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# Producer knowledge and perceptions of biochar for Eastern redcedar management

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Eastern redcedar (*Juniperus virginiana*), a conifer native to the eastern United States, poses a significant threat to the grasslands of the US. Great Plains due to its invasive characteristics and broad environmental tolerance. Current management strategies typically involve mechanical removal of established trees, generating substantial amounts of organic waste that is rarely repurposed. Converting this biomass into biochar presents a sustainable alternative, offering a value-added product that can enhance soil fertility, improve water retention, and sequester carbon—thereby addressing both ecological degradation and climate change while potentially creating new revenue streams for landowners. Despite these benefits, the practice of producing biochar from Eastern redcedar waste remains uncommon in the Great Plains. This study explores the factors contributing to limited adoption by assessing landowner knowledge, perceptions, and attitudes toward biochar, redcedar encroachment, and interest in using and/or producing biochar out of redcedar waste.

KEYWORDS

**nature-based solutions, biochar, eastern redcedar, woody plant encroachment, waste management**

## 1 Introduction

### 1.1 Eastern redcedar spread in the central and southern great plains

Woodland expansion threatens grassland ecosystems globally and has accelerated rapidly across the U.S. Great Plains over recent decades (Van Auken, 2009; Barger et al., 2011; Kaur et al., 2020a,b). During the process of woodland expansion, woody plant encroachment (WPE) gradually shifts ecosystems from herbaceous and grassy species to trees and shrub (University of Nebraska-Lincoln, n.d.). In the Central and Southern Great Plains, the woody plant of primary concern is the eastern redcedar (*Juniperus virginiana*, a.k.a. ERC) (University of Nebraska-Lincoln, n.d.), which is a fast-growing conifer native to eastern North America and tolerant of a wide variety of environmental conditions (United States Department of Agriculture Natural Resource Conservation Service, 2002).

Historically, indigenous people used ERC as a fuel and for medicinal, ceremonial, and religious purposes (Ledford, 2012). Early Euro-American settlers, unaccustomed to the vast treeless expanses of the Great Plains, also valued the tree and aided its spread, often with the encouragement of the federal government. Homesteaders commonly planted ERC as shelterbelts and windbreaks, particularly during

the 1930s, to protect homes and crops from the Dust Bowl's fierce windstorms (Schnelle, 2023). Today, the tree continues to be a popular ornamental plant and offers multiple ecosystem benefits, including shelter, wildlife habitat, carbon sequestration, and soil erosion prevention (McKinley and Blair, 2008). These characteristics make ERC culturally and socially valuable but also contribute to its ability to spread rapidly when not properly managed.

Although native to the prairie landscapes of the Great Plains, prior to Euro-American settlement ERC grew primarily in rugged and remote terrains out of reach of fire, like steep canyons and rocky bluffs (Illeperuma et al., 2023). Indigenous people used fire as a land management and hunting tool on the plains for thousands of years (Kimmerer and Lake, 2001; Roos et al., 2018). This, along with practices like browsing and brush control, prevented ERC growth and stabilized grassland ecosystems (Wilcox et al., 2018). Land management began to change with Euro-American colonization during the mid to late 1800s (Sayre, 2023). In addition to intentionally planting ERC, settlers disrupted traditional ecological practices, nearly eradicated the American bison, suppressed wildfires, and introduced commercial animal agriculture, leading to overgrazing (Wilcox et al., 2018; Schnelle, 2023). More recently, climatic shifts resulting in increased temperatures and drought severity have created conditions favorable for ERC to proliferate and spread (Yang et al., 2024). These changes in land management, land use patterns, and climate (Sayre, 2023) have enabled ERC to thrive and spread across the Great Plains (Engle et al., 2008; Krug et al., 2017).

As a "pioneer species," ERC is one of the first species to establish itself in difficult terrain such as eroded areas, barren clearing, abandoned fields, and disrupted habitats (Schnelle, 2023). Additionally, ERC is tolerant of rocky, alkaline, and salty soils, as well as drought, extreme heat, and below freezing temperatures (United States Department of Agriculture Natural Resource Conservation Service, 2002). Their ability to tolerate unfavorable conditions gives the species characteristics similar to an invasive plant colonizing land outside its native range. ERC grows rapidly, reaching maturity in as little as 7 years, and produces mass amounts of small berry seeds, which are widely dispersed by the wind, birds, and mammals (Horncastle et al., 2004). Seeds can remain viable in the soil for extended periods, allowing for delayed germination and further contributing to their spread (United States Department of Agriculture, n.d.). However, unlike many native trees in the Great Plains, ERC do not resprout after fires (United States Department of Agriculture, n.d.). The widespread suppression of fire has, therefore, eliminated a major natural check on their expansion (Horncastle et al., 2004), altering historic fire regimes and increasing wildfire intensity due to ERC's highly flammable foliage (Coppedge et al., 2001). Combined, these forces have led to the loss of 7.9 million acres of grasslands in the Great Plains, primarily in the south and central regions, as the ecosystem transitions to ERC-dominated woodlands (Natural Resources Conservation Service, 2022).

The Great Plains are one of the most imperiled and least conserved ecosystems in the world, and WPE is one of its top threats (Samson et al., 2004; Natural Resources Conservation Service, 2022). When ERC and other woody vegetation out compete native grassland species, biodiversity declines and ecosystem dynamics shift (Horncastle et al., 2004). Very few herbaceous plants can grow beneath ERCs, with documented productivity declines up to 99% when grasslands transition to closed-canopy ERC stands (Briggs et al., 2002). The resulting habitat loss enables generalist and woodland species to displace grassland species (Coppedge et al., 2001). Grassland birds are particularly sensitive. Once ERC cover exceeds 10%, most species of grassland birds disappear entirely (Chapman et al., 2004). Likewise, ERC leads to the disappearance of most small mammal species (Horncastle et al., 2005) and reduces the abundance of most beetle species (Walker and Hoback, 2007). These combined effects greatly disrupt and degrade grassland ecosystems.

ERC spread also exacerbates water scarcity by reducing soil moisture, streamflow, and groundwater recharge (Kaur et al., 2020a,b). As evergreens, ERC transpire throughout the year and their deep root systems give them access to large volumes of soil water, sometimes even tapping into the water table (Oklahoma State University Extension, 2017). Additionally, ERC canopies intercept more rainfall compared to herbaceous plants, reducing the amount of water reaching the soil and increasing overall evaporation rates (Oklahoma State University Extension, 2017). In fact, ERC closed canopy woodlands can transpire almost all the precipitation that reaches the soil under normal precipitation conditions (Caterina et al., 2014). This water loss impacts plant community composition and can contribute to habitat fragmentation, making it more difficult for native species to thrive (Briggs et al., 2002).

The economic losses associated with uncontrolled ERC encroachment are substantial. On agricultural lands, ERC reduces forage availability, diminishes grazing capacity, and lowers overall rangeland productivity (Kaur et al., 2020a,b). As ERC spreads, it degrades soil quality by depleting essential nutrients such as nitrogen, phosphorus, and potassium (Van Auken, 2007). Once ERC becomes dominant, livestock production can decline by as much as 75% (Fuhlendorf et al., 2008). Additional economic losses are incurred due to wildfire damage and loss of hunting lease revenue (Kaur et al., 2020a,b). In Oklahoma alone, uncontrolled ERC cost an estimated $218 million annually in 2002, a number that more than doubled to $447 million by 2013 (Oklahoma Conservation Commission, 2008). As ERC continues to expand and increase in dominance across adjacent landscape, these economic losses are expected to escalate.

## 1.2 Managing ERC on agricultural lands

Land managers and conservationists have developed multiple techniques to control ERC spread and protect grassland ecosystems. Since over 90% of the Great Plains are privately owned (Robinson et al., 2019), with large swaths devoted to crop production and rangeland, responsibility for controlling ERC spread falls heavily on farmers and other private land managers. Management practices include mechanical control, prescribed fires, browsing, and herbicide (Kaur et al., 2020a,b). The recommended approach depends on the stage of woodland transition (ODAFF

Forestry Service et al., 2013; Natural Resources Conservation Service, 2022). When grasslands remain intact with only small and sparse trees, management focuses on prevention by eliminating seeds and seedlings through prescribed fire (Illeperuma et al., 2023) and biological control (i.e., grazing by goats) (Daines, 2006). Regular prescribed fire is one of the primary means of controlling ERC and is highly economical and efficient (Weir et al., 2017b). Controlled burns are highly effective at inducing mortality in ERC trees < 6 ft tall while less than half of large cedar trees are killed by a single treatment of prescribed fire (Weir et al., 2017a).

Due to prolonged fire suppression and large, established ERC populations, many situations require mechanical or chemical treatment for effective management (Weir et al., 2017a). However, removing mature ERCs through mechanical control is a costly and labor-intensive process that produces a large amount of organic waste (Knezevic et al., 2005). Mechanical methods include hand cutting smaller trees with tree loppers or chainsaws (Knezevic et al., 2005). For denser stands and larger trees, bulldozers or hydraulic tree shears mounted on skid steers can be used (Knezevic et al., 2005). Chemical control with herbicides can be used as spot treatment for individual trees or cover larger areas using broadcast application but this also risks injury to grass and other plant species and is, generally, most effective on small trees (Knezevic et al., 2005).

Following treatment, land managers face the additional task of dealing with the resulting ERC waste. Aside from simply leaving the material in place, the most common method of disposal is to burn the material onsite, producing air pollution (namely carbon and nitrogen oxides and particulate matter) without any of the ecological benefits of prescribed fires. Some land managers simply leave the dead trees standing in place (snags) following a prescribed fire or chemical control (Flanders et al., 2021). However, these snags continue to provide perching opportunities for birds that can further spread ERC seeds (Flanders et al., 2021). Additionally, leaving snags on the landscape contributes to fuel build-up and increases the risk of uncontrolled wildfires (Flanders et al., 2021). Other less common alternatives include turning the trees into woodchips that can be used in landscaping or gardening. However, depending on the degree of ERC infestation, this may produce a greater volume of material than what is practical for individual use. As a result, the scale of the problem, need for ongoing management, and mass amounts of organic waste has sent many in search of alternative and sustainable uses for ERC (Zhang and Hiziroglu, 2010; Craige et al., 2016; Ramli et al., 2017; Kaur et al., 2020a,b).

## 1.3 Biochar application in ERC management

Biochar is a multi-purpose, multi-benefit bio-based product that can be produced from any carbon-based biomass, from agricultural wastes to invasive plant species (Lehmann and Joseph, 2015). Biochar has its roots in ancient times, with one of the most well-known historical examples being Terra Preta in the Amazon. Indigenous Amazonian communities created dark, highly fertile soils by adding biochar, organic matter, and nutrients to the soil, leading to long lasting soil improvements that can still be seen today (Glaser and Birk, 2012). In recent years biochar has shown an increase in scientific research and commercial application, particularly as a Nature-Based Solution (NBS) for sustainable agriculture and climate mitigation (Woolf et al., 2010; Ayaz et al., 2021; Lehmann et al., 2021; Rombel et al., 2022). NBS are concepts, products, and practices adapted from nature that increase environmental sustainability and resiliency as well as enhance existing ecosystem services with additional economic and societal benefits (Federal Emergency Management Administration, 2023). Upcycling biomass waste has the potential for creating a self-sustaining, cyclical economy supported by local residents and regional industry. Using ERC and other woody "invasives" as a feedstock for biochar has recently emerged as a promising solution for the management of organic waste (Nackley, 2015; Yang et al., 2016; Feng et al., 2021; Silwal et al., 2023).

Biochar is created through pyrolysis, the thermal decomposition of biomass under an average temperature of 600 °C in a low oxygen environment (Yang et al., 2016). This process yields three distinct byproducts—liquid fractions (bio-oil), gaseous products (syngas), and solids (biochar)—all of which have the potential to be transformed into productive materials (Yang et al., 2016). Biochar can be made on-site by agricultural producers with relatively inexpensive and easy to use equipment. When the resulting charcoal-like substance is soaked in organic waste (e.g., manures or composts), it becomes "charged" and functions as a slow-release fertilizer (Rombel et al., 2022). Charged biochar offers several advantages over conventional fertilizers, including increased crop yields, improved nutrient use efficiency, enhanced vegetable quality, greater abundance of beneficial microorganisms, reduced pesticide use, lower greenhouse gas emissions, and improved farm profitability (Chew et al., 2020). In contrast, uncharged biochar is particularly useful product in environmental remediation, as it provides habitat for pollutant-degrading microbial communities (Bui et al., 2024) and offers reactive surfaces for chemical bonding (Almanassra et al., 2021). These benefits position biochar as a promising strategy for transforming agricultural waste into a value-added product within regenerative agricultural systems.

Among its many benefits, biochar can help mitigate climate change (Lehmann and Joseph, 2015). When properly land applied, biochar acts as a powerful carbon sequestration tool (Smith, 2016). As such, biochar has been recognized as a promising strategy to address climate change (Hounnou et al., 2024). As a negative emissions technology, biochar has the potential to sequester approximately 0.7 gigatons of carbon *per year* while requiring less land and water resources than other negative emissions technology, such as afforestation or bioenergy with carbon capture and storage (Smith, 2016). Biochar also reduces nitrous oxide, which has a significantly higher global warming potential than carbon dioxide (Smith, 2016). As climate change concerns grow, expanding the use in agricultural or environmental management could play a key role in global carbon reduction efforts.

Prior studies have investigated producer knowledge and perceptions of biochar at various locations across the globe. Outside of the United States, researchers have identified low levels of knowledge and awareness as a major impediment to increased biochar adoption (Latawiec et al., 2017; Niemmanee et al., 2019). In an interview study of Polish famers, Latawiec et al. (2017) found

that nearly 70% of respondents had never encountered the term and only 27% were somewhat familiar with biochar. This lack of awareness was reflected in their willingness to adopt the practice—just 20% expressed interest in using biochar, while 43% indicated no willingness to adopt it (Latawiec et al., 2017). Survey research in Tanzania revealed similarly low rates of familiarity at 27% (Rogers et al., 2021). These studies suggest that limited knowledge about biochar may contribute to a reduced interest among agricultural producers in countries outside of the U.S.

More recent U.S.-based studies suggest greater levels of both awareness and interest in biochar. A 2022 study of famers in New York State found that 72% of respondents were familiar with biochar, 53% expressed interest in using it, and 42% expressed interest in producing it (Sherman, 2022). Respondents identified improving soil quality, reducing runoff, and decreasing the need for fertilizers as the most important potential benefits (Sherman, 2022). Similarly, a recent study of land managers in New Mexico found that 65% were familiar with biochar citing water retention, improved soil quality, and reduced fuel loads as key advantages (Ynfante et al., 2024). Despite these relatively high levels of awareness and interest found in U.S.-based biochar studies, rates of use and production remained low—only 17% of New York farmers reported using biochar and 19% reported producing it (Sherman, 2022) while just 13% of New Mexico land managers reported producing it (Ynfante et al., 2024). In both cases, lack of knowledge was cited as the most prevalent barrier, followed by lack of trusted information, funding, and access to equipment (Sherman, 2022; Ynfante et al., 2024). These findings suggest a persistent disconnect between interest in biochar and its practical application among U.S.-based producers.

Despite the potential of biochar as a NBS for sustainable land management and regenerative agriculture, its use in the Central Great Plains remains low. However, it is unknown what producers in the Central Great Plains know and think about biochar and if this serves as a barrier to the practice becoming more common. In this study, we explore perception and willingness to adopt biochar among agricultural producers in the Central Great Plains state of Oklahoma, focused on its application for ERC waste management.

# 2 Materials and methods

## 2.1 Research objectives and questions

Oklahoma's natural and agricultural lands are under immense threat from environmental degradation. The state is home to approximately 86,000 farms (4$^{th}$ in the nation) spanning 35 million acres (Oklahoma Farm Bureau Foundation for Agriculture, n.d.). Since 2013, irrigated acreage has increased 41% (600,000 acres) and water use in crop production has risen by 27% (662 ac-ft) (Oklahoma State University Extension, 2020). At the same time, the spread of ERC has accelerated dramatically. As of 2008, the USDA Natural Resource Conservation Service (NRCS) estimated that over half of Oklahoma's native landcover now contains 50 or more ERC trees per acre—a 400% increase over the past 50 years (Oklahoma Conservation Commission, 2008). This encroachment has transformed the state's grasslands into woodlands at an estimated rate of almost 10,000 acres (40 km$^2$) per year since the mid-1980s (Wang et al., 2018), affecting both public and private lands. Given these trends, there is an urgent need for sustainable, landscape-scale solutions to address the environmental challenges facing Oklahoma's farmlands.

To our knowledge, no studies have examined attitudes and perceptions of biochar among agricultural producers in Oklahoma or the Southern Great Plains more broadly. However, anecdotal evidence suggests that awareness may be lower than other regions. One Oklahoma official estimated that only one in 100 rural farmers is likely familiar with biochar, with even fewer actively using or producing the product (G. Kloxin, Oklahoma Conservation Commission, personal communication, 2024). Additionally, the extent of producer knowledge—including what biochar is, how it is made, as well as its potential benefits and challenges—remains largely unknown.

This study explores agricultural producers' knowledge and perception of biochar within the Southern Great Plains state of Oklahoma. To guide this investigation, the following research questions were posed:

- What are the current levels of awareness, knowledge, and interest in using and producing biochar among agricultural producers in Oklahoma?
- What producer practices, values, and farm characteristics are associated with biochar interest and use?
- What are the barriers and opportunities for adopting biochar, particularly as a tool for ERC management?

A mixed-method approach was utilized that combined focus groups with a pilot survey. Study participants included agricultural producers (ranchers and farmers), as well as staff from conservation organizations, state regulatory agencies, and agricultural extension offices. Exploratory focus groups informed survey design and provided in-depth understanding of producers' experiences, knowledge, and perceptions. Following focus groups, a pilot survey was employed to generate hypotheses related to patterns of biochar use and interest. Our analysis integrates findings from these two data sources to identify where themes converge and diverge as a starting point for future work in this area.

Study protocol and material were approved by the University of Oklahoma Institutional Review Board—Norman Campus (IRB # 17656).

## 2.2 Focus groups

Focus group participants were identified through online searches as well as researchers' personal networks and recruited through direct email and phone outreach. Recruitment flyers were also distributed around the University of Oklahoma Norman Campus and farm supply stores throughout the Oklahoma City metro area and adjacent rural communities.

Six focus groups took place virtually over Zoom® between November 2024 and January 2025 with 20 total participants (between two and four participants per group). Three focus groups primarily consisted of management and agency staff, while the other three primarily consisted of agricultural producers.

Participants included eight producers, ten management and agency staff, and two extension agents. Discussions ranged from 73 to 88 mins and averaged 83 mins in length.

With participant consent, discussions were audio and video recorded. Focus groups followed a semi-structured interview guide that explored knowledge of and experience with biochar, perceived advantages and disadvantages associated with the use and production of biochar, and ERC encroachment and waste management. To further facilitate discussion, researchers played two short videos (under 3 mins each) during the focus group. The first was a segment of an educational video produced by the biochar company Carbon Gold® and posted on YouTube® that describes what biochar is, its history, and some of its benefits (Carbon Gold, 2019). The second video compiled segments from three other videos found on YouTube demonstrating different methods for producing biochar, including the use of a pit, barrel, and mobile pyrolysis machine. Following each focus group, participants received a brief demographics survey to collect information about gender, age, and race. The response rate on the demographic survey was 70%. As compensation for their time, participants were offered a $25 Amazon gift card.

Focus groups were auto transcribed through Zoom® and reviewed/corrected for accuracy. Transcripts were analyzed qualitatively using NVivo® 15. Data analysis began by coding the focus groups into broad thematic categories based on the interview structure and following a codebook developed collectively by the research team. Codes included familiarity, experience, and benefits of biochar use and production; opportunities and barriers to adoption; response to the biochar videos; information needs; approach to ERC management; and perceived potential of biochar as an alternative ERC waste management strategy. Based on emergent patterns and themes from the initial coding, we conducted a second round of more focused coding to analyze subcategories within the major thematic areas. One researcher (LB) performed all coding with regular discussion and input from the rest of the team to refine codes and resolve questions and ambiguities. A second researcher (LAB) reviewed the coding to ensure consistency.

## 2.3 Online survey

A total of 50 survey questions were developed drawing upon published biochar studies (Latawiec et al., 2017; Niemmanee et al., 2019; Sherman, 2022) and other scholarship on farmer adoption of sustainable technologies (Varyvoda et al., 2025). Following Kaiser et al. (2024), we include constructs for both social, psychological (norms, values, objectives, and perceived self-efficacy), and structural/contextual (skills, knowledge, financial resources, farm size/type) factors. Survey questions were organized into eight blocks with the first five related to biochar (knowledge, interest, use, production), two related to ERC encroachment and waste management, one on producer values and needs, and one on farm/profession characteristics (see Supplementary Material for full survey). Additional demographic questions were included to identify potential trends related to age, gender, race/ethnicity, or education. The survey utilized branching logic to target questions to participants based on whether they had heard of biochar, used biochar, or produced biochar, in sequence. Questionnaire validation was conducted by obtaining expert review by an Environmental Sociologist and Research Scientist at the University of Oklahoma Institute for Public Policy Research and Analysis (IPPRA). Additionally, functionality testing was conducted by providing varied and unconventional responses across different question types to confirm that the survey properly handled all inputs without producing errors.

The survey was distributed online through Qualtrics® and took approximately 10-15 mins to complete. Inclusion criteria required that participants be 18 years of age or older and farm or manage land in Oklahoma. All participants received a core set of questions that covered interest in biochar application and production, values, farm information, and demographics. Participants with previous knowledge and experience with biochar, as well as those who managed ERC on their land, were given additional questions related to those topics. Of the 28 individuals who began the survey, those who did not meet eligibility criteria or completed less than 85% of the questions were excluded, resulting in a final sample of 20 participants.

Survey recruitment followed a similar approach to the focus groups but placed greater emphasis on agricultural producers and land managers. A survey invitation was emailed to focus group participants and others who indicated interest by responding to a recruitment flier or a cold email outreach. Personal and professional contacts were also asked to assist in recruitment by sharing the survey invitation through their networks. The survey was open for 4 weeks during February and March 2025. To encourage participation, two email reminders were sent during that time and participants were offered a $25 Amazon gift card following the survey.

Data analysis was performed in SPSS® to assess descriptive statistics and test for significance of association between variables. Significance was determined using the Fisher's Exact Test (2-sided) and is reported at the 5% level. Outcome variables of interest included interest in using biochar, interest in producing biochar, experience using biochar, and experience producing biochar. Significance was tested between outcome variables and measures of sustainable values and practices, farm size, and farm type, all transformed into binary variables (Table 1). Due to the small sample size and exploratory nature of the study, the results presented here describe trends within our sample and are not generalizable to a larger population.

# 3 Results

## 3.1 Demographics and farm characteristics

Focus group participants were evenly split between men and women (both 50%, $n = 7$) and most identified as white (79%, $n =$'11) (see Table 2). The most frequent age range was between 30 and 39 years old (43%, $n = 6$) with most remaining focus group participants aged 40 or older (50%, $n = 7$). Online survey respondents had a similar gender breakdown,

TABLE 1 Variable coding.

| Variable | Survey item | Coding | Notes |
|---|---|---|---|
| **Biochar interest** | | | |
| Using | How interested are you in **using** biochar? | 1 = Very interested, somewhat interested, or currently use 0 = All other responses | Recode of Likert scale responses |
| Producing | How interested are you in **producing** biochar? | 1 = Very interested, somewhat interested, or currently use 0 = All other responses | Recode of Likert scale responses |
| **Biochar experience** | | | |
| Using | Have you ever personally **used** biochar? | 1 = Yes 0 = No | |
| Producing | Have you ever personally **produced** biochar? | 1 = Yes 0 = No | |
| **Farm type** | | | |
| Small farm | How many acres do you farm or manage for agricultural purposes? | 1 = 200 acres or less 0 = Less than 200 acres | Recode of open-ended responses |
| Grow crops | Do you grow or farm crops? | 1 = Yes 0 = No | |
| Manage livestock | Do you raise or manage livestock? | 1 = Yes 0 = No | |
| **Practices** | | | |
| Compost | Do you compost (reuse decaying organic material as a soil amendment)? | 1 = Yes 0 = No | |
| Regenerative or sustainable farm | I practice regenerative or sustainable agriculture | 1 = Strongly agree 0 = All other responses | |
| **Values and norms** | | | |
| Stewardship importance | Being a good steward of the land is important to me | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |
| Sustainability interest | I am interested in learning more about regenerative or sustainable agriculture | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |
| Profit orientation | Finding ways to increase profitability is important to the survival of my operation | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |
| Social norms | Most producers I know practice regenerative or sustainable agriculture | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |
| Social expectations | People who are important to me expect me to be a good steward of the land | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |
| Perceived self-efficacy | I know how to manage soil health on my farm | 1 = Strongly agree 0 = All other responses | Recode of Likert scale responses |

with half identifying as women (50%, $n = 10$) and 45% as men ($n = 9$; Table 1). As for race, 70% identified as white ($n = 14$), 10% Native American ($n = 2$), and 10% multiple races ($n = 2$). Three-quarters of respondents fell between the ages of 35 and 64 (75%, $n = 15$), evenly split between the three decades of 35-44, 45-54, and 55-64 years old. Pertaining to education, 85% percent had at least some college ($n = 17$). The highest level of education for half of the participants was a bachelor's degree (50%, $n = 10$) followed by an associate's degree (20%, $n = 4$).

Survey respondents varied widely in their farming experience, income, and farm type. Forty percent have been farming for 20+ years ($n = 8$), with another 40% between 1 and 10 years ($n = 8$; Table 3). The highest proportion of respondents (30%, $n = 6$) reported negative income related to their farming operation while the most frequent positive income category was $50,000 - $99,999 (15%, $n = 3$). Farm size ranged from 1 to 3,000 acres and averaged 531 acres. Small farms (<200 acres) were slightly more common than large farms (55%, $n = 11$ vs. 40%, $n = 8$). Most respondents (70%, $n = 14$) manage livestock on their farm and about half (45%, $n = 9$) grow crops. The most common types of livestock raised were cattle (40%, $n = 8$) and poultry (35%, $n = 7$) and the most common crops grown were vegetables (40%, $n = 8$).

Most survey respondents indicated that they practice composting (55%, $n = 11$) and, out of the 9 respondents who grow row crops, just over half do so without the use of chemical pesticides (55%, $n = 5$). The most common farm problems identified were drought (80%, $n = 16$) and invasive or nuisance species (60%, $n = 12$). All categories of farm problems ($n = 10$) were selected by at least one participant except for soil or water pollution.

Due to biochar's association with sustainability and regenerative agriculture, the survey asked about producers' farming values and norms (Table 4). Sixty percent ($n = 12$) agreed or strongly agreed that they practice sustainable or

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TABLE 2 Participant demographics for focus groups and survey.

| Response options | Focus groups ($N = 17$)* | Survey ($N = 20$) |
|---|---|---|
| **Gender** | | |
| Woman | 7 (50.0%) | 10 (50.0%) |
| Man | 7 (50.0%) | 9 (45.0%) |
| Missing | 0 (0.0%) | 1 (5.0%) |
| **Race** | | |
| Asian | 1 (7.1%) | 1 (5.0%) |
| Black or African American | 0 (0.0%) | 0 (0.0%) |
| Native American | 0 (0.0%) | 2 (10.0%) |
| White | 11 (78.6%) | 14 (70.0%) |
| Multiple | 1 (7.1%) | 2 (10.0%) |
| Prefer not to say | 1 (7.1%) | 0 (0.0%) |
| Missing | 0 (0.0%) | 1 (5.0%) |
| **Age in years**† | | |
| 21-29 [25–34] | 1 (7.1%) | 1 (5.0%) |
| 30-39 [35–44] | 6 (42.9%) | 5 (25.0%) |
| 40-49 [45–54] | 2 (14.3%) | 5 (25.0%) |
| 50-59 [55–64] | 3 (21.4%) | 5 (25.0%) |
| 60 + [65+] | 1 (7.1%) | 2 (10.0%) |
| Prefer not to say | 1 (7.1%) | 0 (0.0%) |
| Missing | 0 (0.0%) | 2 (10.0%) |
| **Level of education** | | |
| Less than a high school diploma | - | 1 (5.0%) |
| High school diploma or GED | - | 1 (5.0%) |
| Some college | - | 2 (10.0%) |
| Associate's degree | - | 4 (20.0%) |
| Bachelor's degree | - | 10 (50.0%) |
| Advanced degree | - | 1 (5.0%) |
| Missing | - | 1 (5.0%) |

*Focus group demographics based on response rate of 70% of 20 total participants.

†Age categories for the focus group survey and online survey varied slightly. Age range for focus group participants is listed first, followed by the age range for survey participants in brackets.

TABLE 3 Farm characteristics ($N = 20$).

| Response options | Frequency (percent) Mean (std dev), min-max |
|---|---|
| **Amount of time farming (years)** | |
| Less than 1 year | 2 (10.0%) |
| 1-5 years | 4 (20.0%) |
| 6-10 years | 4 (20.0%) |
| 16-20 years | 1 (5.0%) |
| 20 + years | 8 (40.0%) |
| Missing | 1 (5.0%) |
| **Gross farm income** | |
| Negative income | 6 (30.0%) |
| $0-$999 | 1 (5.0%) |
| $1,000-$9,999 | 2 (10.0%) |
| $10,000-$49,999 | 2 (10.0%) |
| $50,000-$99,999 | 3 (15.0%) |
| More than $100,000 | 1 (5.0%) |
| Prefer not to say | 4 (20.0%) |
| Missing | 1 (5.0%) |
| Farm size (acres) | 530.7 (888.0), 1-3,000 |
| Small (<200 acres) | 11 (55.0%) |
| Large (>200 acres) | 8 (40.0%) |
| Missing | 1 (5.0%) |
| Manage livestock | 14 (70.0%) |
| Grow crops | 9 (45.0%) |
| Pesticide use* | 5 (55.0%) |
| Compost | 11 (55.0%) |
| **Problems on the farm** | |
| Soil acidity | 3 (15.0%) |
| Low soil quality | 8 (40.0%) |
| Soil or water pollution | 0 (0.0%) |
| Low water retention | 6 (30.0%) |
| Cost of fertilizer | 8 (40.0%) |
| Agricultural runoff | 2 (10.0%) |
| Flooding | 1 (5.0%) |
| Drought | 16 (80.0%) |
| Invasive or nuisance species | 12 (60.0%) |
| Other problems | 2 (10.0%) |
| No problems | 1 (5.0%) |

*Percentage out of respondents who grow row crops.

regenerative agriculture, and almost all agreed on the importance of being a good steward of the land ($n = 19$, 95%). Similarly high numbers (85%, $n = 17$) expressed interest in learning more about sustainability and saw increasing profitability as important to the survival of their operation. Measures for perceived norms and expectations related to sustainability were more mixed. While 80% ($n = 16$) agreed that others expect them to be good stewards of the land, only 25% ($n = 5$) said that most producers they know practice regenerative or sustainable agriculture. On a measure for perceived self-efficacy, respondents rated themselves highly with 85% ($n = 17$) agreeing that they know how to manage soil health on their farm. Notably, several survey questions under sustainability values and norms were left unanswered by a large number of respondents.

TABLE 4 Sustainability values and norms ($N = 20$).

| Response options | Strongly agree | Agree | Disagree | Strongly disagree | Missing |
|---|---|---|---|---|---|
| I practice regenerative or sustainable agriculture | 9 (45.0%) | 3 (15.0%) | 3 (15.0%) | 1 (5.0%) | 4 (20.0) |
| Being a good steward of the land is important to me | 15 (75.0%) | 4 (20.0%) | 1 (5.0%) | 0 (0.0%) | 0 (0.0%) |
| Interested in learning more about sustainability | 11 (55.0%) | 6 (30.0%) | 1 (5.0%) | 0 (0.0%) | 2 (10.0%) |
| Increasing profitability is important to the survival of my operation | 11 (55.0%) | 6 (30.0%) | 0 (0.0%) | 0 (0.0%) | 3 (15.0%) |
| Most producers I know practice regenerative or sustainable agriculture | 2 (10.0%) | 3 (15.0%) | 5 (25.0%) | 3 (15.0%) | 7 (35.0) |
| People who are important to me expect me to be a good steward of the land | 8 (40.0%) | 8 (40.0%) | 0 (0.0%) | 0 (0.0%) | 4 (20.0) |
| I know how to manage soil health on my farm | 8 (40.0%) | 9 (45.0%) | 3 (15.0%) | 0 (0.0%) | 0 (0.0%) |

## 3.2 Biochar awareness, experiences, and perceptions

Farmers' knowledge, experience, and perceptions of biochar varied widely across Oklahoma's farmer community, from people who have never heard of it to ones who use it regularly. Half of the online survey respondents (50%, $n = 10$) had some familiarity with biochar prior to the survey, 35% ($n = 7$) had experience using biochar, and 20% ($n = 4$) had experience producing it. Focus group participants were more familiar with biochar compared to survey respondents, with 95% ($n = 19$) having prior knowledge or familiarity with the product. However, experience using and producing biochar was similar to survey respondents, with 35% ($n = 7$) of focus group participants having used biochar and 15% ($n = 3$) having produced biochar.

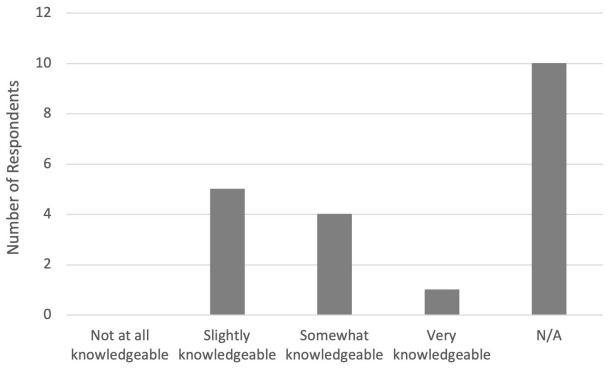



FIGURE 1
Bar graph showing survey respondents' self-reported level of biochar knowledge by Likert category (N/A represents respondents who were not asked about their level of biochar knowledge because they reported not having been aware of biochar).

### 3.2.1 Biochar knowledge

Of the survey respondents already familiar with biochar (50%, $n = 10$), the vast majority self-reported as either somewhat (40%, $n = 4$) or slightly (50%, $n = 5$) knowledgeable about biochar (Figure 1). Most participants ($> = 70\%$) also agreed with six out of 10 factual statements about biochar (Table 4), including that biochar is a carbon rich material (90%, $n = 9$), can improve soil quality (80%, $n = 8$), is simple to make (80%, $n = 8$), improves crop health (70%, $n = 7$), retains water in the soil (70%, $n = 7$), and removes pollutants from soil/water (70%, $n = 7$).

There was less consensus among respondents on biochar's climate benefits, ability to reduce the need for agrichemicals, potential harm to soil, and appropriate feedstocks (Table 5). Only 20% ($n = 2$) agreed that biochar can help prevent greenhouse gas emissions and reduce the need for chemical fertilizers, while 70% ($n = 7$) were unsure, needed more information, or had no opinion. Forty percent ($n = 4$) agreed that biochar could harm the soil if used in excess, but the same number needed more information (40%, $n = 4$). Likewise, opinions were split on whether biochar could be made from any organic waste: 50% ($n = 5$) agreed and 50% ($n = 5$) disagreed. Based on the factual statements, the average biochar knowledge score was 5.9, ranging from a perfect score (agreement with 10/10 factual statements) to 30% (agreement with 3/10 factual statements).

Although more familiar with biochar overall, most focus group participants also described their knowledge as limited and only a few articulated a deeper understanding of what biochar is and how it works. Participants saw biochar as a niche but growing topic of interest among farmers, variously describing it as "a shiny new thing" (Participant 4), "a sexy topic" (Participant 3), and a "hot topic" (Participant 6). However, participants saw most of these trends coming from outside the state and region. A state employee, for example, said that the increased interest in biochar reflected federal priorities: "I believe that's something the EPA [U.S. Environmental Protection Agency] is trying to push as a more ecological waste management option" (Participant 5). Within the state, participants observed that most interest tended to be concentrated within small farm and urban gardening communities.

Focus group participants described less buzz among Oklahoma producers more broadly. An extension agent working in western

TABLE 5 Biochar knowledge ($N = 10$). Includes only respondents aware of biochar prior to the survey.

| Response options | Agree | Unsure, need more info, no opinion | Disagree |
|---|---|---|---|
| Biochar is a carbon rich material | 9 (90.0%) | 1 (10.0%) | 0 (00.0%) |
| Biochar is simple to make | 8 (80.0%) | 1 (10.0%) | 1 (10.0%) |
| Improves soil quality | 8 (80.0%) | 2 (20.0%) | 0 (00.0%) |
| Improves crop health | 7 (70.0%) | 3 (30.0%) | 0 (00.0%) |
| Retain water in soil | 7 (70.0%) | 3 (30.0%) | 0 (00.0%) |
| Remove pollutants from soil/water | 7 (70.0%) | 3 (30.0%) | 0 (00.0%) |
| Biochar can be produced from any organic waste | 5 (50.0%) | 0 (0.0%) | 5 (50.0%) |
| Harms soil when used in excess | 4 (40.0%) | 4 (40.0%) | 2 (20.0%) |
| Expensive compared to other soil amendments* | 3 (30.0%) | 5 (50.0%) | 2 (20.0%) |
| Prevent greenhouse gas emissions | 2 (20.0%) | 7 (70.0%) | 1 (10.0%) |
| Reduces the need for chemical fertilizers | 2 (20.0%) | 7 (70.0%) | 1 (10.0%) |
| Not a miracle* | 2 (20.0%) | 6 (60.0%) | 2 (20.0%) |

*Opinion based questions not included in biochar knowledge score.

Oklahoma, for example, said that "Farmers know about it, but I never had a question put to me or had any discussion with any farmer" (Participant 20). A sheep rancher with about 150 acres likewise noted that, "Nobody that I've talked to has used it" (Participant 17). This is indicative of how some producers felt that if they were to pursue using or producing biochar, that they would need to figure things out on their own: "So it's just me doing research on what would work in my small garden and then thinking about how that would work on a larger scale" (Participant 17). Participants widely described turning to the internet to learn more about biochar and its potential uses and benefits.

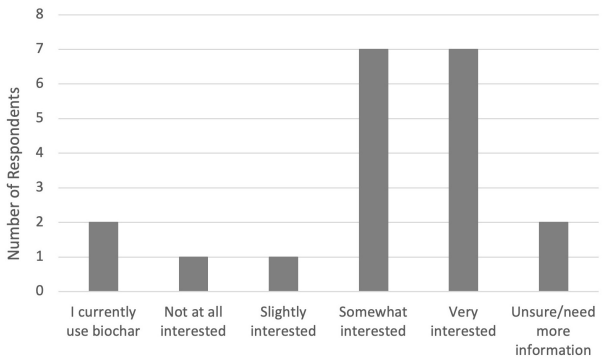



FIGURE 2
Bar graph showing survey respondents' level of interest in using biochar by Likert category.

## 3.2.2 Biochar use

Despite relatively low levels of awareness and use within our survey sample, eighty percent ($n = 16$) were either very or somewhat interested in using biochar on their farms (including those who currently use the product) and only 5% ($n = 1$) had no interest in using (Figure 2). The most common reasons identified to use biochar were to improve soil health (80%, $n = 16$) and water retention in the soil (65%, $n = 13$), followed by reducing the need for chemical fertilizer (45%, $n = 9$) and improving crop health (45%, $n = 9$; Table 6). On average, respondents identified 3.2 compelling reasons for using biochar.

Out of the seven survey respondents with experience using biochar, most (71.4%, $n = 5$) described their experience as neutral while the remaining 28.6% ($n = 2$) reported very positive experiences. These respondents also varied widely in their confidence using biochar, with an almost even split between those reporting being not at all (28.6%), slightly (14.3%), somewhat (28.6%), and very confident (28.6%). At the time of the survey, 42.9% of respondents no longer used biochar. The same number had been using biochar for 2 years or less, with only 14.3% ($n = 1$) using it for more than 5 years.

Focus group participants' perceptions of biochar were also overwhelmingly positive. For Participant 10, a state employee working in waste management, biochar is "a proven technology." Several producers wanted to see biochar gain greater traction among the farming community. One small vegetable farmer saw "great results with it" and "wanted to be a part of making it more of a mainstream and future thing for farmers and educators" (Participant 16). A sheep rancher interested in using biochar to improve their pastureland described biochar as part of making their farm sustainable:

> *If we're going to grow this farm, if we're going to get it to the point where we can hand it down to the next generation and have it be something and be productive… we've got to add carbon to the soil… because it retains the water, and the microbes and, just increas[es] the soil health. (Participant 17)*

Other producers stressed water retention, particularly during times of drought, and climate benefits, but, like the survey respondents, most saw soil and plant health as the primary benefits.

TABLE 6 Interest and reasons for and against using biochar ($N = 20$).

| Response options | Frequency (percent) Mean (std dev), min-max |
|---|---|
| Interest in using biochar | |
| Currently use | 2 (10.0%) |
| Very interested | 7 (35.0%) |
| Somewhat interested | 7 (35.0%) |
| Slightly interested | 1 (5.0%) |
| Unsure/need more info | 2 (10.0%) |
| Not at all interested | 1 (5.0%) |
| Number of reasons *for* using biochar | 3.2 (2.0), 0.0-8.0 |
| Improve soil health | 16 (80.0%) |
| Improve water retention in soil | 13 (65.0%) |
| Reduce the need for chemical fertilizers | 9 (45.0%) |
| Improve crop health | 9 (45.0%) |
| Remove pollutants from soil, such as heavy metals | 6 (30.0%) |
| Increase profitability of my operation | 5 (25.0%) |
| Prevent greenhouse gas emissions | 3 (15.0%) |
| Other convincing uses | 2 (10.0%) |
| There are no convincing reasons for me to use biochar | 1 (5.0%) |
| Number of reasons *against* using biochar | 2.1 (1.8), 0.0-6.0 |
| I don't know enough about biochar | 10 (50.0%) |
| I don't know how to apply biochar to my farm/land | 9 (45.0%) |
| Biochar is too expensive | 7 (35.0%) |
| I don't know where to purchase or obtain biochar | 7 (35.0%) |
| I'm not convinced biochar would benefit my farm or operation | 4 (20.0%) |
| I don't have any concerns or reasons preventing me from using biochar | 4 (20.0%) |
| I'm concerned that biochar may harm my soil or crops | 2 (10.0%) |
| Other reasons prevent me from using biochar | 2 (10.0%) |

Focus group participants with experience using biochar (35%, $n = 7$) described applying biochar directly in their gardens or crops, emphasizing its benefits in terms of moisture retention and enhanced microbial activity when integrated with compost or mixed into planting beds. An organic cannabis producer, for example, said "We use biochar in our soil. We use biochar every week... The plants really respond to carbon dumping in soil" (Participant 19). Participant 16, a vegetable farmer with about 10 acres, had been using biochar for 5 years and had a positive experience applying biochar to his vegetable beds to "increase soil tilth" and "transport healthy microbes and bacteria and fungi to those beds" (Participant 16). However, some participants also cautioned that the results could be difficult to measure: "You just know it's working but how do you quantify it? That's the hard part" (Participant 16). One participant who was less enthusiastic about biochar did not see any changes after applying it once on their garden: "We didn't actually see the outcome of it.... We didn't see any change and just kept right on doing other things" (Participant 14).

Although most producers saw biochar positively, both survey respondents and focus group participants raised concerns. For survey respondents, the most common reasons *against* using biochar were inadequate knowledge about biochar (50%, $n = 10$) or how to apply it (45%, $n = 9$). Other frequently cited reasons included biochar being too expensive (35%, $n = 7$) and not knowing where to purchase or obtain biochar (35%, $n = 7$). On average, respondents identified 2.1 reasons against using biochar.

Focus group participants also emphasized low levels of general knowledge but raised additional concerns that were not strongly reflected in survey findings, including biochar's potential to cause harm (a concern shared by only 10% of survey respondents). Participant 16, the small vegetable gardener, emphasized that biochar has "such high potential" but "can be either very good or very bad." In response to the video on the benefits on biochar, multiple participants cautioned against presenting biochar as a "magic bullet":

> *It's useful, but I feel like it's missing half the story because when you're missing the microbes, biochar won't replace those. You're going to have to have multiple additives for your soil to actually get the health back, and it completely skips that part, so you make it look like it's a miracle drug that's going to fix everything. And people who don't have the education to understand soil and the webs of life aren't going to see that and they're just going to get disappointed using it. (Participant 1)*

Others saw the need for more detailed information on application and local research demonstrating how biochar performs within Oklahoma's specific agricultural soils. One irrigation specialist, for example, raised questions about local efficacy, saying that:

> *[In Oklahoma,] we have 100 different climatic conditions, you know, many different kinds of soils. I am interested in how [biochar] performs in different climatic conditions and different soils. Every soil is different composition, how it is managed, it varies from one person to the other. (Participant 20)*

Other producers wanted to know how biochar affects soil pH and performs based on different types of feedstock and other soil additives.

For one participant, these concerns came from firsthand experience. A soil scientist working for one of Oklahoma's Tribal nations recounted a negative personal experience with biochar:

> *We just applied it to our lawn [where] we had some bare areas that we thought it could help benefit… Well, the grass that was there was no longer, it was eliminated completely [by the biochar]. And it just wasn't successful. But I know it was my failure, not the product failure. (Participant 4)*

For this participant, the experience highlighted the need for "a lot of education on correct application" for the public.

### 3.2.3 Biochar production

Interest in biochar production among survey participants was slightly lower than interest in use but still most (65%, $n = 13$) expressed interest in producing biochar (Table 7). Twenty percent ($n = 4$) were unsure or needed more information and 10% ($n = 2$) had no interest in producing biochar (Figure 3). The most common reasons identified to produce biochar included producing it for personal use (55%, $n = 11$) and selling it for profit (40%, $n = 8$; Table 6). Secondary reasons included helping with waste management (30%, $n = 6$) and that it may be faster and more efficient than composting (30%, $n = 6$). The most common reasons identified against producing biochar included not knowing enough about how to make biochar (55%, $n = 11$) and not having the right equipment or set-up to make biochar (55%, $n = 11$). The predominant secondary reason was not having a need or use for biochar (50%, $n = 10$).

Out of the four survey respondents with experience producing biochar, half ($n = 2$) described their experience as neutral while the other half ($n = 2$) reported very positive experiences. All four (100%) were very confident in their ability to produce biochar yet at the time of the survey, half were no longer producing biochar. Reasons for discontinuing production included cost and time. The other two respondents had been producing biochar for 1-2 years (25%, $n = 1$) and over 5 years (25%, $n = 1$). The most common production method was using a barrel (50%, $n = 2$), followed by pit (25%, n = 1) and wok (25%, n = 1). Seventy-five percent of respondents used local trees for feedstock (two reported using oak trees and the third did not specify).

Out of the 20 focus group participants, only three (15%) had experience producing biochar. One married couple with a 500-acre cattle and goat ranch experimented using the barrel method and found that "it takes a lot of time, it's nothing that's going to happen overnight" (Participant 14). The output was also small: "It was kind of a joke when we opened the canister, there was maybe two quarts of biochar. [I said,] 'Oh, wow, that took like almost an entire probably 12 h!'" (Participant 11). After this first attempt, they decided the output was not worth the time and effort. A pecan farmer who was hearing about biochar for the first time arrived at a similar conclusion: "It would take a lot of energy, a lot of manpower.… The benefit wouldn't outweigh the cost" (Participant 13).

For many larger farmers, the problem of scale dampened the appeal of producing biochar. An extension agent with 180 acres of his own land, managed primarily for wildlife, questioned "the economics of the whole thing" given the "the amount of energy, time, all that goes into it. How is this ever going to be a net benefit?" (Participant 12). Multiple participants concluded that producing biochar only made sense for smaller operations:

> *On a big scale, you know, it doesn't make sense, the economics. When you're actually doing it [farming] for business, it doesn't make sense. But if you're doing it as a hobbyist in your backyard and you're just trying to make a difference in the world, it makes sense. (Participant 12)*

The energy demands of biochar production raised concerns about the environmental cost of the process, with some farmers

TABLE 7 Interest and reasons for and against producing biochar ($N = 20$).

| Response options | Frequency (percent) Mean (std dev), min-max |
|---|---|
| **Interest in the production of biochar** | |
| Currently produce | 1 (5.0%) |
| Very interested | 6 (30.0%) |
| Somewhat interested | 6 (30.0%) |
| Slightly interested | 1 (5.0%) |
| Unsure/need more info | 4 (20.0%) |
| Not at all interested | 2 (10.0%) |
| Number of reasons *for* producing biochar | 1.8 (1.0), 1.0-4.0 |
| I can produce biochar for my own personal use | 11 (55.0%) |
| I can produce and sell biochar to increase the profitability of my operation | 8 (40.0%) |
| Biochar production can help with waste management | 6 (30.0%) |
| Creating biochar is faster and more efficient than composting | 6 (30.0%) |
| Other reason to produce biochar | 3 (15.0%) |
| There are no convincing reasons to produce biochar | 0 (0.0%) |
| Missing | 1 (5.0%) |
| Number of reasons *against* producing biochar | 1.9 (1.3), 0.0-5.0 |
| I don't know enough about how to make biochar | 11 (55.0%) |
| I don't have the right equipment or set up to make biochar | 11 (55.0%) |
| I don't have any need or use for biochar | 10 (50.0%) |
| Making biochar is too time consuming | 6 (30.0%) |
| I don't have excess agricultural or forestry waste to turn into biochar | 6 (30.0%) |
| I would prefer to purchase biochar | 3 (15.0%) |
| I don't have any concerns or reasons preventing me from producing biochar | 2 (10.0%) |
| Other | 0 (0.0%) |

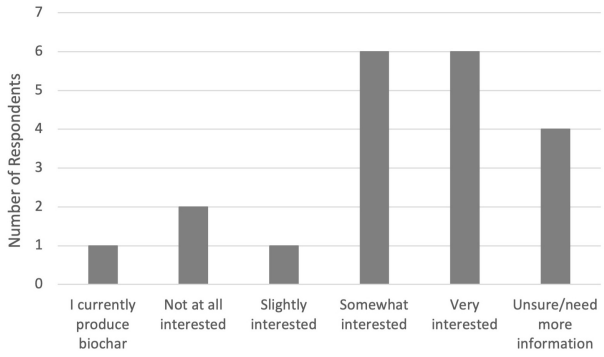



FIGURE 3
Bar graph showing survey respondents' level of interest in producing biochar by Likert category.

questioning whether the energy consumption could offset the carbon sequestration benefits that biochar promises. In discussing ways to make participating in the production process more economical for large operations, participants suggested carbon credits, third-party operations, and mobile pyrolysis units shared among multiple producers or land managers.

## 3.3 Predictors of biochar adoption and interest

Using Fisher's exact test of independence, multiple variables showed associations with producer interest and experience with biochar within our sample. Although only three relationships reached significance at the 5% level, we also report those with probable associations at the 10% level because they suggest patterns in need of further investigation. We found no significant association predicting interest in biochar use or production at the 5% level (Table 8). While just beyond the significance threshold ($p$-value = 0.06), respondents who practiced composting were more likely to express interest in producing biochar.

More variables showed significant relationships with experience using and producing biochar (Table 9). Large farms (over 200 acres) were significantly more likely to have experience producing biochar compared to small farms ($p$-value = 0.02). Large farms also showed an association with experience using biochar but failed to reach significance ($p$-value = 0.07). Perceived self-efficacy predicted experience with biochar as well. Producers who "strongly agreed" that they knew how to manage soil health were more likely to have experience using ($p$-value = 0.06) and producing ($p$-value = 0.01) biochar. Additionally, producers who practice composting were more likely to have experience producing biochar ($p$-value = 0.09).

Notably, those who self-identified as practicing regenerative or sustainable agriculture were no more likely than other producers to have interests or experience in biochar. Measures of social values, norms, and expectations related to sustainability and land stewardship likewise failed to show a significant relationship.

## 3.4 Opportunities and barries to adoption in ERC management

Just under half of the survey respondents (45%, $n = 9$) reported problems with ERC on their property but just over half (60%, $n = 12$) actively managed ERC on their property. Out of those who actively managed ERC, the most common methods of disposal were burning the material on site (75%, $n = 8$) and leaving the waste on the land (33%, $n = 4$). When asked about the level of satisfaction with their current method of managing ERC waste, most either indicated that they were satisfied (25%, $n = 3$) or unsure (25%, $n = 3$). Additionally, most respondents were only slightly interested in producing biochar out of ERC waste (33%, $n = 4$) but two people indicated that they were very interested (17%, $n = 2$) and one person indicated that they already make biochar out of ERC waste.

Compared to survey respondents, focus group participants expressed stronger enthusiasm about the potential to use biochar in ERC waste management. An extension agent, having only seen the problem worsen since the mid-1990s, saw the need to "start thinking outside the box" (Participant 12). A rancher with about 350 acres described the appeal of turning ERC into biochar:

> *I'm going to clear all these trees on my land and I'm either going to let it just rot over the next decades and all that carbon goes back in the atmosphere, or we could lock it away and improve, you know, homes for microbes in the soil and benefit soil. (Participant 15)*

Within his network of farmers, he saw "a lot of deep interest…[about] how they can improve soil health and rid a lot of these overly abundant woody species on their land" (Participant 15). Biochar presented a potential "win-win" to address both. Although Participant 15 had been contemplating the use of biochar to reclaim grazing land from ERC on his own ranch, it remained theoretical: "[I] have no way to accomplish that yet. It's just so much volume [of ERC]. Like, it's unbelievable volumes."

Although participants expressed strong support for the idea in the abstract, converting ERC into biochar presented the same challenges as biochar production generally, including the issues of time, cost, energy, and scale. A state conservation officer supporting small urban farmers noted that the "greatest resource need for a farmer is time" (Participant 3). This meant that if a producer's primary goal was removing ERC, introducing biochar into the process would not be the "fastest most efficient way to do it." He, therefore, concluded, "it's a great idea to try to utilize a negative and make it a resource, but it's really going to have to be somebody that's interested in producing biochar" more than removing ERC (Participant 3). Although most farmers were unlikely to convert ERC to biochar on their own, participants saw strong potential for market development. Participant 3 again explained that, in many places throughout the state "it can be challenging…to find any carbon amendment, not just biochar….So, I like the idea of maybe another market kind of coming into play."

Several participants suggested collaborative efforts to overcome the barriers to biochar adoption. Since the mass amounts of biomass from ERC would make off-site production challenging,

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TABLE 8 Fishers Exact Test (2-sided) on Interest in Biochar Use and Production.

| Response options | Interest in using biochar | | | Interest in producing biochar | | | Total |
|---|---|---|---|---|---|---|---|
| | No | Yes | *p* | No | Yes | *p* | |
| **Small farm** | | | | | | | |
| No | 1 (33.3%) | 7 (43.8%) | 1.00 | 3 (50.0%) | 5 (38.5%) | 1.00 | 8 (42.1%) |
| Yes | 2 (66.7%) | 9 (56.2%) | | 3 (50.0%) | 8 (61.5%) | | 11 (57.9%) |
| **Manage livestock** | | | | | | | |
| No | 0 (0.0%) | 5 (31.2%) | 0.53 | 1 (16.7%) | 4 (30.8%) | 1.00 | 5 (26.3%) |
| Yes | 3 (100.0%) | 11 (68.8%) | | 5 (83.3%) | 9 (69.2%) | | 14 (73.7%) |
| **Grow crops** | | | | | | | |
| No | 3 (100.0%) | 7 (43.8%) | 0.21 | 3 (50.0%) | 7 (53.8%) | 1.00 | 10 (52.6%) |
| Yes | 0 (0.0%) | 9 (56.2%) | | 3 (50.0%) | 6 (46.2%) | | 9 (47.4%) |
| **Compost** | | | | | | | |
| No | 2 (66.7%) | 7 (43.8%) | 0.58 | 5 (83.3%) | 4 (30.8%) | 0.06 | 9 (47.4%) |
| Yes | 1 (33.3%) | 9 (56.2%) | | 1 (16.7%) | 9 (69.2%) | | 10 (52.6%) |
| **Regenerative or sustainable farm** | | | | | | | |
| No | 1 (50.0%) | 3 (21.4%) | 0.45 | 2 (33.3%) | 2 (20.0%) | 0.60 | 4 (25.0%) |
| Yes | 1 (50.0%) | 11 (78.6%) | | 4 (66.7%) | 8 (80.0%) | | 12 (75.0%) |
| **Perceived self-efficacy** | | | | | | | |
| No | 3 (75.0%) | 9 (56.2%) | 0.62 | 4 (57.1%) | 8 (61.5%) | 1.00 | 12 (60.0%) |
| Yes | 1 (25.0%) | 7 (43.8%) | | 3 (42.9%) | 5 (38.5%) | | 8 (40.0%) |
| **Profit oriented** | | | | | | | |
| No | 2 (66.7%) | 4 (28.6%) | 0.52 | 3 (50.0%) | 3 (27.3%) | 0.60 | 6 (35.3%) |
| Yes | 1 (33.3%) | 10 (71.4%) | | 3 (50.0%) | 8 (72.7%) | | 11 (64.7%) |
| **Stewardship importance** | | | | | | | |
| No | 2 (50.0%) | 3 (18.8%) | 0.25 | 2 (28.6%) | 3 (23.1%) | 1.00 | 5 (25.0%) |
| Yes | 2 (50.0%) | 13 (81.2%) | | 5 (71.4%) | 10 (76.9%) | | 15 (75.0%) |
| **Sustainability interest** | | | | | | | |
| No | 2 (66.7%) | 5 (33.3%) | 0.53 | 3 (50.0%) | 4 (33.3%) | 0.63 | 7 (38.9%) |
| Yes | 1 (33.3%) | 10 (66.7%) | | 3 (50.0%) | 8 (66.7%) | | 11 (61.1%) |
| **Social expectations** | | | | | | | |
| No | 0 (0.0%) | 8 (53.3%) | 1.00 | 3 (60.0%) | 5 (45.5%) | 1.00 | 8 (50.0%) |
| Yes | 1 (100.0%) | 7 (46.7%) | | 2 (40.0%) | 6 (54.5%) | | 8 (50.0%) |
| N | 4 (20.0%) | 16 (80.0%) | | 7 (35.0%) | 13 (65.0%) | | 20 (100%) |

Sample size for each test differs because of missing data (see Table 4).

participants responded positively to the mobile pyrolysis machine either owned and operated by a third party or purchased jointly:

> *I think the incentive is going to have to come through the form of some type of cost sharing. I think that's what really gets the attention [of producers], and… this whole collaborative approach, this landscape scale approach. (Participant 8)*

By pooling resources and sharing equipment, farmers could reduce the individual financial burden and logistical complexity of biochar production.

## 4 Discussion

Similar to previous biochar research, our study finds relatively widespread biochar awareness and interest among producers in our samples combined with low levels of adoption. The level of interest in using biochar was quite high among survey respondents (80%), particularly for the purpose of improving soil health (80%) and water retention (65%). However, most respondents cited a lack of knowledge, either about biochar (50%), how to apply it (45%), or where to obtain it (35%), as a primary reason not to use it. This aligns well with the findings of other U.S.-based biochar

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TABLE 9 Fishers Exact Test (2-sided) on Experience Using and Producing Biochar.

| Response options | Experience using biochar | | | Experience producing biochar | | | Total |
|---|---|---|---|---|---|---|---|
| | No | Yes | *p* | No | Yes | *p* | |
| **Small farm** | | | | | | | |
| No | 3 (25.0%) | 5 (71.4%) | 0.07 | 4 (26.7%) | 4 (100.0%) | 0.02 | 8 (42.1%) |
| Yes | 9 (75.0%) | 2 (28.6%) | | 11 (73.3%) | 0 (0.0%) | | 11 (57.9%) |
| **Manage livestock** | | | | | | | |
| No | 3 (25.0%) | 2 (28.6%) | 1.00 | 4 (26.7%) | 1 (25.0%) | 1.00 | 5 (26.3%) |
| Yes | 9 (75.0%) | 5 (71.4%) | | 11 (73.3%) | 3 (75.0%) | | 14 (73.7%) |
| **Grow crops** | | | | | | | |
| No | 7 (58.3%) | 3 (42.9%) | 0.65 | 8 (53.3%) | 2 (50.0%) | 1.00 | 10 (52.6%) |
| Yes | 5 (41.7%) | 4 (57.1%) | | 7 (46.7%) | 2 (50.0%) | | 9 (47.4%) |
| **Compost** | | | | | | | |
| No | 6 (50.0%) | 3 (42.9%) | 1.00 | 9 (60.0%) | 0 (0.0%) | 0.09 | 9 (47.4%) |
| Yes | 6 (50.0%) | 4 (57.1%) | | 6 (40.0%) | 4 (100.0%) | | 10 (52.6%) |
| **Regenerative or sustainable farm** | | | | | | | |
| No | 4 (40.0%) | 0 (0.0%) | 0.23 | 4 (33.3%) | 0 (0.0%) | 0.52 | 4 (25.0%) |
| Yes | 6 (60.0%) | 6 (100.0%) | | 8 (66.7%) | 4 (100.0%) | | 12 (75.0%) |
| **Perceived self-efficacy** | | | | | | | |
| No | 10 (76.9%) | 2 (28.6%) | 0.06 | 12 (75.0%) | 0 (0.0%) | 0.01 | 12 (60.0%) |
| Yes | 3 (23.1%) | 5 (71.4%) | | 4 (25.0%) | 4 (100.0%) | | 8 (40.0%) |
| **Profit oriented** | | | | | | | |
| No | 5 (45.5%) | 1 (16.7%) | 0.33 | 6 (46.2%) | 0 (0.0%) | 0.24 | 6 (35.3%) |
| Yes | 6 (54.5%) | 5 (83.3%) | | 7 (53.8%) | 4 (100.0%) | | 11 (64.7%) |
| **Value land stewardship** | | | | | | | |
| No | 4 (30.8%) | 1 (14.3%) | 0.61 | 5 (31.2%) | 0 (0.0%) | 0.53 | 5 (25.0%) |
| Yes | 9 (69.2%) | 6 (85.7%) | | 11 (68.8%) | 4 (100.0%) | | 15 (75.0%) |
| **Sustainability interest** | | | | | | | |
| No | 6 (50.0%) | 1 (16.7%) | 0.32 | 7 (50.0%) | 0 (0.0%) | 0.12 | 7 (38.9%) |
| Yes | 6 (50.0%) | 5 (83.3%) | | 7 (50.0%) | 4 (100.0%) | | 11 (61.1%) |
| **Social expectations** | | | | | | | |
| No | 6 (60.0%) | 2 (33.3%) | 0.61 | 7 (58.3%) | 1 (25.0%) | 0.57 | 8 (50.0%) |
| Yes | 4 (40.0%) | 4 (66.7%) | | 5 (41.7%) | 3 (75.0%) | | 8 (50.0%) |
| N | 13 (65.0%) | 7 (35.0%) | | 16 (80.0%) | 4 (20.0%) | | 20 (100%) |

Sample size for each test differs because of missing data (see Table 4).

studies. In both cases (New York and New Mexico), a lack of knowledge was cited as the most prevalent barrier to use (Sherman, 2022; Ynfante et al., 2024). Secondarily, survey respondents cited the expense of biochar as a reason against using it (35%), which also aligns well with a lack of funding, which was described as a secondary barrier by Sherman (2022) and Ynfante et al. (2024).

Survey respondents were generally more interested in using biochar than producing it. This may be related to the commitment required to become a producer and the desire to establish prior value, reflected in the 40% of respondents who saw increasing the profitability of their operation as a compelling reason for producing biochar. At the 10% significance level, interest in producing biochar ($p$-value = 0.06) or even having experience producing biochar ($p$-value = 0.09) is associated with practicing other sustainable agricultural techniques, namely composting. This may indicate that those who have found success in practicing other sustainable agricultural techniques may desire expanding their repertoire of practices and gives them some confidence in doing so.

Additionally, while focus group discussions suggested that biochar production is most economically feasible for small farms due to scalability challenges, survey results revealed a significant correlation between larger farms (>200 acres) and prior experience with biochar production ($p$-value = 0.02). This discrepancy may stem from differing interpretations of farm size: our survey classified farms over 200 acres as "large," whereas focus group participants may have considered this relatively small, especially in the context of Oklahoma, where the average commercial farm exceeds 1,000 acres. Furthermore, only 26% (n = 5 of the 19 respondents who reported this demographic) operated farms classified as hobby or backyard farms (≤5 acres). These inconsistencies in terminology or representation may have contributed to a disconnect between perceived ideal farm size for biochar production and the patterns observed in the data.

A predominant reason against producing biochar is a lack of knowledge, particularly on how to make it (55%). Self-reported levels of biochar knowledge appear to align well with actual levels of biochar knowledge. Most respondents who were familiar with biochar (90%) self-reported limited to moderate levels of biochar knowledge and the majority of participants (70% or greater) agreed with over half (60%) of factual biochar statements. Notably, the number of survey respondents who selected unsure/need more info/no opinion on factual biochar statements ranged from 10-70%. Biochar's climate benefits, for example, was one of the statements with high levels of "unsure" responses (70%). A potential reason may lie in the uncertainty of offsetting greenhouse gas emissions from using fossil fuel to power the production process with the carbon sequestration gains by reincorporating biochar onto the land. The controversial nature of climate change and climate action, a point raised during focus groups, may also help explain this response.

Lastly, a notable metric is that half of the participants (50%) disagreed with the statement that biochar can be produced from any organic waste, which may be indicative of a lack of knowledge regarding the production of biochar. Education and training may, thus, increase the level of interest in and production of biochar. Many focus group participants shared that by the end of the session, they had learned significantly more about biochar and its potential just by engaging in the facilitator-led discussion and hearing others knowledge on the topic. Biochar education efforts have already proven successful in other contexts. Midwest extension services have successfully increased awareness and adoption of biochar through workshops and educational programming (Colclasure et al., 2024). Similar initiatives in Oklahoma could leverage these approaches to not only demonstrate biochar's benefits and address barriers to adoption but also increase accessibility to this knowledge.

The growing interest in sustainable agriculture among Oklahoma farmers suggests that biochar could play a complementary role in broader regenerative farming practices. Farmers who are already invested in sustainable land management are more inclined to experiment with biochar, seeing it as a tool that aligns with their environmental goals. However, the success of such initiatives will depend heavily on the availability of support systems, including training, funding, and clear guidance on biochar's application and benefits.

There was a greater number of survey respondents that indicated they were actively managing ERC compared to the number that indicated they had a problem with ERC. This perhaps indicates that some participants once had a problem with ERC and had been able to control it using proper management or that they are proactively managing their land for ERC for reasons besides having a problem with ERC growth. Although there was a moderately high level of interest in biochar production (65%) there was a mixed level of interest in producing biochar out of ERC waste, with 33% saying they were only slightly interested. This difference may be explained if producers generally desire to produce biochar out of other organic material, which was not captured by the survey. Since the majority of survey respondents burn ERC waste onsite, a major challenge to ERC biochar adoption may lie in producers switching from a waste management technique that they know works and that they consider relatively easy to one that requires more investment of both time and resources. Educational resources that discuss the benefits of making biochar over burning the material may increase the level of interest in making biochar out of ERC waste. Additionally, not having the right equipment or set-up to make biochar was cited as another reason against producing it (55%). Providing resources in the form of grants or low-interest loans may also increase the level of interest in and production of biochar. The focus groups also raised many challenges associated with creating biochar out of ERC at the scale that would be required for large infestations. This issue is one that is not easily addressed at the individual level and requires collaboration to pool resources or establish a new market.

Our study has several limitations. As a small and non-representative sample, our study is exploratory and hypothesis-generating. As such, these preliminary findings suggest potential avenues for future investigation but cannot be generalized to Oklahoma or US farmers more broadly. The small survey sample also limited our statistical power and ability to detect patterns which may emerge in larger samples. This may help explain our lack of correlations related to biochar interest, where only one out of twenty tests approached significance.

Certain demographic groups were overrepresented within our survey sample. Compared to national (U.S.) and Oklahoma producer statistics, our survey was more representative of women (50% vs. 36% for the nation and 38% for Oklahoma) and non-Native producers of color (20% vs. <5% nationally and <2% for Oklahoma) (United States Department of Agriculture National Agriculture Statistics Service, 2024a,b). Additionally, our survey was more representative of Native Americans at the national level (10% vs. <2% nationally) but equally representative of this demographic for the State of Oklahoma (United States Department of Agriculture National Agriculture Statistics Service, 2024a,b). Our survey sample was also proportionally younger, with the majority (75%) falling between 35 and 64 years old for the survey while the national and state (OK) proportion for this age range is 53% (United States Department of Agriculture National Agriculture Statistics Service, 2024a,b). Lastly, the survey was more representative of newer producers with 50% having farmed for 10 years or less compared to 30% nationally and 32% for Oklahoma (United States Department of Agriculture National Agriculture Statistics Service, 2024a,b). These differences are likely due to

biases in the demographics of those who were aware of the study and personal/professional levels of interest in participating, more broadly, or in biochar, more specifically.

This study likely over-represented people with some level of biochar awareness, knowledge, or experience. Half of the online survey participants (50%) had some familiarity with biochar prior to the survey, approximately one-third (35%) had experience using biochar, and one-fifth (20%) had experience producing it. This is much larger than the rough approximation personally communicated to the authors (1% of rural farmers are likely familiar with biochar, with even fewer using or producing it) (G. Kloxin, Oklahoma Conservation Commission, personal communication, 2024) and assessment from focus group participants. It is likely that our study attracted participants with a higher level of personal/professional interest in biochar, motivated by a desire to discuss the topic.

Similarly, our study may have disproportionately attracted producers already engaged in some form of sustainable agricultural practices with over half of the participants indicating that they compost and over half of row crop producers indicating that they farm without chemical pesticides. A large proportion (60%) indicated that they practice sustainable or regenerative agriculture, and almost all agreed on the importance of being a good steward of the land. However, these terms were not explicitly defined within the survey and were left to interpretation and opinion by the respondent. Since there was an overrepresentation of producers already practicing some form of sustainable agricultural practice, this would have likely resulted in an increase in biochar knowledge and/or interest, skewing the overall survey results. Although a large proportion (85%) expressed interest in learning more about sustainability, this doesn't necessarily translate to direct action in either learning more about sustainability or implementing sustainable practices. Participating in the survey itself may have acted to increase this desire or been an actionable step toward their goal of learning more. Overall, the limitations and biases of this pilot study may help better inform the development of future, larger-scale, representative studies.

## 5 Conclusion

The study provides useful insights into the barriers, perceptions, and opportunities related to adoption of biochar and more sustainable waste management practices for ERC. These findings can help to develop targeted outreach and education strategies to promote biochar as an option for sustainable land management. The goal of the research was to support sustainable farming, restore ecosystems, and address waste management challenges associated with ERC by overcoming individual and structural challenges that serve as barriers to adoption. By conducting public outreach and facilitating discussion, this goal was achieved on a small scale through participants' engagement in the study itself.

Our findings suggest that while biochar holds significant promise as both a waste management tool for invasive ERC and a soil amendment for improving agricultural sustainability, its adoption faces significant challenges. While knowledge, information, and skills remain key barriers to increased adoption, the educational and material infrastructure that could help address these gaps currently does not exist in Oklahoma. As such, even some of the most enthusiastic proponents of biochar in our study struggled to envision pathways to widespread adoption. Since integrating biochar into ERC management at scale requires new practices, technologies, and markets, developing more communities of practice and organizational support offers one potential step in this direction. Collaborative approaches, financial incentives, and greater dissemination of localized research could play a critical role in overcoming these barriers and facilitating broader adoption of biochar in Oklahoma's farming community. Ultimately, the future of biochar in Oklahoma depends on addressing these challenges through targeted technical support from local extension services, financial support such as cost-share programs and/or conversation grants and education opportunities such as field tours and demonstration site visits, ensuring that farmers can access both the knowledge and resources needed to make informed decisions. While biochar may not yet be a widely adopted technology, its potential to contribute to sustainable land management, particularly in addressing the challenges posed by Eastern Red Cedar, suggests that it warrants further exploration and support.

As Oklahoma faces increasing challenges from both climate change and the encroachment of invasive red cedar trees, finding a long-term and sustainable solution is critical for the future of agricultural and natural lands. Current methods of controlling ERCs are not only costly but lack a long-lasting ecological benefit. These practices often leave landowners with limited options, leading to a lack of sustainable land management. However, biochar offers a unique opportunity to address both the environmental degradation caused by WPE and the need for soil amendments. Biochar's potential to improve soil health, enhance water retention, and sequester carbon can make a tangible impact on land productivity while providing farmers and ranchers with an additional revenue stream.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by OU Norman Campus Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

LH: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft. LB: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project

administration, Supervision, Writing – original draft. SP: Formal analysis, Investigation, Writing – original draft. LB: Data curation, Formal analysis, Writing – original draft. RN: Funding acquisition, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2025.1718022/full#supplementary-material

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