CO HB 23-1069 Pilot Study Recommendation Outline

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The following document has been prepared in accordance with Colorado house bill 23-1069 to provide recommendations for the development of a pilot program to study the use of biochar in the plugging of oil and gas wells.

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Project Overview

Background

Since the mid-1800s, millions of oil and gas wells have been drilled in the U.S., and as of 2018, around 2.1 million inactive wells remain unplugged (Raimi et al., 2021). Many of these wells are abandoned due to insufficient financial assurance for proper decommissioning, leaving the cost of plugging left to taxpayers (Bureau of Land Management, 2019). Unplugged wells pose significant risks, including methane emissions and contamination of surface and groundwater from degrading well materials (Kang et al., 2016). On average, unplugged wells emit far more methane than plugged wells, contributing to greenhouse gas (GHG) emissions and environmental hazards (Riddick et al., 2024). Addressing this issue is critical for both environmental and public health (Ku et al., 2024).

Colorado, the fifth-largest crude oil producer in the U.S., has over 53,000 active wells, primarily in the Denver-Julesburg Basin (U.S. Energy Information Administration, 2023). As of 2023, there are approximately 33,000 unplugged and abandoned wells in the state, contributing significantly to methane emissions, well above the national average (Riddick et al., 2024). Biochar, a carbon-rich bio-based material derived from various feedstocks, has shown potential as an additive in well-plugging operations due to its ability to enhance well integrity and sequester carbon, offsetting CO_2e emissions (Lin et al., 2023). However, its effectiveness varies based on production methods and field conditions, and thus an under-explored solution for reducing GHG emissions in Colorado's oil and gas sector (Liu et al., 2022).

Greenhouse Gas Impact & Outcomes

Colorado has set ambitious GHG emission reduction goals, targeting a 50% cut by 2030, 75% by 2040, and achieving net-zero emissions by 2050, based on 2005 levels of 140 million metric tons of CO_2e (GHG Pollution Reduction Roadmap 2.0, 2023). The oil and gas industry, responsible for 14.4% of the state's 2005 emissions, plays a critical role in meeting these targets (Colorado Oil and Gas Association, 2023). One key opportunity for emission reductions lies in orphan well plugging, which traditionally requires large amounts of cement, a significant GHG emitter. Utilizing biochar as an alternative in well plugging could lower emissions. For instance, plugging 1,000 orphaned wells in Colorado with biochar could reduce emissions by 8,994 tonnes CO_2e, accounting for a 0.04% reduction in the 2005 baseline emissions from oil and gas (Roth et al., 2024). If biochar were applied to all 33,000 unplugged wells in the state, the emissions reduction could be as much as 1.5%.

On a national level, the impact of using biochar in well plugging could be substantial. With over 2.1 million unplugged wells across the U.S., plugging them with biochar could reduce CO_2e emissions from an average of 11.4 tonnes to 2.4 tonnes per well (Roth et al., 2024). This equates to a total reduction of roughly 18.9 million tonnes of CO_2e nationwide. As the U.S. shifts toward renewable energy, more wells will require decommissioning, and expanding the use of biochar in well plugging can contribute to national GHG reduction targets while supporting long-term sustainability goals. By integrating biochar, well-plugging can become a more environmentally responsible practice, helping to advance the country's transition to a low-carbon future.

Technical Description

Final Report Overview

A recent assessment report that was prepared in accordance with Colorado house bill 23-1069 provided an in-depth analysis of the potential for using biochar in oil and gas well plugging operations (Roth et al., 2024). The findings show that biochar, a carbon-rich material derived from various feedstocks, offers several promising applications, including its use as a cement additive, a gas sorbent, and a means of carbon sequestration to offset CO_2e emissions. Early studies demonstrate that biochar can lower GHG emissions and improve cement strength under specific conditions, making it a valuable addition to plug and abandonment (P&A) operations. However, biochar's effectiveness varies based on production methods, feedstock choice, and environmental conditions, which means further research is needed to understand its full potential in these applications.

A review of state and federal laws revealed that biochar, along with other supplementary materials, is not explicitly mentioned in regulations governing well plugging. Both Colorado's code of regulations and federal regulations would require a variance to be granted before biochar or any non-standard material could be used in cement mixtures for well plugging. This indicates that before biochar can be widely adopted for P&A operations, regulatory approval is necessary. These findings suggest that legislative updates or special permissions may be required for biochar to be used on a large scale in oil and gas infrastructure projects, but the environmental benefits warrant further investigation into how these approvals could be obtained.

The report highlighted challenges in modeling the chemical and physical effects of incorporating biochar into cement due to its variability. Existing geomechanical models, such as the pore partitioning model, often underestimate cement strength when biochar is included, and models that assess the impact of high temperatures in oil and gas wells do not account for supplementary materials like biochar. This uncertainty underscores the need for further experimental testing to understand how biochar behaves in these environments. To address this, the report included laboratory tests on biochar-cement mixtures using biochar derived from woody biomass and mixed with Portland cement in varying percentages. The tests showed that up to 3% biochar addition improved flow rate and compressive strength, though chloride and sulfate ions slightly reduced strength over a 28-day period, while produced water (PW) had no significant effect. These results suggest biochar can enhance cement strength under controlled conditions, but further long-term testing is needed to confirm its durability in well environments, especially in the presence of common chemicals.

The report also conducted a cost analysis comparing traditional well-plugging methods to those incorporating biochar. Adding biochar increased costs by 2%, largely due to the material's purchase price. However, biochar could offer environmental benefits and the potential to earn carbon credits, which could offset these costs. The life cycle assessment (LCA) examined various biochar production methods, including stationary systems like rotary kilns and mobile carbonizers, and showed that biochar can significantly reduce emissions from well-plugging, lowering CO_2e emissions from 11.4 tonnes to as little as 0.64 tonnes per well, depending on the production method. Additionally, biochar's ability to serve as a long-term carbon sink was a critical finding. When used in well-plugging, biochar can trap carbon indefinitely, helping offset emissions from other oil and gas processes. While current carbon markets do not recognize biochar for carbon credits in this application, the report suggested that future regulatory changes may allow operators to earn credits, making biochar a more attractive and viable option for reducing emissions in the industry.

One concern raised in the report was the potential hazards and technical challenges associated with biochar's use in well-plugging. The density of the biochar-water slurry used as a spacer plug (SP) that is placed between cement plugs is lower than that of traditional materials, raising questions about its ability to hold cement plugs in place. This could compromise the effectiveness of the well-plugging operation if the biochar spacer fails to support the cement barrier adequately. Additionally, there are potential health and environmental risks related to biochar production, especially if feedstocks like biosolid sludge or animal waste are used, as these can release volatile organic compounds (VOCs) and other harmful contaminants. The report stressed the importance of monitoring biochar feedstock sources and production methods to minimize risks to local communities and ecosystems.

To address concerns raised in the report, a pilot-scale experiment was recommended to validate the effectiveness of biochar in well-plugging. This experiment would involve monitoring wells plugged with biochar to assess their long-term ability to trap gases, prevent leaks, and endure the harsh conditions typical in oil and gas environments. The pilot study should also explore biochar's behavior under various wellbore conditions, such as elevated temperatures and pressures, and its interactions with contaminants like chloride and sulfate. Additionally, the study should consider the community impacts of using biochar in plugging orphaned oil and gas wells. The report concluded that biochar has both the technical and logistical potential to be used in well-plugging operations, offering significant environmental benefits, such as reducing the oil and gas industry's carbon footprint, preventing the release of harmful gases, and providing the opportunity to earn carbon credits. However, further testing and pilot-scale validation are necessary to confirm these findings and ensure safe, effective integration of biochar into well-plugging practices. These recommendations lay the foundation for the next phase of the project, which involves developing a comprehensive experimental plan to assess biochar's potential in well-plugging on a larger scale.

Project Objectives

The proposed work aims to advance the use of biochar in orphan well plugging by optimizing biochar properties for enhanced carbon sequestration and emissions reduction. Specifically, the project will involve laboratory testing of different biochar types to identify the optimal characteristics for well integrity and maximum carbon sequestration potential. Following this, two orphan wells will be plugged—one using biochar and the other using traditional methods—allowing for comparative monitoring of methane emissions and VOCs. In parallel, the project will engage in environmental justice community outreach, ensuring active participation from local stakeholders and addressing community concerns related to the impacts and benefits of the project. The proposed project has a duration of 4 years and integrates laboratory research, field testing, emissions monitoring, and community engagement to deliver both environmental and social benefits.

Task 1 – Laboratory Testing (25 months)

- Manufacture biochar from various feedstocks (timber residuals, municipal biosolids, grassy biomass) with tailored properties and particle sizes.
- Test the density and rheology of spacer plug-biochar mixture (SPbc) with various biochar formulations under heat and pressure, conduct chemical tests (rotor, SSST, drop angle), and assess methane sorption to identify optimal mixes. Ion and DOC sorption, rheology changes, and cement curing tests will also be performed.
- Determine the property requirements of the SPbc to support placement of the cement through material testing and plug placement experiments in combination with simulations to simulate downhole conditions.

Task 2 – Downhole Experiment (16 months)

- Select two wells with similar characteristics for the study, one to be plugged traditionally and one with biochar in the SP, ensuring compliance with regulatory standards.
- Conduct baseline in addition to 1-,2-,3-, and 12-month post-plugging methane and VOC emission measurements at both wells, using static flux chambers to quantify emission differences.

- Analyze air samples collected during the pilot study and compile results for final reporting.

Task 3 – Environmental Justice Outreach (24 months)

- Conduct community identification and mapping to locate disproportionately affected communities, focusing on those near orphan wells and biochar manufacturers.
- Facilitate community engagement through workshops, meetings, and focus groups, ensuring transparent communication and addressing community concerns about air quality, health risks, and biochar production.

Final Deliverables

The final deliverable for this pilot study will be a comprehensive technical report detailing the experimental evaluation of biochar in well-plugging operations. It will include laboratory results assessing various biochar feedstocks and thermochemical conversion methods to determine optimal properties for carbon sequestration and wellbore integrity. Downhole data, including methane emissions and VOC measurements, will be presented alongside a comparative analysis of biochar-plugged and non-biochar wells, focusing on any necessary modifications to standard well-plugging practices. The report will also address environmental justice considerations through community involvement, operational insights, and best practices, concluding with recommendations for future studies, policy adjustments, and scalability opportunities for biochar use in the oil and gas industry.

Work Plan

Task 0: Project Management

Team Members

The following team members contributed to developing this pilot study experimental plan and have expressed interest in continuing work on the project. While not guaranteed participation if the project proceeds, they are suggested as potential partners and have the capacity to contribute and complete the outlined work.

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Coordination & Research

Project management for this study will be overseen by CSU, led by Thomas Borch, Brooke Ballenger, and Jason Quinn. This team will be responsible for overseeing all aspects of project coordination and ensuring timely completion of tasks and deliverables. The entire team will hold quarterly teleconferences to review progress, coordinate tasks, and ensure alignment with project objectives. University researchers will periodically spend time at the field sites during key phases of the project, such as the well plugging operations and emissions monitoring, to oversee and support fieldwork. Annual reports will be prepared to provide an overall update on project progress, technical developments, and the alignment of project goals.

End-of-task reports will also be submitted to summarize findings and key outcomes as each task is completed, ensuring that all team members and stakeholders remain informed.

Risk management, project changes, and quality assurance

The team will develop standard operating procedures that will be shared documents to assure that the biochar sample analysis is consistent and of high quality. For project changes, the leadership team will work together to discuss changes to the project to minimize risks.

Potential Funding Opportunities

Several opportunities exist to secure funding for the pilot program on biochar use in well plugging. The Bipartisan Infrastructure Law Section 40601(d) offers $4.7 billion for orphaned well plugging, with $4.3 billion directed to state programs. These funds, managed by the Department of the Interior's Orphaned Wells Program Office, can be accessed to cover remediation, plugging, and reclamation of orphan wells on state and private lands. Additionally, the Methane Emissions Reduction Program, managed by the Environmental Protection Agency (EPA), provides financial support for projects aimed at reducing methane emissions from petroleum and natural gas systems. This program could help fund research into biochar's effectiveness in mitigating methane emissions, which is a critical component of this experimental plan.

Two grant opportunities were identified during a search of grant websites, as outlined in Table 1 below. A challenge encountered in evaluating potential funding sources was that many deadlines had already passed, prior to the December 1st target for this pilot study plan. Due to the timing limitations, many funding opportunities were unavailable by the time an application could be prepared. To address this, it is recommended that grant websites (such as grants.gov and energy.gov/eere/fundings) be checked periodically when capacity allows for applying to relevant funding opportunities. Search terms used included "biochar," "well plugging," "carbon storage," "orphan wells," "carbon sequestration," "carbon capture," and "methane monitoring."

Table 1: Identified Grant Opportunities for Pilot Study Funding

Opportunity Title	Agency	Opportunity Status	Close Date	Amount
Notice of Intent to Issue Funding Opportunity Announcement #DE-FOA-0003343 entitled Undocumented Orphaned Well Research and Development	DOE-NETL	DE-FOA-0003377[1]	01/31/2025	Varies
BIL – Carbon Utilization Procurement Grants under Bipartisan Infrastructure Law Section 40302	DOE-NETL	DE-FOA-0002829[2,3]	04/30/2025	50,000-500,000 with minimum of 50% cost-sharing from awardees

[1] https://www.grants.gov/search-results-detail/355391
[2] https://www.grants.gov/search-results-detail/349523
[3] https://www.energy.gov/fecm/funding-notice-bipartisan-infrastructure-law-carbon-utilization-procurement-grants

Private foundations also represent a potential funding source. The Terraset Climate Foundation and the Quadrature Climate Foundation both support initiatives that combat greenhouse gas emissions, including innovative approaches such as biochar to reduce methane and sequester carbon. Oil and gas companies aiming for sustainability goals are another avenue for potential collaboration and funding. For example, companies like Shell, which has committed to achieving net-zero emissions by 2050, may be interested in supporting or partnering on projects that align with their emissions reduction strategies.

Emerging legislation on industrial emissions and carbon removal may also offer additional funding opportunities. Bills focused on reducing industrial carbon emissions often include provisions for carbon sequestration technologies. The pilot program could also explore other sources of funding through collaboration with industry partners and additional grants tied to sustainability, methane reduction, and carbon capture initiatives. By leveraging the support from both federal and private sources, the pilot program stands to advance its goals of reducing greenhouse gas emissions while improving well-plugging practices.

Task 1: Laboratory Testing

Background

Relevance

In our previous report, we investigated potential use of biochar both as an additive to cement used to plug oil wells, and in the SP that sits between cement plugs. Although well known for its gas sorption properties, it was concluded that because the cement is submerged in PW, and because properly plugged wells do not emit organic gases, the primary purpose behind using biochar would be to sequester carbon. Oil drilling and cement manufacturing are both industries that emit large volumes of CO_2e, and by permanently sequestering carbon in the form of biochar in these wells, the carbon footprint of the well-plugging industry is decreased (Roth et. al, 2024). When tested as a cement additive, it was found that only 3% biochar by mass could be added to cement without drastically altering its rheology, which must remain constant and low to ensure workability. Although the biochar-cement did not show decreased functionality, it was concluded that far more biochar could be stored in the SP rather than the cement. SP does not cure like cement, and it was suggested that up to 15% biochar by mass could be added in without compromising the integrity of the SP (Roth et. al, 2024). However, the unique physical and chemical characteristics of biochar mean its addition will dramatically alter the properties of the SP, necessitating small scale testing before a full-scale pilot study can begin. To date, there are no known studies investigating the use of biochar as a SP additive.

While our previous report evaluated woody biomass for biochar production due to its high carbon content and abundance as a feedstock in Colorado, evaluating other feedstocks in addition to woody biomass will help identify the most promising characteristics of biochar used in well plugging. Biochar derived from municipal biosolid feedstock present a promising method for managing persistent pollutants like PFAs by potentially mineralizing them during pyrolysis or immobilizing them within the SP during well plugging, minimizing their environmental mobility. Grassy biomass, characterized by its high cellulose content and rapid growth rate, presents a renewable and cost-effective feedstock for biochar production. Its fibrous structure contributes to enhanced carbon retention and stability, while its porous surface aids in capturing contaminants, making it an effective option for environmental remediation. Evaluating these three feedstocks will provide insights into their performance under well-plugging conditions, helping determine which feedstock offers the best balance between environmental impact, carbon sequestration, and material properties for long-term field deployment.

Significant federal, state, and local investments in forest management across Colorado aim to enhance forest resiliency and reduce wildfire risks to communities. These efforts generate substantial quantities of woody biomass, particularly as insect infestations and disease have led to large amounts of standing dead wood throughout the state. The 2020 Colorado Forest Action Plan (CSFS 2020) set forth two key goals for the forest products industry: to build resilient industry capacity for meeting forest management needs and to increase the number of forested acres treated annually through cost-effective utilization of resources. Despite these efforts, only an estimated 5% of biochar consumed annually in Colorado is produced from local forest ecosystems, due in part to data gaps on the availability, accessibility, and harvesting of woody biomass (Baral et al., *In Review)*. Addressing these gaps presents an opportunity to better utilize Colorado's forestry resources for biochar production, supporting both environmental management and industry needs.

Existing Literature

The primary purpose of a SP in drilling wells is to prevent upward movements of fluids. If properly done, SP achieves long-term wellbore integrity and reliable zonal isolation (Gordon et. al, 2008). Chemical and physical characteristics within an oil well can greatly alter the composition of the SP that will work best for plugging it. The most important aspects to consider are:

- Effectiveness of the SP to ensure cement placement in the producing zones and proper placement to protect water resources.
- The characteristics of the drilling fluid used, and the chemistry of the mud and filter cakes present in the well (oil or water based).
- The presence of salts in the PW and their potential to destabilize the hydrated bentonite.
- The peak pressure and temperature the fluid will be subjected to.

Broadly, SP is a mud-laden fluid that is placed between cement plugs and/or in sections of the well that are not cemented (Calvert and Smith, 1994). Biochar, due to its absorptive properties, will likely act as a rheology modifier and a water retention agent. Previous work (Roth et. al, 2024) finds that the addition of even 1% biochar by mass results in a significant increase in viscosity due to water sorption, and to keep rheology constant, other additives may need to be tuned in the presence of biochar. Keeping constant rheology across all tested batches is essential to ensure the SPbc is workable and can be pumped with existing equipment.

Bentonite-based SPs are common due to bentonite's ability to cool drill bits, effectively carry drill cuttings, maintain hydraulic pressure in the well, form a stable mud cake, and display dynamic rheological properties (Luckham et. al, 1999; Dutta et. al, 2016; Hosterman et. al, 1992). Bentonite is denser than water and can act as a weighting agent, but the primary role bentonite plays in the oil and gas industry is as a viscosifyer. When suspended in water, bentonite can expand up to three times its original volume, creating a highly viscous non-Newtonian fluid that displays shear thinning and thixotropic properties. In other words, the rheology and viscosity of bentonite suspensions are shear (flow and placement), time, and pressure dependent (Choi et. al, 2017). This makes modelling bentonite-SP for downhole application difficult, as pressure dramatically changes downhole (Dixon et. al, 2002). Biochar will likely lower the density of the SPbc, and increase the viscosity (Roth et. al, 2024). Density of the mixture can be increased with other weighting agents such as barite, and viscosity can be lowered with surfactants or viscosifiers, but due to the multifunctional role of bentonite, either bentonite concentrations *or* weighting agent/surfactant/viscosifyer concentrations should be varied for each test. Changing the relative additive quantities will change the chemistry of the SPbc, and many tests will need to be performed to find the optimal mixture.

The addition of biochar makes this SP novel. Biochar is a highly porous carbon material prepared when organic matter is heated in the absence of oxygen (pyrolysis). Depending on the organic matter of origin and the pyrolysis conditions used to form it, biochar can display different chemical and physical properties. For example, woody organic matter high in lignin shows different porosity and better stability than biochar prepared from something like grass. The pyrolysis temperature, rate, and reactor conditions will change the carbon content of the final biochar, which may influence the material's stability and carbon storage capabilities (Roth et. al, 2024).

Chemical considerations of a designed SP

SPs are complex to design because they have very specific chemical and physical requirements that must be met to successfully plug a well. The primary chemical purpose of SP is to remove any traces of oil-based drilling fluid (OBDF) that may remain from the drilling process. OBDF forms a muddy layer along the sides of the oil well (also called a mud cake or filter cake) that must be cleared away before plugging as the oils can prevent the curing of the cement slurry pumped downhole. Even a thin layer of OBDF can prevent the curing of a cement surface (Khalili et. al, 2023). Incomplete curing of the cement plug results in poor zonal isolation and potential migration of contaminated fluids and gasses within and without the well. Drop angle testing can be used to simulate the ability of SP to clear OBDF.

Physical considerations of a designed SP

The primary physical purpose of SP is to zonally isolate the region of the well it is placed in from other parts of the well, and the surrounding formation (Wilson et. al, 1990). To do this, the SP must replace mud leftover in the well from the drilling process and remain physically stable under variable temperatures and pressures. The most important physical characteristics to consider when designing an SP are the density and rheology of the SP under variable pressures and temperatures. The SP that is placed between the cement plugs is used to support placement of the cement in required zones if the well is not fully cemented. All well materials should be designed to exert a pressure that is below the fracture gradient and above the pore pressure at depth (API RP 65-3).

Density: Maintaining the correct density is critical for proper zonal isolation: if the SP is too dense, the hydrostatic pressure in the column could crack the surrounding formation, resulting in pressure loss and leached contamination. Conversely, if density is too low, fluids and gases from the formation or other areas of the well may migrate, leading to environmental damage (Gordon et. al, 2008). Colorado state codes require the operator to fill non-cemented intervals with wellbore fluids "dense enough to exert hydrostatic pressure greater than the highest formation pressure encountered. Unless approved otherwise, water, mud, or another approved fluid must be used between all plugs. If mud is needed to keep wellbore fluids static before setting plugs, it must have a minimum weight of 9 pounds per gallon". The density required to exert hydrostatic pressure greater than the highest formation pressure expected and the density to support cement plug placement will be determined during this study. Biochar, being an extremely low-density material, requires balancing with the addition of heavier materials to ensure SPbc density remains constant and is comparable to the requirements of the SP with no biochar. Biochar is also highly porous, and its density may change with pressure. Therefore, the density of the SPbc should be tested over the range of temperatures it will encounter down the well.

Rheology: Bentonite-based SP displays unique rheologic properties – when suspended in water, bentonite mixtures display both shear-thinning and thixotropic properties, meaning the rheology of the suspension is highly pressure dependent. As a shear thinning material, viscosity of aqueous bentonite mixtures (and therefore SP) decreases with increasing shear strain (Luckham et. al, 1999). Because rheology of bentonite mixtures is pressure dependent, it is important to model mud-SP interactions over the range of pressures present within wells to ensure proper displacement.

Measuring rheology is typically accomplished through use of a rheometer or viscometer according to API standard 13B-1 (Elochukwu et. al, 2022; Choi et. al, 2017). In addition to physical testing, mathematical models like the Bingham Model, the Herschel-Bulkley Model, or the Power Law Model have also been routinely used to model the rheology of SP. The Herschel-Bulkley Model (eq. 2) has been shown to be the most accurate model for particle and slurry suspensions such as cement and would be applicable to bentonite/water mixes (Salimi et. al, 2024; Choi et. al, 2017).

Equation 1

$$\sigma = k\gamma^n + \sigma_y$$

Where σ = shear stress, k = consistency index, γ = shear rate, n = flow index, and σ_y = yield stress.

Shadravan et. al (2015) outlines several other physical parameters that should be met when considering SP design. These include friction pressure hierarchy, minimum pressure gradient, velocity profile, and fluid retention. All these parameters ensure full and efficient physical removal of the drilling mud, and more information about them can be found in the source publication.

Chemical Resistance of SPbc in a Saline or Hydrophobic Environment

Salts present in PW vary in type and quantity between wells, but always contain very concentrated sodium chloride. Other salts of interest include chlorides and sulphates of calcium, potassium, and magnesium (Boyd et. al, 2023; Jeong et. al, 2023; Pichtel et. al, 2016; Neff et. al, 2011). To test chemical changes to the SPbc when in highly saline conditions, a rheometer should be used since the primary concern for salt interaction with the SPbc is changes to viscosity and yield stress (Vipulanandan et. al, 2018; Elochukwu et. al, 2022). Rheometers can also be used to look at changes to shear strain over time (Choi et. al, 2017). Although not written about SP specifically, some researchers follow API standard 13B-1 when measuring changes to viscosity over time (Elochukwu et. al, 2022). This standard outlines protocols for testing viscosity by using a viscometer/rheometer, which can measure viscosity at varying shear rates. One approach to modifying biochar density involves pyrolyzing pelletized feedstocks (Riva et al., 2021). Using a HTHP rheometer may be best for this application to see if salt impacts SPbc rheology at different temperatures and pressures (Choi et. al, 2017).

Methods for Quantifying Methane Gas Sorption

There are many existing methods for testing methane sorption/dissolution for a variety of materials, the simplest being headspace gas chromatography. This test involves sealing the sorbent material with a known quantity of gas (for this application, methane), and directly analyzing the headspace for changes in methane concentration over time (Sithersingh et. al, 2012). Although this method cannot offer insight into sorption mechanism, it is simple, widely used, and effective with many material types. Regardless of sorption mechanism, direct headspace sampling should provide a straightforward measurement of the SP's methane sorbing abilities. If a headspace test is conducted on an SPbc sample, it is likely that most of the gas interaction will be with the biochar, not the SP. A more homogenous SPbc mix may be achieved with smaller biochar particle size, but how this will change the gas sorption properties of the SPbc is unclear. A test could be designed to simulate methane migration through SP and SPbc to determine expected methane sorption of the SPbc.

Objectives

Overall, considerations of biochar feedstock and preparation can have considerable changes on the amount of carbon sequestered in the well and stability in the well plugging SP.

The objective of this task is to evaluate the different feedstocks and biochar preparations, including those derived from forestry biomass as part of ongoing forest management efforts in Colorado, to help determine which ones possess the best chemical and physical characteristics for incorporation into the well-plugging process, ensuring both integrity and carbon sequestration. This task will focus on determining the properties and property requirements of the material (generally bentonite based) that is placed between the solid cement plugs with the addition of biochar. The material properties will be targeted so that the optimal ratios of biochar/bentonite/water are identified with the goal of ensuring the cement plugs are properly placed and that all materials meet or exceed code requirements and identified requirements.

Subtasks

Summary

Biochar samples from three different feedstocks (woody biomass, municipal solids, grassy biomass) with varying particle sizes and densities will be produced by two different biochar manufacturers. The biochar will be shipped to the university and national laboratories for further testing to determine the optimal properties for well integrity and carbon sequestration. In laboratory testing, SPbc will undergo chemical tests to ensure effective well sealing. Testing will also focus on rheological properties, wettability, and the compatibility of SPbc with cement. Further assessments will involve methane and DOC sorption, as well as SPbc's chemical resistance in saline and hydrocarbon environments. Methane sorption testing will account for variations in temperature, pressure, and biochar size, while DOC testing will analyze organic compounds in PW. This task will also assess the feasibility of using Colorado's forest biomass for biochar production, leveraging investments in forest management to support well-plugging efforts.

Approach

Biochar Sample Manufacturing

<u>Ashwood Biochar</u>

Ashwood Biochar will produce biochar using a diverse range of feedstocks, including timber residuals, municipal biosolids, and grassy biomass. The timber feedstock will be initially received as wood chips and processed through a hammer mill for size reduction. Once reduced, the feedstock will be dried to a moisture content of less than 10% using a rotary kiln dryer powered by compressed natural gas (CNG) to ensure consistent moisture levels for optimal pyrolysis. The feedstock will undergo thermochemical conversion in indirect-fired rotary kiln gasifiers, which utilize CNG for initial startup and subsequently operate on syngas or biogas generated from the gasification process. The gasification parameters, including temperature and pressure, will be modulated to produce biochar with tailored physicochemical properties, suitable for the intended applications and laboratory testing.

To achieve the desired particle size distribution and density, both Pin Mixer and Pan Agglomeration techniques will be employed based on the product specifications. Biochar with a bulk density of approximately 40 lbs/ft^3 will be produced, while higher densities can be attained through blending. Additionally, pelletized biochar will be produced to achieve harder, high-density biochar. Particle size distribution will range between 1 mm to 4 mm, with screening and adjustment available for larger particle size specifications if required.

The production process is designed to maximize energy efficiency through heat and syngas recycling. Once the gasifier achieves steady-state operation, excess syngas and biogas will be conditioned and reused on-site for various applications, including electricity generation via a natural gas genset. Additionally, renewable natural gas (RNG) will be produced through further conditioning of the syngas, contributing to an integrated energy recovery system.

The biochar will be transported to the designated university and national laboratory facilities upon completion of production.

Biochar Now

Biochar Now will leverage its established production capabilities to provide small amounts of biochar for testing. The biochar will be produced using feedstock primarily sourced from beetle-killed pine wood. The wood undergoes pre-processing, which includes shredding the raw material into large chunks. These chunks are then fed into a reactor where the pyrolysis process occurs. The wood is exposed to temperatures ranging between 550°C and 600°C for up to 10 hours in a vacuum, ensuring optimal biochar production for carbon sequestration and other applications. The reactors used in biochar production are powered by the energy released from the pyrolysis process itself, with supplementary electricity powering the electronic control systems. To ensure clean air emissions, propane is used as needed to maintain the proper temperatures in the emission stacks.

Biochar produced through this process will be available in multiple particle sizes and density ranges to accommodate specific testing needs:

- **Powder size**: Particles below 50 mesh.
- **Small size**: Ranges between 26 mesh to 50 mesh.
- **Medium size**: 3 mm to 26 mesh.
- **Chip size**: Half-inch down to 3 mm.

One biochar sample representative of each particle size range (four in total) will be transported to the designated university and national laboratory facilities upon completion of production.

Laboratory Testing of SPbc

Chemical Testing of Designed SP

The chemical compatibility of the SPbc with curing cement must be investigated. In our previous study, it was found that large biochar plugs that formed directly next to a cement surface inhibited the curing of the cement. This could be due to sorption and release of water or plasticizers (Roth et. al, 2024), which are large non-polar additives like surfactants. Because biochar is so buoyant, it is likely to sit at the top of the SP, directly next to the cement plug. While this effect can be minimized by decreasing the particle size of the biochar, it is still likely to be present to some degree. Because biochar aggregation and OBDF can prevent cement curing, testing cement-SPbc compatibility is important. To this end, compressive strength of curing cement in contact with SPbc should be assessed. Briefly, curing molds should be filled halfway with SPbc, while the remainder of the mold should be filled with cement slurry and the molds sealed. After 1, 4, 7, and 28 days of curing at constant temperature and humidity, the cement should be demolded, separated from the SPbc, and tested for compressive strength (Roth et. al, 2024). The following data and observations should be recorded over the curing period:

- Binding behavior of the cement and SPbc
- Incomplete curing at the SPbc/cement interface
- Change in compressive strength compared to a cement sample in contact with pure water
- Change in compressive strength between clean SPbc and SPbc contaminated with OBDF
- Change in compressive strength between SPbc and SP when both are contaminated with OBDF

If any of these tests, particularly those involving OBDF, yield poorer cement curing or compressive strength, it can be concluded that the addition of biochar to the S\P may result in a well plug with lower integrity and poor zonal isolation. Incomplete curing of the cement plug can allow for the migration of contaminated fluids within and without the well, and potentially lead to the escape of toxic gases such as methane.

Chemical Resistance of SPbc in a Saline or Hydrophobic Environment

To test if the designed SPbc is more vulnerable to certain salts over others, the SPbc should be added to solutions of the salts outlined in Table 2 and tested via viscometer over time. At least one sample of PW with characterized salt concentrations should be tested with the SPbc parallel to the individual ion tests. This test should be continued as long as possible to predict changes in the SPbc in ageing wells. Additionally, to test any sorption of salts over time, the salt solution containing SPbc should be regularly sampled and analyzed with ion chromatography to observe changes in ion concentration (Roth et. al, 2024).

Table 2: Common salts in PW and recommended testing concentrations. (Jeong et. al, 2023; Boyd et. al, 2023; Pichtel et. al, 2016; 2016; Neff et. al, 2011; Zaman et. al, 2021)

Ion	Literature Concentration range (mg/L)	Approximate testing concentration range (mg/L)	Recommended testing concentration range (Molar)
Na^+	23 – 57.3	500 - 60,000	NaCl: 0.1 - 1
	713		
	10,200		Na_2SO_4: 0.05 – 0.5

	132-97,000		
K^+	0.130 – 3.1	25 - 1000	KCl: 3E-4 – 0.01
	37.4		
	47.6		K_2SO_4: 1.5E-4 – 0.005
	24-4,300		
Ca^{2+}	2.530 – 25.8	100 - 1000	$CaCl_2$: 0.001 – 0.01
	1380		
	76		$CaSO_4$: 0.001 – 0.01
	13-29,222		
Mg^{2+}	0.530 – 4.3	25 - 200	$MgCl_2$: 1E-4 – 0.002
	32.4		
	99.4		$MgSO_4$: 1E-4 – 0.002
	8-6,000		
SO_4^{2-}	0.210 – 1.170	50 - 1000	
	61.4		
	2-1,650		
Cl	46.1 – 141	10,000 - 100,000	
	12,600		
	23,903		
	80-200,000		

Because SP is designed to interact with hydrocarbons present in drilling mud and PW, it is unlikely that the addition of biochar will positively or negatively influence its hydrocarbon resistance. However, since biochar is able to sorb hydrocarbons, additional testing on SPbc should be carried out in the presence of hydrocarbons to ensure this. To test the resistance of the SPbc submerged in oily solutions, the same protocol outlined above for salts can be used, but only PW should be used for these tests. The chemical makeup of organics present in PW is highly complex, and changes between wells. For this reason, chemical analysis of the PW before and after the addition of SPbc will better test its hydrocarbon resistance and sorption than testing one organic compound at a time (Jeong et. al, 2023).

Modeling SP Aging & Stability

There do not seem to be any published standard methods for testing the aging of SP. Theoretically, extending the salt and hydrocarbon immersion tests should illustrate any changes to the SPbc's rheology and viscosity over time, which play a large role in maintaining zonal isolation in SP zones. Other tests to model aging are physical changes to the SP in response to intense heat and pressure or cement curing.

Quantifying Methane Gas Sorption

Direct headspace sampling will be performed to provide a straightforward measurement of the SP's methane sorbing abilities. The headspace sampling test will consider the following to ensure proper modelling of the conditions faced inside a well:

1. Variable temperature: temperature increases as depth of the well increases, and with increasing temperature, methane solubility in water decreases (Gabrowska et. al, 2022)
2. Variable pressure: methane solubility in water increases with increasing pressure (Gabrowska et. al, 2022). Also, pressure greatly changes the rheological properties of the fluid, which may change the sorption mechanism. Higher pressure may yield a more fluid-like state making gas dissolution the primary mechanism behind methane capture, which could theoretically capture far more gas than monolayer adsorption which could occur under lower pressure, more solid conditions.
3. Variable biochar size: Biochar of different sizes (assessed by SEM) will be blended with one SP combination and a headspace sorption test will be conducted as described above. Important to determine if biochar is floating on top of the SP or if it is homogeneously distributed.

Quantifying DOC Sorption

The SPbc will be submerged in a sample of whole PW, and the DOC characterized over time. Multiple methods can be used to fully characterize the DOC of PW. DOC analysis of PW can be broken into six categories: surfactants, polycyclic aromatic hydrocarbons (PAHs), nonpurgeable organic carbon (NPOC), total organic nitrogen (TON), total petroleum hydrocarbons (TPH), and total benzene, toluene, ethylbenzene, and xylenes (BTEX) (Gal Zaman et. al, 2021; Jeong et. al, 2023). The analytical methods involved in testing for each of these categories are summarized in Table 3.

Table 3: Examples of analytical methods used to characterize DOC in PW (Jeong et. al, 2023; Boyd et. al, 2023; Wilbur et. al, 2004)

DOC Class	Significance	Method
NPOC	This analysis removes inorganic carbon before characterization, is straightforward, and includes surfactants	Total Organic Carbon Analysis (ex. Shimadzu TOC analyzer) to characterize NPOC and TN.
TON	This group contains any nitrogen-containing organics.	
TPH	TPH is the sum of all volatile petroleum hydrocarbons and extractable petroleum hydrocarbons including diesel range organics and gasoline range organics. Their characterization can give picture	Concentrations and characterization following EPA 8015B (GC/FID) and EPA 8260B (GCMS). This method removes surfactants from the analyte but is more complex than TOC analysis

	of larger scale changes happening in a sample	
BTEX	BTEX chemicals have known environmental and human health risks	
PAH	PAHs are extremely hydrophobic and harmful to human health, making separate analysis important for risk assessment	Extraction following EPA 3510C (Liquid/liquid extraction) Analysis following EPA 8270E (which includes quantification) or atmospheric pressure MS + QTOF
Surfactants	These molecules are larger and contain a polar end group, making their analysis incompatible with the other small, hydrophobic compounds	Solid phase extraction using Hydrophilic-Lipophilic balanced cartridges to concentrate surfactants and remove salts LC/TOF/MS to characterize surfactants, but cannot quantify them

<u>Density Characterization of SPbc</u>

Density testing will determine whether the SPbc formulations meet the required density of 9 lbs/gal, ensuring adequate support for cement placement in well-plugging applications. Initial tests will involve preparing SPbc mixes with varying biochar concentrations to ascertain the maximum biochar content that maintains this density threshold. Lab-based placement tests and LBM simulations (Garcia et al., 2023) will provide insights into the capacity of these formulations to support cement placement effectively, simulating the conditions they would encounter in field settings.

<u>Rheology Characterization of SPbc</u>

Rheology testing will be conducted to evaluate the flow characteristics of SPbc mixes, critical for supporting zonal isolation in well operations. Using high-accuracy instrumentation available at NETL, such as the Anton-Paar MCR 302e and the OFITE Model 900 Viscometer, tests will assess how SPbc's viscosity and flow behavior change under pressure and temperature variations. These tests will analyze whether SPbc formulations retain sufficient flowability to support cement placement, prioritizing rheology stability for effective displacement and zonal isolation.

<u>Consistency Thickening Time Tests</u>

The consistency thickening time tests will measure the duration over which the SPbc slurry remains pumpable, a key factor for successful well plugging. Using the CTE M15-400

Rotating Paddle Consistometer, standard in the oil and gas industry, these tests will simulate field pumping conditions, determining the optimal composition of SPbc that provides extended workability while ensuring quick setting post-placement.

Plug Material Placement Tests

Plug material placement tests will simulate the ability of SPbc to maintain wellbore stability and support cement plugs during both placement and hydration. NETL's specialized experimental setup will be used to evaluate the physical stability of SPbc mixes under well-like conditions, ensuring they effectively hold wellbore fluids static and support the cement during critical phases.

Gas Migration Tests

Gas migration tests will quantify methane sorption in SPbc by flowing methane through SPbc columns, assessing the material's adsorption potential at varying biochar concentrations. This test will provide data on methane containment efficacy within the SPbc, with particular focus on adsorption efficiency as a function of biochar concentration, which is critical for evaluating emissions reduction.

Permeability and Flow Testing with NMR

Using Nuclear Magnetic Resonance (NMR), permeability tests will examine the gas movement through SPbc mixes, enabling a detailed understanding of flow pathways and interactions between gas and biochar within the SPbc. This analysis will aid in optimizing biochar content for effective containment while minimizing permeability.

Simulated Biochar Distribution and Sorption Tests

Simulations will analyze the distribution of biochar within the SPbc, exploring its impact on adsorption properties. These tests will assess biochar dispersion methods to maximize gas sorption, evaluating scenarios that mimic field flow conditions and simulating biochar's interaction with gas in the SPbc.

Percolation Tests for Gas Flow

Percolation tests will determine the effectiveness of SPbc in allowing controlled gas flow and maximizing adsorption within well-plugging applications. Using a specialized apparatus, these tests will measure gas flow rates through SPbc formulations, establishing the conditions that optimize gas containment and emissions mitigation in plugged wells.

These tests together will provide a comprehensive assessment of SPbc performance, facilitating the development of optimized SPbc formulations for effective well-plugging and emissions control.

Geospatial Analysis and Woody Biomass Availability

A geospatial analysis will be conducted to evaluate the availability and accessibility of woody biomass in Colorado, based on recent research and estimates derived from Forest Inventory and Analysis (FIA) data on non-reserved land Prentice et al. (In Review); Roth et al., 2024). This analysis will transform tabular biomass estimates into spatial data, incorporating key variables such as slope, road proximity, wildlife habitats, and the distance to existing biochar production facilities. The resulting spatial datasets will provide valuable insights into the most accessible and viable sources of woody biomass for biochar production across the state.

Deliverable

- A report will be submitted to the principal investigator (PI) documenting the biochar's particle size, thermochemical conversion conditions, and ultimate and proximate analysis (moisture, ash, volatile matter, fixed carbon, and elemental composition) of the manufactured biochar samples. The report will also include air quality monitoring data from the biochar manufacturing facility, covering particulate matter, carbon monoxide, nitrogen oxides, and VOCs.
- A report detailing the wettability and impact of different SP mixes on cement curing will be submitted to the PI. This report will include results from the SSST and drop angle tests, cement compressive strength over time, and observations on curing behavior.
- A report will be submitted to the PI documenting the geospatial analysis of woody biomass availability in Colorado. The report will include spatial data on biomass quantities, accessibility factors such as slope and road proximity, and the distance to biochar production facilities. It will also provide an assessment of data gaps and recommendations for improving biomass utilization in alignment with the goals of the Colorado Forest Action Plan.
- A report will be submitted to the PI documenting research to identify property requirements for the SP, the results of testing to establish the recommended mix ratios of the bentonite/water/biochar that achieves those requirements, and recommendations on requirements for using and placing biochar in the SP that are based on scientific tests, experiments, and relevant simulations.

Organization

Team Member Roles

<u>Ashwood Biochar</u> & <u>Biochar Now</u> will be responsible for manufacturing and shipping of various biochar samples.

<u>CSU, Thomas Borch Lab</u> will be responsible for tests concerning cement curing and compressibility, wettability (drop angle), DOC analysis, and ion sorption.

<u>NETL</u> will be responsible for tests concerning headspace analysis, density characterization of SPbc, rheology characterization of SPbc, consistency thickening time tests, plug material

placement tests, gas migration tests, permeability and flow testing with NMR, simulated biochar distribution and sorption tests, and percolation tests for gas flow.

The CSFS will be responsible for conducting geospatial analysis to assess the availability and accessibility of woody biomass in Colorado.

Timeline & Budget

Below is a breakdown of the anticipated costs and timelines associated with each component of Task 1.

1. **Production of Biochar for Experimental Testing**
    a. **Estimated Costs:** $1,750-$3,250
    b. **Estimated Timeline:** 1 month.
    c. **Description:** Biochar from Biochar Now can be shipped to both the university and the national laboratory immediately upon order confirmation, with no delays due to existing stockpiles. 4 different samples will be shipped. Biochar from Ashwood Biochar will take approximately two weeks to produce and will be shipped to both locations immediately after manufacturing. 5-10 different samples for each feedstock varying in density and size distribution will be shipped.
        i. Biochar Now: $250 (includes biochar samples and shipping cost)
        ii. Ashwood Biochar: $100/gallon biochar
2. **Testing for Optimized Properties and Well Integrity – National Laboratory**
    a. **Estimated Costs:** $976,000
    b. **Estimated Timeline:** 24 months.
    c. **Description:** The material property requirements of the SP need to be determined based on experiments. Testing and experiments need to be conducted with various biochar formulations under relevant well conditions (e.g., overburden pressure, under placement conditions, etc.), and assessing performance in the well to support cement placement in required zones, and assessing methane sorption of the biochar to identify optimal mixes (in combination with other properties identified by the University Lab).
        i. Personnel: $570,000
        ii. Materials and supplies: $40,000
        iii. Indirect Costs: $366,000
3. **Testing for Optimized Properties and Well Integrity - University Laboratory**
    a. **Estimated Costs:** $696,150
    b. **Estimated Timeline:** 24 months.
    c. **Description:** This involves testing the density and rheology of SPbc with various biochar formulations under heat and pressure, conducting chemical tests (rotor, SSST, drop angle), and assessing methane sorption to identify optimal mixes. Ion

and DOC sorption, rheology changes, and cement curing tests will also be performed.

   i. Personnel: $320,000
   ii. Materials and supplies: $45,000
   iii. Equipment use charges and instrument fees: $45,000
   iv. Other Direct Costs: $45,000
   v. Indirect Cost Rate: 53%

4. **Geospatial Analysis and Woody Biomass Availability**
   a. **Estimated Costs**: $40,000
   b. **Estimated Timeline**: 12 months.
   c. **Description**: This task will focus on evaluating biomass availability through geospatial analysis, identifying potential areas for biomass sourcing based on slope, road access, and proximity to production facilities. It will require 0.5 FTE of a research associate salary at CSU at 28% fringe rate.

Task 2: Down Hole Pilot Study

Background

Relevance

A downhole study is essential for bridging the gap between laboratory research and practical application of biochar in well plugging. While laboratory experiments provide valuable insights into the material's potential, they do not account for the full complexity of downhole conditions. By gathering data from field conditions, the study will help build regulatory confidence in the technology, as it will validate biochar's long-term stability and efficacy under real operational conditions, which is essential for moving the technology beyond theoretical and laboratory applications.

Existing Literature

All current studies on the use of biochar in well plugging have been confined to controlled laboratory environments, with no field-based research available to date. While these studies offer valuable insights into biochar's mechanical properties and potential applications, in situ testing is essential to assess its effectiveness in real-world conditions where factors such as pressure, temperature, and fluid dynamics can vary significantly (Roth et al., 2024). This task represents the first field-based investigation of biochar in well plugging, laying the groundwork for its potential broader adoption in orphan well plugging efforts.

Objectives

The objective of this task is to quantify and compare methane and VOC emissions from a well plugged traditionally and a well plugged using SPbc by selecting and testing four wells within a single basin (i.e., DJ basin) based on critical baseline factors such as age, depth, well chemistry, and methane emissions. The goal is to demonstrate the feasibility of using biochar in downhole well plugging, to provide the critical evidence needed to convince regulators, operators, and investors of the technology's safety, effectiveness, and sustainability.

Additionally, documenting operational challenges and necessary modifications to well-plugging practices will help inform the potential wider deployment of biochar in orphan well plugging operations.

Subtasks

Summary

To quantify emissions from wells plugged traditionally and those using a biochar additive, the pilot study will first select four wells within a single basin. The selection will be based on critical factors such as well age, depth, operator, well chemistry, and initial methane emissions. Well chemistry tests will include TDS and IC tests to quantify PW salinity and DOC profiling using THP/BTEX measurements. Wells with similar characteristics will be prioritized to ensure consistent and comparable data. Once the four wells are identified, baseline methane emissions will be measured one month before plugging begins, using static chambers placed over each well. Baseline testing will also include analysis of gas composition and fluid properties to ensure the wells are as similar as possible. From these four wells, two with the most comparable characteristics will be selected for plugging—one will be plugged using biochar, and the other with traditional materials.

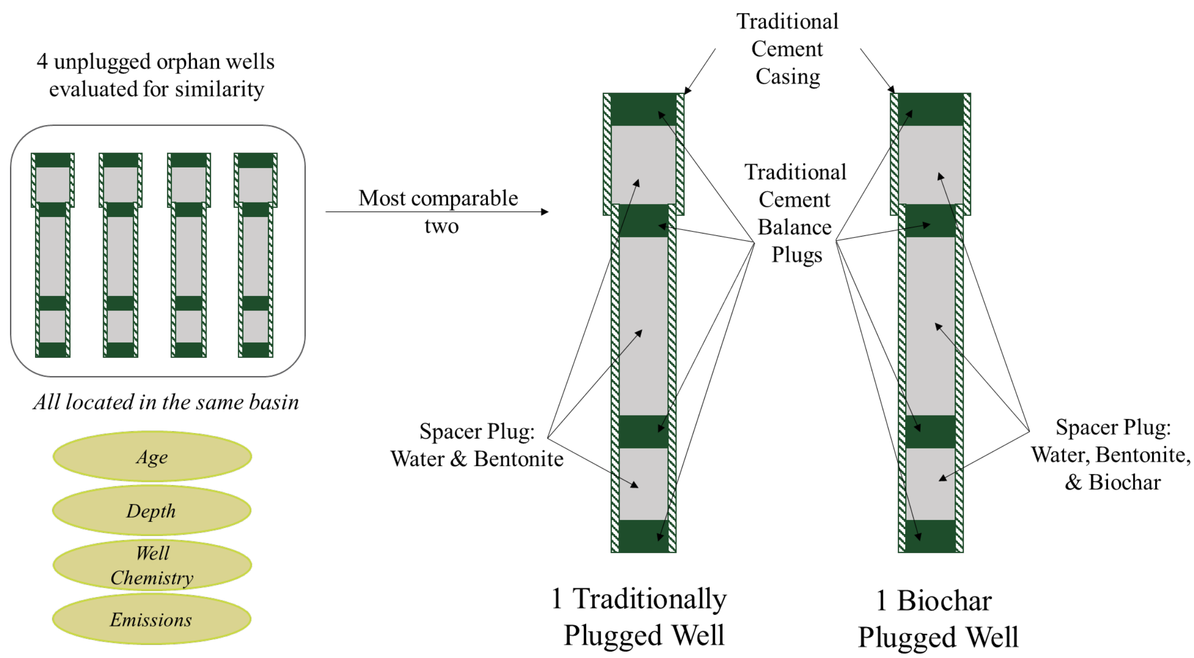

Figure 1: Illustration of the pilot study set up for evaluating four selected wells, followed by selection of two comparable wells- one plugged with biochar and one with traditional materials.

The well plugging operations for this project will be carried out by the well-plugging operator, adhering strictly to the Colorado Well Plugging Rules (400 Series) and in line with the project's objective of testing SPbc in orphan wells. A variance for using biochar in the SP will be sought from the Colorado Energy and Carbon Management Commission (ECMC) as Rule 434(3) requires prior approval for materials not typically used in plugging operations. After plugging is completed, once monthly methane emission and VOC measurements will be conducted at 1-, 2-, 3-, and 12-month timepoints, starting one-week post-plugging. The location of each well will be recorded using GPS coordinates, and any well where H_2S is detected either before or after plugging will be excluded from further measurement.

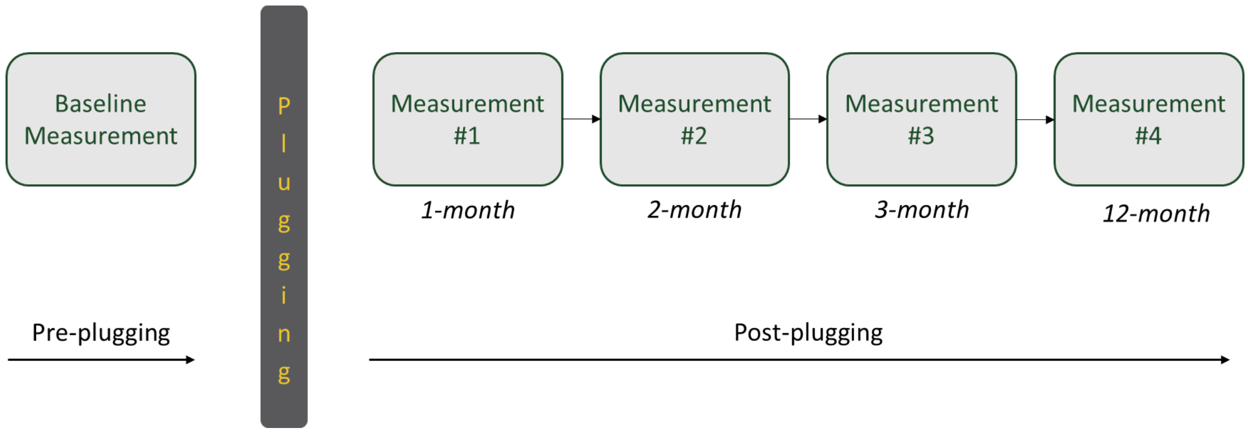

Figure 2: Sequence of measurements for methane emissions from a biochar plugged well and traditionally plugged well.

Approach

Well Selection and Baseline Testing

The selection of wells displaying similar physical and chemical characteristics is crucial for data reproducibility. Some criteria for measuring the 'similarity' of two wells could include total dissolved solids (TDS), TPH and BTEX profile, bottomhole temperature and pressure, maximum depth, chemicals used during fracking, and any maintenance chemicals added to the well over time. Assuming the selected wells are part of the same drilling site, many of these variables can be controlled. However, chemical testing should still be carried out to ensure similar chemistry exists within the selected wells.

Maximum depth, fracking chemicals, and maintenance chemicals used should all be information supplied by the company that drilled the well. Depth information is useful when calculating the volume of SP and cement to prepare and can influence the bottomhole pressure and temperature. Fracking and maintenance chemicals can vary widely based on the supplier, but the only detail of importance is whether they are using oil-based or water-based chemicals. OBDF and other organic chemicals present in the well may prevent cement curing, making the cleaning properties of SPbc of utmost importance. However, if water-based additives are used, this property becomes less important, and the SPbc can be designed to prioritize other properties like rheology or temperature resistance for example.

Downhole temperature and pressure are extremely important variables to ensure well similarity. Theoretically, wells of similar depth drilled into similar formations should display similar maximum temperatures and pressures, but since the rheology of the SPbc is pressure dependent, exact measurements must be completed prior to a pilot test. If a permanent installation already exists at the well in question to monitor bottomhole pressure and temperature, acquiring this data is very simple. However, if no such installation exists, several options are available to acquire temperature and pressure data. Because pressure and temperature data are essential to both the drilling process and the plugging process, the method used to measure them should be left to the company contracted to plug the well, as protocols and equipment are likely already in place for this reason. However, to lower the cost of this operation, and because relative data between wells is more valuable for this purpose than exact data, this report recommends downhole recording over surface readout (Veneruso et. al, 1991).

TDS and ion chromatography (IC) data can be used to quantify the salinity of the PW. This, along with a general profile of the DOC present are essential to ensure the chemical conditions facing the SPbc within the tested wells are similar. TDS will be performed to gain data that can describe the inorganic conditions within the well without having to chemically quantify every inorganic species present. This is very easily calculated by measuring conductivity of the solution, and converting that measurement to TDS with Equation 2:

Equation 2 $$TDS\ (mg/L) = k \times EC\ (\mu S/cm)$$

Where k is a constant quantifying the ratio of TDS/EC that changes based on the activity of all dissolved ions in the solution, and ionic strength of the solution (Rusydi et. al, 2018). Due to its high salinity, k for PW is 0.7, the value used for sea water (Rusydi et. al, 2018). A second evaporation test can be performed in parallel to further quantify TDS. This test involves evaporating any water or organics from a PW sample, leaving only salts, the final mass of which can be used to calculate the initial salt concentration (EPA 160.1). Further characterization of the identities of the salts present in the PW can be carried out using inductively coupled plasma mass spectrometry (ICP-MS) or inductively coupled plasma atomic emission spectrometry (ICP-AES) as detailed in EPA 200.7 or EPA 6010B (Jeong et. al, 2023), if needed. If the tested wells are drilled into the same formation, it is unlikely the types of salts present will vary much, therefore the total salinity modelled by TDS is more relevant for this project. The most common ions present in the PW will be chloride and sodium. Their extremely high concentrations make testing for their relative presence within wells is important. This can be measured in a very simple IC test.

Although TDS and IC are simple and useful methods of characterizing the salinity of PW within a well, no such simple test exists for quantifying organics. Detailed methods for measuring the organic fraction of PW can be found in Task 1. Here, only THP/BTEX analysis will be conducted. This test, following EPA 8015B (GC/FID) and EPA 8260B (GCMS) characterizes 30 organic molecules commonly encountered in PW. Although not every possible molecule in the sample is accounted for, this method provides quantitative data as well as characterization, allowing levels of these chemicals in different PW samples to be compared. If other information such as surfactant presence or total nitrogen is desired, more tests detailed in Table 3 can be added to the PW analysis.

Pre- and Post-Measurement & Quantification of Methane Emissions

The field measurement component will comprise one field campaign monthly which will be conducted at 1-, 2-, 3-, and 12-month timepoints following well plugging in addition to baseline measurements. During each field measurement, one traditionally plugged well and one well plugged using a biochar additive will initially be screened using an ABB Micro-portable GHG Analyzer (MGGA; 1-sigma CH_4 precision < 0.9 ppb over 1 sec; range 0 to 100 ppm). Initial screening will include the wellhead and the surrounding area up to a distance of 10 m. This distance is the likely farthest extent of any subsurface emission following preferential pathways (Cho et al., 2022; Jayarathne et al., 2024; Riddick et al., 2021, 2019). VOC samples will be collected from the static flux chamber in parallel to methane measurements.

A recent study has shown that methane emissions from newly plugged wells in Colorado were undetectable during screen with the MGGA (Riddick et al., 2024). Therefore, regardless of initial screening, the well head will be enclosed in a static flux chamber (Collier et al., 2014; Pihlatie et al., 2013) containing the MGGA. The static flux chamber is a fixed volume enclosure placed over an emission source and emission rate is calculated from the rate of change of methane concentration inside the enclosure (Riddick et al., 2022). This method is typically used to quantify very small emissions from natural sources (< mg CH_4 h^{-1}) and not recommended for measuring abandoned wells (Riddick et al., 2022). However, as emissions are expected to be very small this method will show any emission coming from the plugged wellhead if left for a long enough time.

The static flux chamber will be constructed following the American Carbon Registry guidelines (ACR, 2022) where:

- The chamber footprint should cover the well and up to a one-meter buffer around the well
- Be constructed from a material that has no degassing or sorption of methane
- The chamber should have a detachable base, inserted between 2 and 6 cm into the ground surface, and be installed before any measurement.
- The upper chamber component should have a vent tube with the length being dependent on the wind speed.
- The chamber must be airtight.
- Fans must be used to ensure that the methane inside the chamber is well mixed and positioned to provide sufficient circulation without affecting the pressures.

The MGGA will measure any change in gas concentration and the emission calculated from the linear increase in concentration (C, g m^{-3}) over time (t, s) and the volume of the chamber (V, m^3) (Equation 3).

Equation 3

$$Q = \frac{dC}{dt}.V$$

With a chamber of 1 m^3 and using the MGGA, the static chamber will be able to quantify methane emission down to 1 µg CH_4 h^{-1} if left over the well head for one hour. Static chamber measurements will be repeated over the well head three times with each lasting one hour. This static chamber method will also be used to quantify the emission over any methane enhancements detected in the soil around the well head. Measurements will be conducted at one well head per day. Outcomes of the project will be presented in data sent to the PI at the end of four months from the start of the measurements.

The CSU ATS will provide clean, evacuated whole air 1.4-liter Silonite®-coated stainless steel canisters coupled to METEC staff to collect VOC samples at the start and end of each hour (Entech Instruments). Each canister fills in approximately 15 seconds. Collected canister samples will be returned to the laboratory of Jeff Collett at ATS for speciated VOC analysis (Ku et al., 2024). Canisters will be cleaned using an Entech 3100 Canister cleaning system before field deployment by evacuating the canister to 10^{-2} torr and purging with ultra-high purity nitrogen for 8 cycles at 80 °C. Laboratory blank samples are collected by filling cleaned canisters with ultra-high purity nitrogen.

Methane and speciated VOCs will be measured in each canister sample by gas chromatography (GC) at the ATS. Methane is analyzed using a Shimadzu GC-8A equipped with a digital temperature programmer and flame ionization detector (FID). The analytical column consisted of two 6' x 1/8" O.D. stainless steel columns packed with Porapak Q. Samples are injected at room temperature, and the column oven temperature is held at 40 °C. Ultra-high purity nitrogen (Airgas Inc., NI UHP300) is used as a carrier gas and zero air (Airgas Inc., AI UZ300) plus ultra-high purity hydrogen (Airgas Inc., Hy UHP300) is supplied to the FID. A methane standard (SCOTT-MARRIN Inc., CA, USA), 20.41 ± 1% ppmv in ultrapure nitrogen, is used to calibrate the working standard. At least five working standard injections are analyzed in each analysis batch to assess system drift or malfunction. The methane measurement precision (1 relative standard deviation, RSD) is 4%. The methane method detection limit (MDL) is 0.21 ppmv.

Fifty VOCs, including major components of emissions from oil and gas wells (Hecobian et al., 2019; Ku et al., 2024) will be measured in each canister sample. This includes major components of oil and gas emissions, such as ethane, propane, and other alkanes as well as air toxics including benzene, toluene, ethylbenzene, and xylenes (BTEX). Measurements will be made using a custom, multi-channel GC system described in previous studies (Benedict et al., 2019). The system includes three GCs and five detectors (three FIDs, one electron capture detector (ECD), and one mass spectrometer (MS)). Analyzed gases included C_2-C_{10} non-methane hydrocarbons (NMHCs, including linear, branched, and cyclic alkanes, alkenes, alkynes, and aromatics) and C_2 halocarbons. The system is calibrated using a certified mixed hydrocarbon standard (HC Mix56, Airgas, PA, USA). Multiple working standards are analyzed during each analysis batch to check system drift and to derive VOC response factors. The measurement precision (1 RSD) for most target VOCs is between 2 and 5%. The accuracy for the calibration standard is ± 5%.

Site selection and plugging of the wells will be done before METEC staff start the measurements. All site access, health and safety admin and coordination with landowners will be arranged for the METEC staff before the start of measurements. Methane emissions (triplicate 1-hour measurements over the well head only) will be measured at four wells in the DJ Basin one month before plugged. Of these four sites, one will be selected by the larger project team for traditional plugging and one well for plugging with biochar. Methane emission quantification will then be done at these wells at 1-, 2-, 3- and 12-month timepointsfollowing well plugging (starting one week after plugging).

Well Plugging Operations

The well plugging operations for this project will be carried out by the well-plugging operator, adhering strictly to the Colorado Well Plugging Rules (400 Series). Two wells will be selected, one for traditional plugging and one where biochar will be incorporated into the SP. A variance for using the SPbc will be sought from the Colorado Oil and Gas Conservation Commission (COGCC), as Rule 434(3) requires prior approval for materials not typically used in plugging operations.

The first step will involve mobilizing all necessary equipment to the well site. This includes the rig, cement pump truck, wireline truck, tanks, pits, and additional support equipment. All mobilization will follow standard protocols to ensure the well site is prepared for plugging, with thorough inspections of the wellbore and surrounding site to verify that conditions are safe and suitable for plugging operations.

Once the site is ready, the wellbore will undergo a series of preparation steps. Initial well pressure testing will be conducted to assess the well's condition. The well will then be circulated to remove any residual contaminants or fluids, ensuring that the wellbore is clean and ready for the plugging process, in accordance with Rule 434(1), which requires that the wellbore be in a static state before any plugs are set.

The first plug will be set to isolate production perforations to prevent the migration of oil, gas, or water into unintended formations, as required by Rule 434. Additional plugs will be set to isolate specific zones within the wellbore. Each plug will be placed using cement plugs, as required, and verified through pressure testing. The intervals between plugs will be filled with SP of sufficient density to maintain hydrostatic pressure, per Rule 434(1), ensuring that each zone is effectively isolated. In the well where biochar will be used, SPbc will be placed between the plugs (pending variance approval).

Once the subsurface plugs have been placed and verified, the final surface plug will be set, completing the plugging operation. This plug will ensure that the wellbore is sealed from the surface to the subsurface, preventing any further fluid migration. A waiting period of five days will be observed before capping the well, as stipulated by Rule 434(5), to monitor for any signs of failure in the plug. The well will then be sealed and capped within 90 days after placing the final plug.

Biochar Manufacturing for Well Plugging

Based on the biochar properties determined through laboratory testing to be optimal for well integrity and carbon sequestration (including feedstock type, particle size, density, and thermochemical conversion parameters), Ashwood Biochar will produce the required bulk biochar in the specified amount for incorporation into the SP. Ashwood will handle the mixing of the biochar with bentonite at their manufacturing facility, ensuring the mixture meets the specifications required for use in the well-plugging process. Once the biochar-bentonite mixture is prepared, it will be shipped to Colorado. The logistics of shipping will be finalized at the time of production, based on what is deemed most efficient. Options include shipping directly to the PI, the well site, or the well-plugging operators, depending on the logistical needs and timing of the well-plugging operations.

Deliverable

- A report will be submitted detailing the well's PW salinity using TDS and ion chromatography (IC), along with dissolved organic carbon (DOC) profiling via THP/BTEX measurements.
- Emission data for one traditionally plugged well and one plugged with biochar additive will be submitted to the PI. Measurement data will include date, time, methane mass emission rate (g CH_4 s^{-1}), mass emission rates (g s^{-1}) of measured VOCs, air temperature (°C), relative humidity (%), wind speed (m s^{-1}), wind direction (°), and atmospheric pressure (Pa).
- A report after well plugging will be submitted to the PI in compliance with Rule 434(3), including information on the type of fluids and cement used, the depths at which plugs were set, and the results of all pressure tests and wireline assessments. Additionally, the report will include success/failures during the well plugging process, the methodology for incorporating biochar (timeline, mixing, etc), challenges encountered, and any required modifications to the standard well-plugging practices.

Organization

Team Member Roles

Ashwood Biochar will manufacture and ship bulk biochar, and handle mixing with bentonite for well-plugging.

CSU, Thomas Borch Lab will perform TDS and IC tests to quantify PW salinity and conduct DOC profiling using THP/BTEX measurements.

CSU, METEC will conduct baseline and monthly field campaigns over three months, measuring methane emissions at the well sites using an ABB Micro-portable GHG Analyzer and static flux chambers.

A-Plus Wells will manage the well-plugging operations, including equipment mobilization, wellbore preparation, and setting plugs, incorporating biochar in the SP, and securing a variance.

CSU, ATS will quantify baseline and monthly emissions of speciated VOCs at the well sites.

Timeline & Budget

Below is a breakdown of the anticipated costs and timelines associated with each component of Task 2.

1. **Well Selection and Baseline Testing**
    a. **Estimated Costs:** $68,850
    b. **Estimated Timeline:** 4 months.
    c. **Description:** The costs and timeline for testing the discussed variables is highly dependent on the presence or absence of established protocol. If the company overseeing the selected wells already have depth, pressure, and temperature data, the only costs will be in doing the salinity and organic tests.
        i. Personnel: $30,000
        ii. Materials and supplies: $5,000
        iii. Equipment use charges and instrument fees: $5,000
        iv. Other direct costs: $5,000
        v. Indirect cost rate: 53%
2. **Pre- and Post-Plugging Emissions Measuring**
    a. **Estimated Costs:** $33,326
    b. **Estimated Timeline:** 12 months.
    c. **Description:** The project team at CSU, one Research Scientists (TBC, 0.85 calendar months), and a Graduate Research Assistant (TBC, 0.6 calendar months) over a 12-month period. Labor costs are based on salary plus fringe plus overhead. Fringe rates are calculated at the federally negotiated rates for each employee category. Travel costs include 12 days of CSU Motor pool vehicle use fees and mileage (@ $0.48 per mile). CSU's negotiated indirect cost recovery rate is 54% MTDC.
        i. Personnel: $15,241
        ii. Travel: $1,740
        iii. Materials & Supplies: $1,311
        iv. Indirect Costs: $9,991
3. **Well Plugging Operations**
    a. **Estimated Costs:** $285,000
    b. **Estimated Timeline:** 1 month.
    c. **Description:** For a well with a total depth of 7,000 feet or less, the plugging process typically takes between 5 to 7 days. The second well will be plugged no later than 14 days after the first well is completed. The estimated cost, assuming no abnormal conditions, ranges between $18.00 and $20.00 per foot, which includes the disposal of fluids. In many cases, wellbore fluids may be present in the wellbore before plugging can begin. These fluids need to be safely removed

prior to initiating the plugging process to ensure proper well closure. This cost considers biochar usage in downhole fluid at 5 tonnes (4.2 rounded up from assessment report).

   i. Traditional Well Plugging: $140,000/well (7,000 ft measured depth)
   ii. Biochar: $1,000/tonne

4. **Quantification of Emission Measurements**
   a. **Estimated Costs:** $76,550
   b. **Estimated Timeline:** 15 months.
   c. **Description:** The project team at CSU, one Research Scientist (Zhou, 2.5 months), one postdoc (Ku, 1.5 months), and one faculty member (Collett, 0.5 months). Labor costs are based on salary plus fringe. Fringe rates are calculated at the federally negotiated rates for each employee category. Materials include purchase of sample canisters and inlets and shipping cases; shipping charges. Equipment use charges are assessed on a per sample cost for use of the GC system. CSU's negotiated indirect cost recovery rate is 54% MTDC.
      i. Personnel: $41,083
      ii. Materials and supplies: $6,000
      iii. Equipment use charges: $2,625
      iv. Indirect Costs: $26,842

Task 3: Environmental Justice & Community Engagement

Background

Relevance

Incorporating environmental justice (EJ) into this study ensures that biochar deployment in well plugging addresses the disproportionate environmental and health impacts on vulnerable communities near oil and gas infrastructure. While the primary focus is on biochar's technical performance, EJ integration promotes equitable outcomes fostering distributive and procedural justice[4], transparency, and supporting trust among stakeholders. Additionally, it helps regulators and policymakers evaluate the broader societal benefits of biochar, enhancing public support, regulatory approval, and the long-term viability of the technology.

Existing Literature

Communities located near oil and gas infrastructure, particularly in proximity to orphaned wells, are exposed to increased risks of methane emissions and groundwater contamination (U.S. Department of the Interior, 2023). These environmental hazards are known to contribute to respiratory health issues and exacerbate existing socioeconomic inequalities. These communities have also dealt with negative mental health impacts, like chronic stress and depression, due to the uncertainty and powerlessness community members experience (Malin 2020). Distributive and procedural environmental injustices have characterized unconventional

[4] What spaces and communities are disproportionately impacted by environmental bads like pollutants and hazards and who has a seat at the table to make related decisions, using accessible and translated information.

drilling generally (Malin Mayer and Hazboun 2023). For example, in 2016, Colorado communities were legally barred from making local-level decisions about when, where, or whether oil and gas development would take place (Malin et al., 2019; Malin et al., 2018). Research on biochar applications suggests its efficacy in mitigating environmental contaminants, positioning it as a viable solution for reducing health risks in affected populations (Khan et al., 2024). Trottier et al. (2019) emphasizes the critical role of community engagement in environmental remediation efforts. Involving affected communities in decision-making processes enhances procedural justice and transparency while fostering trust, ensuring that interventions are tailored to meet local needs. This is especially significant in tribal regions, where orphaned wells disproportionately affect culturally important lands and resources and poor communities or communities of color that have been the most disproportionately impacted by environmental risks and hazards (Mohai et al 2009; Roberts et al. 2018).

While much research focuses on active drilling and its aftermath, the presence of abandoned and/or unplugged wells can create similar environmental inequities if not carefully assessed and engaged with communities. Our previous assessment report noted concerns regarding the emission of VOCs and associated odors, particularly in communities near manufacturing facilities. However, it was noted that the study in question investigated biochar with extreme contamination as a worst-case scenario (Hossain et al, 2011). Typically, well-designed pyrolysis units produce biochar with minimal VOC contamination, reducing the likelihood of odors. Air emissions during biochar production are another concern, with most modern pyrolysis units employing a two-stage process that includes full combustion of pyrolysis gases. This method parallels processes in biomass and coal incineration plants, where emissions of nitrogen and sulfur compounds can be controlled using scrubbers. Proper air cleaning technologies are essential to minimize the release of harmful gases, ensuring that the impact on local air quality remains negligible. This body of work suggests that, when managed properly, biochar production can operate within safe environmental limits.

Objectives

The primary objective of this task is to engage communities, particularly those disproportionately impacted by orphaned and unplugged wells, in the planning and execution of a biochar-based well-plugging project. By integrating environmental justice principles and community feedback, the project aims to address concerns related to biochar manufacturing and well-plugging operations while promoting transparency. Environmental justice principles will include considerations around: distributive, procedural (both defined), recognition (marginalized groups or more-than-humans recognized as having legal standing or ability to participate), and restorative justice (remediating polluted landscapes and repairing social relationships to be more equitable). Additionally, increased awareness and education about biochar's environmental benefits, such as carbon sequestration and emissions reduction, are expected to foster local support and encourage the broader adoption of sustainable well-plugging practices across the industry.

Subtasks

Summary

The study will engage communities near biochar manufacturers and abandoned wells, particularly those facing higher risks due to proximity to methane emissions and groundwater contamination, by working with members of the Center for Environmental Justice at CSU to oversee the engagement process. Leaders of the Center for Environmental Justice, particularly Dr. Stephanie Malin, have experience in working with populations affected by oil and gas operations and has been identified as a potential collaborator, along with the Geospatial Centroid at CSU. This partnership will enable effective community outreach and feedback integration throughout the project, ensuring transparency and responsiveness to community concerns.

Key outcomes include creating spaces for inclusive and transparent decision-making and gathering community feedback, particularly on issues related to biochar manufacturing and well-plugging operations using biochar. Through various community engagement techniques, including community meetings and community-based research design and data, the project aims to foster trust among local stakeholders by addressing their concerns. The data gathered from these interactions will inform recommendations for integrating environmental justice considerations into future well-plugging projects involving biochar.

Approach

We have included the Center for Environmental Justice as a partner organization, given their expertise in EJ and experience working with communities impacted by oil and gas operations. Further, the Geospatial Centroid will conduct detailed spatial analysis will be conducted to identify communities most at risk. This analysis will guide the community engagement strategy, focusing outreach efforts on communities living near orphaned wells and biochar manufacturers. The results of this analysis will be used to tailor the study's communication and outreach efforts to meet the specific needs of each community.

The Center for Environmental Justice will develop key questions and determine the best methods for community engagement, addressing concerns around biochar manufacturing and well-plugging activities. This feedback will help shape the final project design, ensuring responsiveness to local needs. The full research team will maintain close collaboration with the Center for Environmental Justice throughout the study, with frequent meetings to discuss community feedback, address emerging concerns, and coordinate community feedback into the study design where applicable.

Deliverable

- A key deliverable of this subtask will be a detailed report outlining the EJ approaches followed, community feedback, and any interventions or adjustments made based on input from stakeholder groups. This report will also include recommendations for how future well-plugging projects using biochar can incorporate EJ principles.

Organization

Team Member Roles

The Center for Environmental Justice, with experience working with communities affected by oil and gas operations, will be contracted to carry out all key aspects of Task 3. The Geospatial Centroid will provide support during the mapping phase and during identification of communities.

Timeline & Budget

Below is a breakdown of the anticipated costs and timelines associated with each component of Task 3. The timeline is expected to be concurrent with Tasks 1 and Tasks 2 of this document.

1. **Initial Phase: Community Identification and Spatial Analysis**
    a. **Estimated Costs:** $40,000-$45,000
    b. **Estimated Timeline:** 6 months.
    c. **Description:** Collaborating on the spatial analysis (Geospatial Centroid), helping to identify communities (Center for EJ (Malin) and the Geospatial Centroid), and planning outreach strategies (Center for EJ (Malin)). Preparing community-specific communication strategies, developing questions, coordinating with the research team (Center for EJ (Malin)).
        i. 40-60 hours/month for the Geospatial Centroid's work: ~$24,000
        ii. 1 month FTE (which will cover either a course buyout + fringe) or 1 month of salary + fringe: ~$16,000-~$20,000
2. **Active Engagement Phase: Community Engagement & Meetings**
    a. **Estimated Costs:** $56,000-$72,000
    b. **Estimated Timeline:** 12 months.
    c. **Description:** Organizing community meetings, workshops, and focus groups, plus gathering and processing feedback. Costs for Malin from the CEJ are based on typical faculty compensation allowances billed in monthly increments. The Graduate student support is based on a $40/hr rate. An estimated $10,000 is built in for incentives across communities and participants, as well as research implementation, data collection, and analysis fees.

i. 2 months FTE (which will cover a course buyout + fringe) and 1 month of salary + fringe: $36,000
ii. 6 months of community outreach, data collection, analysis, and interpretation from a hired, hourly graduate student: $10,000
iii. Incentives for participation: $10,000
iv. Costs of meetings/interviews as community engagement: $10,000 (may cover additional personnel expenses).
v. If conducting a survey across communities becomes evidently useful, an online or hybrid mail/online survey may be conducted: $7,000-10,000
vi. Additional research assistance as required: $6,000

3. **Evaluation & Adjustment Phase: Final Feedback Gathering & Reporting**
   a. **Estimated Costs:** $43,300-$44,000.
   b. **Estimated Timeline:** 6 months.
   c. **Description:** Refining project design based on final feedback, organizing wrap-up meetings or follow-ups with the community. Coordinating final project outcomes and ensuring community feedback is integrated. Costs are based on estimates detailed below.
      i. Report Creation
      ii. Final feedback Gathering
         1. FTE, covering course buyout + fringe and 1 month of salary + fringe: $36,000
         2. 2-3 months of data analysis and interpretation from a hired, hourly graduate student: $3,300-$4,900
         3. Data analysis components, including transcription of interviews, survey analysis, and/or time spent in meetings to follow up: $4,000-$6,000

Additional Considerations

In this study, we are focusing on biochar's role in SP for well-plugging applications, but there is strong potential for biochar to be used in cement in the future. Biochar's ability to reduce permeability could address issues like gas migration, which is particularly critical in cases of subsurface over pressurization that can lead to leaks in plugged wells (Barbhuiya et al., 2024). Incorporating biochar into cement could enhance its sealing properties by limiting gas or fluid migration pathways. While this study focuses on biochar in SP due to optimizing carbon sequestration, its potential to improve the performance of cement in well-plugging applications warrants future investigation.

Incorporating biochar into soil during well site remediation offers considerable environmental and carbon sequestration benefits, making it a valuable addition to the study, even if it is not explicitly outlined in the bill. Biochar can improve soil health by enhancing nutrient retention, increasing water-holding capacity, and stabilizing soil structure, which helps mitigate the negative ecological effects caused by well pad construction. Its ability to adsorb contaminants such as hydrocarbons and heavy metals makes it effective in reducing the mobility of these pollutants, preventing them from leaching into groundwater or entering the food chain (Yatsyshyn et al., 2022). Biochar can also help accelerate soil restoration around the well pad site, promote seed germination and vegetation growth, and thus help companies meet their restoration goals faster and cheaper.

Beyond environmental restoration, incorporating biochar into well site remediation also creates an opportunity to generate carbon credits. Unlike its use in well plugging, where methodology is still being developed, the use of biochar in soils is already an accepted practice for carbon credit generation. Including biochar for surface remediation in the study could provide a valuable pathway for calculating potential carbon credits, making the project even more beneficial in terms of carbon capture and ecological sustainability.

Summary of Project Timeline and Deliverables

Timeline	Tasks	Deliverables
Months 1-25	**Laboratory Testing:** Manufacture biochar, assess SPbc properties (density, rheology, etc.)	Lab report on optimal biochar properties, including well integrity tests
Months 1-12	**Geospatial Analysis & Biomass Availability:** Map biomass sources, assess accessibility	Spatial data report on biomass sources, including access constraints and recommendations for improved biomass use
Months 1-24	**Environmental Justice & Community Outreach:** Community mapping, engage stakeholders	Community feedback summary report, documentation of EJ activities and responses
Months 26-29	**Baseline Testing for Downhole Pilot Study:** Select wells, measure TDS, IC, methane	Baseline data report on well characteristics (TDS, methane emissions, organic profile)
Months 30	**Well Plugging Operations** Conduct plugging with and without biochar in SP on selected wells	Report on well-plugging operations, detailing plug placement, SP composition, and modifications required
Months 29-42	**Methane Emissions Monitoring** Baseline, 1-, 2-, 3-, and 12-month monitoring at wells	Emissions data report, including methane and VOC measurements from static flux chambers
End of Year 4	**Final Report Submission:** Summarize all phases, findings, and policy insights	Final technical report, publications, data repository with field and lab results, community engagement insights

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