,000 metric tons per year or ~3846 tons per day) is based on the amount available in 10 selected feedlots in the Twin Falls area. This annual manure amount requires the use of multiple refinery units, assuming a processing capacity of 50 metric tons per day for each unit. The number of portable refineries could affect the total annual cost of the collection-processing-distribution network flow and the total annual GHG emissions. This

Table 8
Effect of the moisture content of raw manure on cost and environmental impacts.

Cases	Moisture Content (%)	Biochar Production ($/metric ton)	GWP (kg CO2 eq. per metric ton)
Main Case	80	237	951.1
Case 1 (−15%)	65	233	941.1
Case 2 (+15%)	95	242	954.4

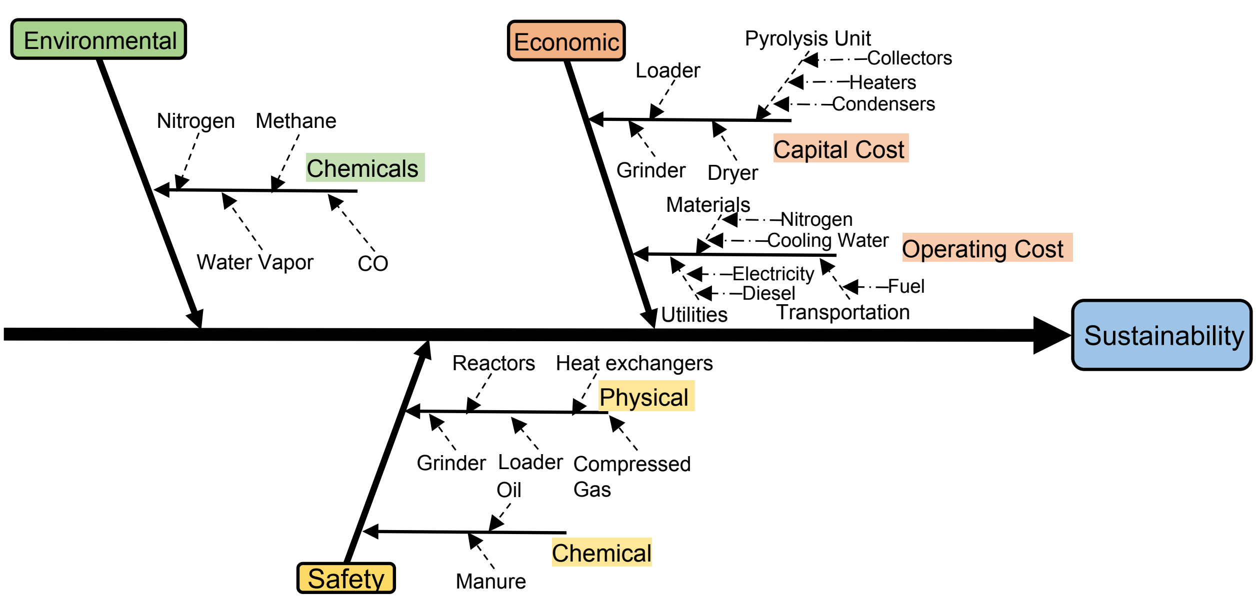


Fig. 9. Fishbone diagram of process sustainability.

study considered two cases in addition to the main case that employs two refineries. In Case 3, the number of refineries is decreased to one, and in Case 4, the number of refineries is increased to four.

Total biochar production cost is found to change monotonically with the number of portable refineries utilized (Fig. 10). Compared to the main case study, in Cases 3 and 4, biochar production cost per metric ton could increase by around 16% and decrease by about 8%, respectively (Table 9). Optimally, utilizing four portable refineries in Case 4 produces the largest amount of biochar for the lowest cost. While a higher number of refineries would increase environmental impacts of biomass collection, size reduction, and transport per day of operation, it would only slightly increase (0.1%) the environmental impacts per metric ton of biochar. Emissions released during upstream operations have a detrimental effect on environmental performance because these operations mostly rely on energy provided by fossil fuel. GWP 100 could increase by 42 kg CO_2 eq. per metric ton of biochar (4.4%) in Case 3 and decrease by 1.1 kg CO_2 eq. per metric ton of biochar (0.1%) in Case 4, with respect to the main case (Fig. 11).

Due to the high level of uncertainty associated with future prices of biofuel and biochar, market prices of these bioproducts have been reported to have the largest impact on the net present value of main critical variables [43]. According to Laird (2009), the optimal amount of biochar for soil amendment is between 20 and 25 tons per acre. However, significant improvements to crop growth can be seen with as little as 0.9–2.2 tons per acre [93]. Assuming biochar price points between $231-$283, the soil application cost could be anywhere between $208-$623 per acre [32]. In this study, the resulting unit price for biochar production ($/ton) from cattle manure, using the developed Genetic Algorithm computational solution, indicates a reasonable comparison to the prices reported in recently published studies of operations with similar capacity (Table 10). Recycling agricultural organic materials has the potential to address several national priorities (e.g., food security, energy security, water security) and sustainability challenges (e.g., environmental pollution from petroleum-derived products). Besides, using nutrient-rich biomass for biochar production and subsequent soil application is one of the most promising approaches for biomass management and sustainable agriculture as this practice could simultaneously reduce the risk of agricultural runoff-introduced nutrient loading and improve crop growth and yields [21,94].

It should be noted that biochar-based soil conditioner has many environmental benefits, which are not the focus of the current study (Fig. 4). Future research should extend environmental assessment for the cradle-to-grave system boundary to include biochar-based soil amendment that can facilitate the monetization of environmental benefits and avoided environmental costs, such as soil degradation and water pollution [95].

6. Conclusions

Producing biochar from animal manure is a potential approach to address several sustainability challenges, including manure management, inorganic fertilizer overuse, water-nutrient pollution due to agricultural runoff, and integrated crop-livestock farming. In addition, manure-based biochar can promote carbon management systems and GHG emission mitigation efforts. This study focuses on converting cattle manure to value-added products (e.g., biochar and bio-oil), using mixed pyrolysis reactors (i.e., fast and slow pyrolysis). The proposed evaluation procedure for multi-criteria decision making can overcome the existing deficiencies of earlier published studies, which are: (i) inconsistencies in addressing multiple aspects of sustainability (i.e., economic and environmental), (ii) incorporation of uncertainties in biomass supply and pretreatment requirements, and (iii) effective multi-criteria decision support system and computational solution that can facilitate decision making analysis. This study integrates technological aspects of manure-based biochar production with sustainability concepts in order to address commercialization challenges by exploring the economic and environmental feasibility, uncertainty parameters, mixed reactors, and portable conversion process. The results show that the proposed conversion pathway and method can reduce the bioproduct production cost and manure environmental impacts, and enhance sustainability benefits across manure-to-biochar supply chains. This study motivates the need for efficient pretreatment processes and distributed refineries to address the upstream and midstream challenges (e.g., collection, transportation, and dewatering) to convert manure-to-biochar near the collection sites. The developed multi-criteria decision making approach utilizes various methods to support and scale up sustainable biochar production. The results can be translated to other regions and countries to mitigate the negative impact of intensive livestock farming while promoting sustainable agriculture. Potential directions for future research include (i) exploration of smart production technology to increase the conversion process yield and reduce the energy used, (ii) exploration of social aspects to investigate the triple bottom line with associated uncertainties, and (iii) exploration of other technologies, system designs, and products

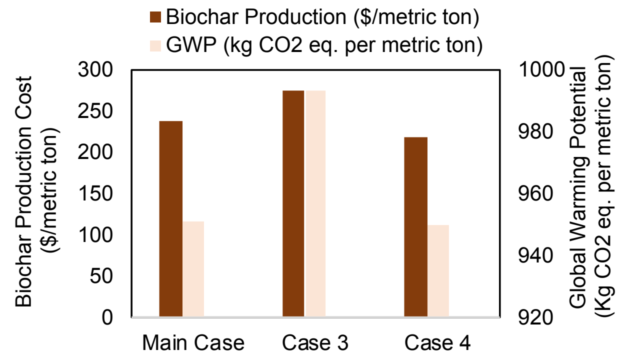


Fig. 11. Effect of utilized portable refinery units on economic and environmental aspects (number of refineries in Main Case, Case 3, and Case 4 are 2, 1, and 4, respectively).

Table 9
Effect of the number of portable refineries on cost and environmental impact.

Cases	Portable Refineries	Biochar Production ($/metric ton)	GWP (kg CO_2 eq. per metric ton)
Main Case	2	237	951.1
Case 3	1	274	993.3
Case 4	4	218	950.0

Table 10
Reported biochar production cost in recent studies.

Reference	Technology	Capacity (ton/day)	Biomass type	Cost ($/ton)	Year
[33]	Slow Pyrolysis[a]	20,000	Pinewood	220–280	2014
[32]	Fast Pyrolysis/ Gasifier[a]	36	Poultry Litter	228–280	2015
[34]	Fast Pyrolysis	6.4	Biosolids	100–400	2019
[35]	Slow Pyrolysis	12	Forest Residue	1044	2019
[41]	Fast pyrolysis[b]	2,000	Rice, Corn, Peanut	75–248, 87–250, 680–1272	2019
[25]	Auger Pyrolysis	151	Wood	474–704	2019
This study	Mixed fast and slow pyrolysis	50	Cattle manure	218–274	2019

[a] Results generated by simulation software.
[b] Case study performed in California, Iowa, and Florida, respectively.

to identify the viable commercial pathways and support bioenergy industry.

CRediT authorship contribution statement

Ethan Struhs (ES) performed the laboratory experiments and received funding; Amin Mirkouei and ES analyzed the data and wrote the paper. Others contributed to the conceptual development and experimental design, as well as revised the manuscript.

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.

Acknowledgements

The authors wish to acknowledge Dr. Michael McKellar (University of Idaho) for his technical inputs on Aspen HYSYS simulation modeling, Dr. Kathleen Lohse (Idaho State University) for inspiring discussions and suggestions, and Dr. Lide Chen (University of Idaho) for providing raw manure used in the experiments, as well as University of Idaho (EIS Grant) and Idaho State University (DCP Grant) for funding this project. The authors also acknowledge the support from the Center for Advanced Energy Studies (CAES).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.115782.

References

[1] NOAA. Carbon dioxide levels in atmosphere hit record high in May 2019. https://www.noaa.gov/news/carbon-dioxide-levels-in-atmosphere-hit-record-high-in-may.
[2] Belmonte BA, Benjamin MFD, Tan RR. Bi-objective optimization of biochar-based carbon management networks. J Clean Prod 2018;188:911–20. https://doi.org/10.1016/j.jclepro.2018.04.023.
[3] Kleiner K. The bright prospect of biochar. Nat Clim Change 2009;1:72–4. https://doi.org/10.1038/climate.2009.48.
[4] Lee J, Yang X, Cho S-H, Kim J-K, Lee SS, Tsang DC, et al. Pyrolysis process of agricultural waste using CO2 for waste management, energy recovery, and biochar fabrication. Appl Energy 2017;185:214–22.
[5] Uchimiya M, Lima IM, Klasson KT, Wartelle LH. Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. Chemosphere 2010;80:935–40. https://doi.org/10.1016/j.chemosphere.2010.05.020.
[6] Lian F, Xing B. Black carbon (biochar) in water/soil environments: molecular structure, sorption, stability, and potential risk. Environ Sci Technol 2017;51:13517–32. https://doi.org/10.1021/acs.est.7b02528.
[7] Xiao X, Chen B, Chen Z, Zhu L, Schnoor JL. Insight into multiple and multilevel structures of biochars and their potential environmental applications: a critical review. Environ Sci Technol 2018;52:5027–47. https://doi.org/10.1021/acs.est.7b06487.
[8] Leng L, Huang H. An overview of the effect of pyrolysis process parameters on biochar stability. Bioresour Technol 2018;270:627–42. https://doi.org/10.1016/j.biortech.2018.09.030.
[9] Biederman LA, Harpole WS. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy 2012;5:202–14. https://doi.org/10.1111/gcbb.12037.
[10] Yao Y, Gao B, Chen J, Yang L. Engineered biochar reclaiming phosphate from aqueous solutions: mechanisms and potential application as a slow-release fertilizer. Environ Sci Technol 2013;47:8700–8.
[11] Agegnehu G, Nelson PN, Bird MI. Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. Soil Tillage Res 2016;160:1–13. https://doi.org/10.1016/j.still.2016.02.003.
[12] Hayyat A, Javed M, Rasheed I, Ali S, Shahid MJ, Rizwan M, et al. Role of biochar in remediating heavy metals in soil. Phytoremediation, Springer; 2016. p. 421–37.
[13] Santos FM, Pires JC. Nutrient recovery from wastewaters by microalgae and its potential application as bio-char. Bioresour Technol 2018;267:725–31.
[14] Gerlach Achim, Schmidt Hans-Peter. The use of biochar in cattle farming 2012. http://www.ithaka-journal.net/pflanzenkohle-in-der-rinderhaltung?lang=en [accessed January 7, 2020].
[15] Tan X, Liu S, Liu Y, Gu Y, Zeng G, Hu X, et al. Biochar as potential sustainable precursors for activated carbon production: multiple applications in environmental protection and energy storage. Bioresour Technol 2017;227:359–72. https://doi.org/10.1016/j.biortech.2016.12.083.
[16] Cha JS, Park SH, Jung S-C, Ryu C, Jeon J-K, Shin M-C, et al. Production and utilization of biochar: a review. J Ind Eng Chem 2016;40:1–15. https://doi.org/10.1016/j.jiec.2016.06.002.
[17] Ali I. Water treatment by adsorption columns: evaluation at ground level. Sep Purif Rev 2014;43:175–205. https://doi.org/10.1080/15422119.2012.748671.
[18] Jeffery S, Verheijen FGA, van der Velde M, Bastos AC. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 2011;144:175–87. https://doi.org/10.1016/j.agee.2011.08.015.
[19] Mirkouei A, Kardel K. Enhance sustainability benefits through scaling-up bioenergy production from terrestrial and algae feedstocks.In: Proc. 2017 ASME IDETCCIE 22nd Des. Manuf. Life Cycle Conf.; 2017.
[20] Mirkouei A. Techno-economic optimization and environmental impact analysis for a mixed-mode upstream and midstream forest biomass to bio-products supply chain. Oregon State University; 2016.
[21] Hersh B, Mirkouei A, Sessions J, Rezaie B, You Y. A review and future directions on enhancing sustainability benefits across food-energy-water systems: the potential role of biochar-derived products. AIMS Environ Sci 2019;6:379.
[22] Hansen S, Mirkouei A, Diaz LA. A comprehensive state-of-technology review for upgrading bio-oil to renewable or blended hydrocarbon fuels. Renew Sustain Energy Rev 2020;118:109548. https://doi.org/10.1016/j.rser.2019.109548.
[23] Hansen S, Mirkouei A. Past infrastructures and future machine intelligence (MI) for biofuel production: a review and MI-based framework. American Society of Mechanical Engineers; 2018. https://doi.org/10.1115/DETC2018-86150.
[24] Delaney M. Northwest Biochar commercialization strategy paper. U.S. Forest Service and the Oregon Department of Forestry; 2015.
[25] Sessions J, Smith D, Trippe KM, Fried JS, Bailey JD, Petitmermet JH, et al. Can biochar link forest restoration with commercial agriculture? Biomass Bioenergy 2019;123:175–85.
[26] Wrobel-Tobiszewska A, Boersma M, Sargison J, Adams P, Jarick S. An economic analysis of biochar production using residues from Eucalypt plantations. Biomass Bioenergy 2015;81:177–82.
[27] Mohammadi A, Cowie AL, Cacho O, Kristiansen P, Anh Mai TL, Joseph S. Biochar addition in rice farming systems: economic and energy benefits. Energy 2017;140:415–25. https://doi.org/10.1016/j.energy.2017.08.116.
[28] Mirkouei A, Mirzaie P, Haapala KR, Sessions J, Murthy GS. Reducing the cost and environmental impact of integrated fixed and mobile bio-oil refinery supply chains. J Clean Prod 2016;113:495–507.
[29] Mirkouei A, Haapala KR, Sessions J, Murthy GS. A mixed biomass-based energy supply chain for enhancing economic and environmental sustainability benefits: a multi-criteria decision making framework. Appl Energy 2017;206:1088–101. https://doi.org/10.1016/j.apenergy.2017.09.001.
[30] Rosas JG, Gómez N, Cara J, Ubalde J, Sort X, Sánchez ME. Assessment of sustainable biochar production for carbon abatement from vineyard residues. J Anal Appl Pyrolysis 2015;113:239–47. https://doi.org/10.1016/j.jaap.2015.01.011.
[31] Panwar NL, Pawar A, Salvi BL. Comprehensive review on production and utilization of biochar. SN Appl Sci 2019;1:168. https://doi.org/10.1007/s42452-019-0172-6.
[32] Huang Y, Anderson M, McIlveen-Wright D, Lyons GA, McRoberts WC, Wang YD, et al. Biochar and renewable energy generation from poultry litter waste: a technical and economic analysis based on computational simulations. Appl Energy 2015;160:656–63. https://doi.org/10.1016/j.apenergy.2015.01.029.
[33] Shabangu S, Woolf D, Fisher EM, Angenent LT, Lehmann J. Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts. Fuel 2014;117:742–8. https://doi.org/10.1016/j.fuel.2013.08.053.
[34] Patel S, Kundu S, Paz-Ferreiro J, Surapaneni A, Fouche L, Halder P, et al. Transformation of biosolids to biochar: a case study. Environ Prog Sustain Energy 2019;38:13113. https://doi.org/10.1002/ep.13113.
[35] Sahoo K, Bilek E, Bergman R, Mani S. Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. Appl Energy 2019;235:578–90. https://doi.org/10.1016/j.apenergy.2018.10.076.
[36] Mirkouei A, Haapala KR, Sessions J, Murthy GS. A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains. Renew Sustain Energy Rev 2017;67:15–35.
[37] Oldfield TL, Sikirica N, Mondini C, López G, Kuikman PJ, Holden NM. Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon. J Environ Manage 2018;218:465–76.
[38] Mirkouei A, Haapala KR, Sessions J, Murthy GS. Reducing greenhouse gas emissions for sustainable bio-oil production using a mixed supply chain. In: ASME 2016 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., American Society of Mechanical Engineers; 2016. p. V004T05A031.
[39] Azzi ES, Karltun E, Sundberg C. Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. Environ Sci Technol 2019;53:8466–76. https://doi.org/10.1021/acs.est.9b01615.
[40] Thers H, Djomo SN, Elsgaard L, Knudsen MT. Biochar potentially mitigates greenhouse gas emissions from cultivation of oilseed rape for biodiesel. Sci Total Environ 2019;671:180–8. https://doi.org/10.1016/j.scitotenv.2019.03.257.
[41] Li W, Dumortier J, Dokoohaki H, Miguez FE, Brown RC, Laird D, et al. Regional techno-economic and life-cycle analysis of the pyrolysis-bioenergy-biochar platform for carbon-negative energy. Biofuels Bioprod Biorefining 2019.

[42] Rajabi Hamedani S, Kuppens T, Malina R, Bocci E, Colantoni A, Villarini M. Life cycle assessment and environmental valuation of biochar production: two case studies in Belgium. Energies 2019;12:2166. https://doi.org/10.3390/en12112166.
[43] Campbell RM, Anderson NM, Daugaard DE, Naughton HT. Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. Appl Energy 2018;230:330–43. https://doi.org/10.1016/j.apenergy.2018.08.085.
[44] El Hanandeh A. Carbon abatement via treating the solid waste from the Australian olive industry in mobile pyrolysis units: LCA with uncertainty analysis. Waste Manag Res 2013;31:341–52. https://doi.org/10.1177/0734242X12465317.
[45] Li B, Ou L, Dang Q, Meyer P, Jones S, Brown R, et al. Techno-economic and uncertainty analysis of in situ and ex situ fast pyrolysis for biofuel production. Bioresour Technol 2015;196:49–56. https://doi.org/10.1016/j.biortech.2015.07.073.
[46] Bushell A. A pricing model and environmental impact analysis for manure-based biochar As a soil amendment. PhD Thesis. Duke University; 2018.
[47] Mau V, Gross A. Energy conversion and gas emissions from production and combustion of poultry-litter-derived hydrochar and biochar. Appl Energy 2018;213:510–9.
[48] Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, et al. Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ Sci Technol 2009;43:12–9. https://doi.org/10.1021/es801217q.
[49] Lysyk TJ, Easton ER, Evenson PD. Seasonal changes in nitrogen and moisture content of cattle manure in cool-season pastures. J Range Manag 1985;38:251. https://doi.org/10.2307/3898978.
[50] Augustin C, Rahman S. Composting animal manures: a guide to the process and management of animal manure compost; 2010.
[51] Choudhury HA, Chakma S, Moholkar VS. Biomass gasification integrated Fischer-Tropsch synthesis. Recent Adv Thermo-Chem Convers Biomass Elsevier 2015: 383–435. https://doi.org/10.1016/B978-0-444-63289-0.00014-4.
[52] Brinker RW, Miller D, Stokes BJ, Lanford BL. Machine rates for selected forest harvesting machines. Circ 296 Revis Ala Agric Exp Stn Auburn Univ; 2002.
[53] U.S. Bureau of Labor Statistics. Producer Price Index by Commodity for Machinery and Equipment: Engineering and Scientific Instruments. FRED Fed Reserve Bank St Louis 1985. https://fred.stlouisfed.org/series/WPU1185 [accessed November 7, 2019].
[54] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 2012;38:68–94. https://doi.org/10.1016/j.biombioe.2011.01.048.
[55] Dickerson T, Soria J. Catalytic fast pyrolysis: a review. Energies 2013;6:514–38.
[56] Manyà JJ. Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. Environ Sci Technol 2012;46:7939–54. https://doi.org/10.1021/es301029g.
[57] Lorimor Jeff, Powers Wendy. Sutton Al. Manure Characterisitics; 2004.
[58] Brewer CE, Schmidt-Rohr K, Satrio JA, Brown RC. Characterization of biochar from fast pyrolysis and gasification systems. Environ Prog Sustain Energy 2009;28: 386–96. https://doi.org/10.1002/ep.10378.
[59] Enders A, Hanley K, Whitman T, Joseph S, Lehmann J. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresour Technol 2012; 114:644–53. https://doi.org/10.1016/j.biortech.2012.03.022.
[60] Eghball B, Power JF, Gilley JE, Doran JW. Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 1997;26:189. https://doi.org/10.2134/jeq1997.00472425002600010027x.
[61] Sandars DL, Audsley E, Cañete C, Cumby TR, Scotford IM, Williams AG. Environmental benefits of livestock manure management practices and technology by life cycle assessment. Biosyst Eng 2003;84:267–81. https://doi.org/10.1016/S1537-5110(02)00278-7.
[62] Aguirre-Villegas H, Larson RA, Ruark MD. Methane emissions from dairy cattle: an overview; 2016:5.
[63] Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour Technol 2012;107:419–28. https://doi.org/10.1016/j.biortech.2011.11.084.
[64] IPCC. 2.10.2 Direct Global Warming Potentials - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing; 2007.
[65] OpenLCA. The source for LCA datasets 2019. https://nexus.openlca.org/database/Agribalyse.
[66] USDA. National Agricultural Statistics Service 2019. https://www.nass.usda.gov/Statistics_by_State/Idaho/Publications/Livestock_Press_Releases/2019/CE_CAT.pdf.
[67] USDA. Animal Manure Management 2019. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211.
[68] USDA. Milk Production 2019. https://www.nass.usda.gov/Publications/Todays_Reports/reports/mkpr0419.pdf [accessed February 4, 2020].
[69] Idaho State Department of Agriculture. Idaho Livestock 2017. https://agri.idaho.gov/main/idaho-livestock/ [accessed February 4, 2020].
[70] Lauer M, Hansen JK, Lamers P, Thrän D. Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry. Appl Energy 2018;222:621–36. https://doi.org/10.1016/j.apenergy.2018.04.026.
[71] Zamora-Cristales R, Sessions J, Murphy G, Boston K. Economic impact of truck-machine interference in forest biomass recovery operations on steep terrain. For Prod J 2013;63:162–73. https://doi.org/10.13073/FPJ-D-13-00031.
[72] Anderson N, Chung W, Loeffler D, Jones JG. A productivity and cost comparison of two systems for producing biomass fuel from roadside forest treatment residues. For Prod J 2012;62:222–33. https://doi.org/10.13073/0015-7473-62.3.222.
[73] Zhou J. Case study: thermal design of a biomass drying process using low grade heat from steel industry; 2011.
[74] IBI. Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil; 2015.
[75] Hans-Peter Schmidt. European Biochar Certificate (EBC) - guidelines version 6.1 2015. https://doi.org/10.13140/RG.2.1.4658.7043.
[76] Lehmann J, Joseph S. Biochar for environmental management: science, technology and implementation. Routledge; 2015.
[77] Uzoma KC, Inoue M, Andry H, Fujimaki H, Zahoor A, Nishihara E. Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag 2011;27:205–12. https://doi.org/10.1111/j.1475-2743.2011.00340.x.
[78] Cao X, Harris W. Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. Bioresour Technol 2010;101:5222–8. https://doi.org/10.1016/j.biortech.2010.02.052.
[79] Atienza-Martínez M, Ábrego J, Gea G, Marías F. Pyrolysis of dairy cattle manure: evolution of char characteristics. J Anal Appl Pyrolysis 2020;145:104724. https://doi.org/10.1016/j.jaap.2019.104724.
[80] Tsai W-T, Hsu C-H, Lin Y-Q. Highly porous and nutrients-rich biochar derived from dairy cattle manure and its potential for removal of cationic compound from water. Agriculture 2019;9:114. https://doi.org/10.3390/agriculture9060114.
[81] Sokhansanj S, Webb E. Evaluating industrial drying of cellulosic feedstock for bioenergy: a systems approach. Biofuels Bioprod Biorefining 2016;10:47–55. https://doi.org/10.1002/bbb.1619.
[82] Solarte-Toro JC, Chacón-Pérez Y, Cardona-Alzate CA. Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material. Electron J Biotechnol 2018;33:52–62. https://doi.org/10.1016/j.ejbt.2018.03.005.
[83] U.S. EIA. State Electricity Profiles 2020. https://www.eia.gov/electricity/state/idaho/.
[84] Flint BR. Analysis and operational considerations of biomass extraction on steep terrain in western Oregon; 2013.
[85] Zamora-Cristales R, Sessions J. Modeling harvest forest residue collection for bioenergy production. J For Eng 2016.
[86] Sorenson CB. A comparative financial analysis of fast pyrolysis plants in Southwest Oregon. MT: The University of Montana Missoula; 2010.
[87] Brown TR, Wright MM, Brown RC. Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. Biofuels Bioprod Biorefining 2011;5:54–68. https://doi.org/10.1002/bbb.254.
[88] Aguirre-Villegas HA, Larson RA. Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools. J Clean Prod 2017;143:169–79. https://doi.org/10.1016/j.jclepro.2016.12.133.
[89] Pattey E, Trzcinski MK, Desjardins RL. Quantifying the reduction of greenhouse gas emissions as a resultof composting dairy and beef cattle manure. Nutr Cycl Agroecosystems 2005;72:173–87. https://doi.org/10.1007/s10705-005-1268-5.
[90] Ebner JH, Labatut RA, Rankin MJ, Pronto JL, Gooch CA, Williamson AA, et al. Lifecycle greenhouse gas analysis of an anaerobic codigestion facility processing dairy manure and industrial food waste. Environ Sci Technol 2015;49:11199–208. https://doi.org/10.1021/acs.est.5b01331.
[91] He Z, Pagliari PH, Waldrip HM. Applied and environmental chemistry of animal manure: a review. Pedosphere 2016;26:779–816. https://doi.org/10.1016/S1002-0160(15)60087-X.
[92] Girotto F, Cossu R. Animal Waste: Opportunities and Challenges. In: Lichtfouse E, editor. Sustain. Agric. Rev., Cham: Springer International Publishing; 2017. p. 1–13. https://doi.org/10.1007/978-3-319-48006-0_1.
[93] Laird D. Farm. Biochar Farms 2009. http://biocharfarms.org/farming/ [accessed June 29, 2020].
[94] Xu M, Gao P, Yang Z, Su L, Wu J, Yang G, et al. Biochar impacts on phosphorus cycling in rice ecosystem. Chemosphere 2019;225:311–9.
[95] Pourhashem G, Hung SY, Medlock KB, Masiello CA. Policy support for biochar: Review and recommendations. GCB Bioenergy 2019;11:364–80.