BIOCHAR IN ANIMAL AGRICULTURE: THE POTENTIAL FOR CASCADING BENEFITS AND RESOURCE CIRCULARITY

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EXECUTIVE SUMMARY

Agriculture is both a major contributor to climate change and one of the most vulnerable industries to its effects (Blandford and Hassapoyannes, 2018; Lipper et al., 2014). Agriculture, forestry, and land use change are estimated to account for 24% of global GHG emissions (IPCC, 2014). Emissions from animal agriculture are particularly high, contributing 16.5% to global GHG emissions (i.e., 69% of the total agricultural sector) (Twine, 2021). Meanwhile, farmers are inextricably affected by extreme weather events that are exacerbated by the changing climate. To mitigate the GHG emissions contributing to climate change and increase resilience to extreme weather events, farmers and ranchers must adopt climate-smart practices. One versatile tool for mitigating and adapting to climate change is biochar.

Biochar is charcoal which is used as a soil amendment or for other environmental management purposes (Lehmann and Joseph, 2015). Its main agricultural benefits include increasing soil water and nutrient holding capacity, remediating contaminants, reducing GHGs and improving soil structure. The organic carbon formed in biochar is highly resistant to decay, lasting for hundreds to thousands of years; thus, producing biochar is a potential method of carbon sequestration (Lehmann and Joseph, 2015).

In addition to its use as a soil amendment, integrating biochar into animal agriculture systems has demonstrated several benefits (Graves et al., 2022, Schmidt et al., 2019). Biochar can be integrated into animal agriculture through feeding, bedding, composting, anaerobic digestion, manure slurries and producing biochar with manure. Through these applications, biochar can reduce ammonia, GHGs, and odors while also improving animal health, production efficiencies, and resource circularity. Incorporating biochar into animal agriculture also increases the quality of biochar by inoculating the surfaces and pores with nutrients and microbes (Joseph et al., 2015; Mia et al., 2017). These improved biochars can then be applied to agricultural soils, improving soil health and climate resilience.

It is important to recognize that the properties and characteristics of biochar vary widely based on the biomass used to make it and the production process. This leads to significant variability in the function of biochar. For that reason, it is essential to understand the characteristics of a given biochar and consider it within a lens of holistic resource management. This review covers the mechanisms and methods of six different applications of biochar in animal agriculture. Biochar has the potential to improve the sustainability of animal agriculture while enhancing and enriching biochar properties for soil application; therefore, providing a cascade of benefits. It is emphasized that partnerships between farmers and researchers are critical to advancing our understanding of biochar at farm scale.

GLOSSARY

- **C**- Carbon
- **CO_2**- Carbon Dioxide
- **CO_2e-** Carbon Dioxide Equivalent
- **CH_4**- Methane
- **N-** Nitrogen
- **N_2O-** Nitrous Oxide
- **NH_3**- Ammonia
- **NH_4^+**- Ammonium
- **PO_4^{3-}**Phosphate
- **GHG**- Greenhouse Gas
- **GWP**- Global Warming potential
- **CAFO-** Concentrated Animal Feeding Operations
- **SA-** Surface Area
- **CEC-** Cation exchange capacity
- **AEC-** Anion exchange capacity
- **Carbon Sequestration-** The removal of carbon from the atmosphere
- **GHG mitigation-** The reduction or avoidance of emitting GHGs
- **Biomass-** Material that comes from living organisms (e.g., plants & animals)
- **Pyrolysis-** The heating of an organic material in a low-to-no oxygen environment
- **Feedstock-** Raw material used to supply or fuel a machine or industrial process

INTRODUCTION

Although charcoal is nothing new to this world, the past two decades have shown an exponential growth in research around the carbon material known as biochar. Unlike traditional charcoal, which is mainly burned for energy, biochar is produced at a higher temperature which improves its suitability for soil applications. Simply put, biochar is charcoal which is used as a soil amendment or for other environmental management purposes (Lehmann and Joseph, 2015). As research continues to grow on the subject, scientists and practitioners have found promise in the material's ability to improve soil water and nutrient retention, remediate contaminants, and abate GHG emissions all while sequestering carbon by slowing down the natural carbon cycle of biomass (Lehmann and Joseph, 2015; Schmidt et al., 2021). There have been many promising results from the use of biochars, but they are by no means consistent, and many of the mechanisms at play are still clouded by uncertainty. Most research has centred around biochars' application in agricultural soil, but its properties can be adapted to many other scenarios. The purpose of this paper is two-fold, (1) highlight the potential of biochar within animal agriculture, and (2) provide science-based recommendations and considerations to farmers and ranchers interested in adopting biochar into their systems.

ORIGINS:

The production and application of biochar is by no means a new concept. The most notable evidence of biochar was discovered in the Amazon basin by Portuguese explorers and named *Terra Preta* or black soil (Woods and McCann, 1999; O'Neill, 2009). These large pockets of deep, rich soil are thought to be middens of the indigenous Amazonia peoples combining charcoal and organic material (e.g. manure, animal remains and pottery) (Woods and McCann, 1999). This is the most cited in its connection to biochar, however, there are many examples of indigenous peoples around the world using charcoal to improve the soil and vegetation in their environment (Lehmann and Joseph, 2015). The description of thriving *Terra Preta* soils published by Woods and McCann (1999) spurred an explosion of research on biochar due to its potential to sequester carbon and improve soil health.

MODERN ANIMAL AGRICULTURE

Perhaps the most jarring example of our agricultural systems concentrating, and intensifying is the transition of animals from pastures to concentrated animal feeding operations (CAFO). CAFOs are a bane to our environment and the sustainability of agricultural systems. Cramped conditions have led to a decrease in animal health and welfare, while increasing local air and water pollution from excess nutrients, and intense odors (Petersen and Sommer, 2011). Ammonia (NH_3), nitrous oxide (N_2O), and methane (CH_4) gasses are associated with animal agriculture and manure management. Such gasses contribute to degraded local air quality and global GHG emissions, N_2O is an especially potent gas with a global warming potential ~273x that of CO_2 (US EPA, 2016).

IMAGE 1: PIGS IN A CAFO (CHENG, 2019)

An alternative to such CAFO's, proposed by regenerative agriculture, is to return animals to pasture in a system of holistic planned grazing. Integrating animals into crop systems and pastures is a core principle of regenerative agriculture as it attempts to mimic the natural movement of ruminants grazing with frequent movement to avoid predators (Brown, 2018). Holistic planned grazing can have greater associated GHG emissions per kg of live weight per animal because it takes longer to raise the livestock, but Stanley et al. (2018) found that C sequestered in pastures by such management practices can completely offset the GHG emissions from grazing. The scientific merits of holistic planned grazing are a topic of debate outside the scope of this report.

Regenerative, rather than extractive farming, should be the goal for meat production, but there are substantial limitations that must be overcome for this system to meet current and future demand. As we transition our agricultural systems to regenerative practices, mitigating the impacts of current practices is critical. Biochar can not only be a useful material in improving the environmental sustainability of animal agriculture but may be essential for resource circularity of a regenerative agricultural system.

Objectives:

1. Examine and explain the science and methodology of applying biochar in animal agriculture.

2. Synthesize the findings and research into a clear decision matrix on best practices for biochar use in animal agriculture.

The next sections will provide background on the production and properties of biochar. As stated, the properties of the material vary widely depending on the biomass feedstock, production process, and age, yielding functionally very different products which is why biochar(s) may be referred to in the plural (Enders et al., 2012). Rather than considering biochar as an ordinary, linear agricultural input, the hope is that readers come away with a comprehensive understanding that biochars can be a component of resource circularity and has the potential to provide a cascade of benefits when integrated into animal agriculture.

BIOCHAR PRODUCTION

Biochar is charred biomass that has gone through a thermochemical conversion (e.g. gasification, pyrolysis, torrefaction). The most common production method is pyrolysis, which thermally degrades biomass into char in a low-to-no oxygen environment. During pyrolysis, biomass is transformed into organic C (in the form of compressed aromatic structures) which are highly resistant to decay, evidenced by biochar lasting for hundreds to thousands of years (Lehmann, 2009; Nguyen et al., 2010).

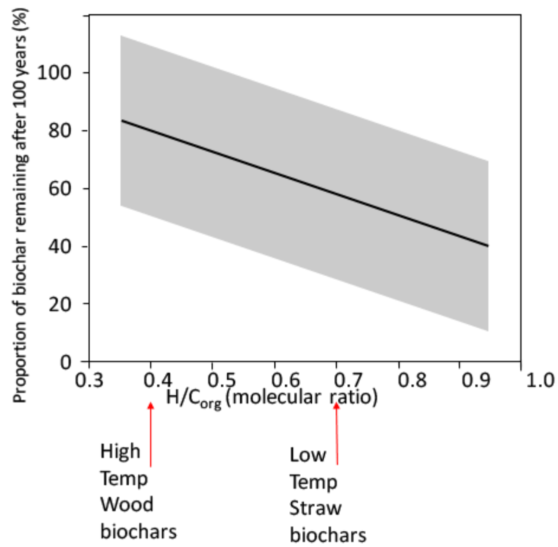

FIGURE 1: COMPOSITION OF H:C RATIO IN RELATION TO BIOCHAR RECALCITRANCE (JOSEPH ET AL., ND).

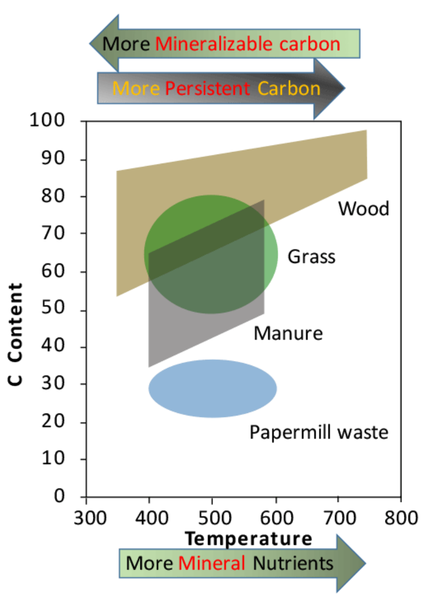

FIGURE 2: COMPARISON OF VARIOUS FEEDSTOCKS AND PRODUCTION TEMPERATURES ON C CONTENT AND RECALCITRANCE (RIGHT) (JOSEPH ET AL., ND)

This conversion from volatile organic matter to stable carbon is considered a potential method for carbon sequestration. Without any modifications, up to 50% of the carbon in the biomass feedstock can be stabilized in the form of biochar (Zhao et al., 2014). This effectively slows down the carbon cycle, as most biomass decomposes and releases ~99% of C within a matter of years or decades, while the C in biochar is thought to last centuries to millennia. Although stability of C in biochars varies based on production temperature and feedstock, the H:C ratio has been deemed an effective method for estimating its' half-life decay rate (Enders et al., 2012).

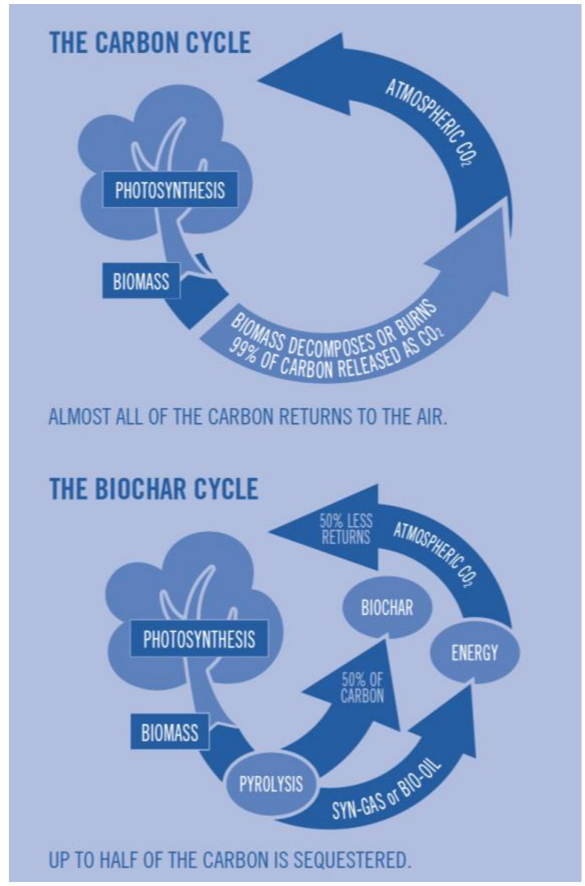

FIGURE 3: THE INTERRUPTION OF THE NATURAL CARBON CYCLE BY PRODUCING BIOCHAR SLOWS THE RELEASE OF C STORED IN BIOMASS (SOURCE:BIOCHAR SOLUTIONS INC)

There are many ways to create biochar via pyrolysis.

The simplest method is to burn dried biomass in a pit preventing oxygen entering the fire from the sides. This has been emulated by flame-cap kilns (*Figure 4)*. By continuously loading layers of biomass, the charred material below is covered and suffocated from oxygen. When all the material has be sufficiently charred, the fire is thoroughly quenched with water. Such methods

FIGURE 4: THE RING OF FIRE BIOCHAR KILN DESIGNED BY WILSON BIOCHAR ASSOCIATES. THE TOP LIT FIRE, LIMITS OXYGEN IN THE LOWER PORTION OF THE BURN, CREATING PYROLYSIS CONDITIONS. (LEFT: WILSON BIOCHAR ASSOCIATES) (RIGHT: DAVID MORRELL)

are relatively inexpensive and mobile, lowering the barrier for small-scale production. That said, this method releases substantially more CO_2; therefore, has lower C sequestration potential.

The other end of the production spectrum is a pyrolysis furnace which is capable of high temperatures and controlled rates of heating. Production with a pyrolysis furnace yields a higher C conversion, meaning more C storage and less CO_2 emitted (Tenenbaum, 2009). Pyrolysis furnaces also produce several co-products including syngas and bio-oil in addition to biochar. Syngas, a fuel gas primarily composed of CO and H_2, can be recirculated and burned to continue powering the pyrolysis furnace or generate electricity. Bio-oil can be refined and used as alternative to fossil fuels. It is worth noting that some pyrolysis units are built to also condense smoke into pyroligneous acid, aka “wood vinegar,” which has demonstrated intriguing agronomic potential as a pesticide and fertilizer, but that is outside the scope of this report. For scientific and commercial purposes, pyrolysis furnaces are preferred for the higher level of control, resulting in a more uniform product (Lehmann and Joseph, 2015).

Pyrolysis can be completed at different speeds, fast pyrolysis is complete within seconds to minutes and yields only ~ 15-20% biochar, the rest being syngas and bio-oil (Lévesque et al., 2021). Slow pyrolysis is defined by a duration longer than 10 minutes, but generally takes hours to days and yields significantly more biochar. This is considered the best method for maximizing biochar quantity and quality (Leng and Huang, 2018).

PHYSICAL & CHEMICAL PROPERTIES OF BIOCHAR

To understand the potential applications of biochar it is crucial to understand the properties of the material itself. The benefits of biochar are generally assigned to its high porosity, surface area (SA), alkalinity, cation and anion exchange capacity, and surface functional groups. The highly porous structure increases water and nutrient holding capacity,

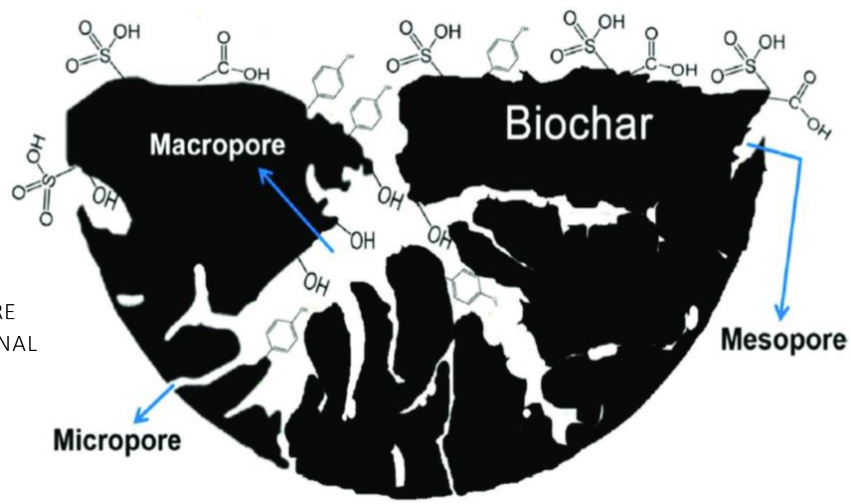

FIGURE 5: DEPICTION OF DIVERSE PORE SPACE SIZES AND CHEMICAL FUNCTIONAL GROUPS ON SURFACE OF BIOCHAR (CHENG AND LI, 2018).

and decreases bulk density (Burrell et al., 2016). Its negatively charged surface can increase soil pH and adsorb and immobilize a range of organic pollutants and heavy metals (Liang et al., 2021). Additionally, depending on feedstock, biochar can provide some amount of available C and nutrients for energy for soil biota and plant uptake.

The feedstock, or source material, used to produce biochar is critical to the final product. Essentially any form of biomass can be used to produce biochar (Lehmann and Joseph, 2015). Popular feedstocks include wood, grass, crop residues (e.g. straw, nut shells, rice hulls, corn stover), biosolids, and manure. To minimize the cost and carbon footprint, it is best to use locally available waste resources. Feedstock selection has a large impact on many of biochar's properties, most namely the mineral and carbon content.

Pyrolysis temperature is the most influential production factor, but heating rate, duration, and oxygen content also influence the final product (Lehmann and Joseph, 2015; Enders et al., 2012). Lower temperatures (<300ºC) produce biochar with lower SA, pH, and electrical conductivity. Whereas high temperatures (>700ºC) begin to reduce the number of functional groups on the surface. Biochar yield and C recovery also decrease as temperatures increase, but C content is also more stable at higher temperatures. With these approximate thresholds in mind, practitioners and scientists have generally concluded that mid-range temps

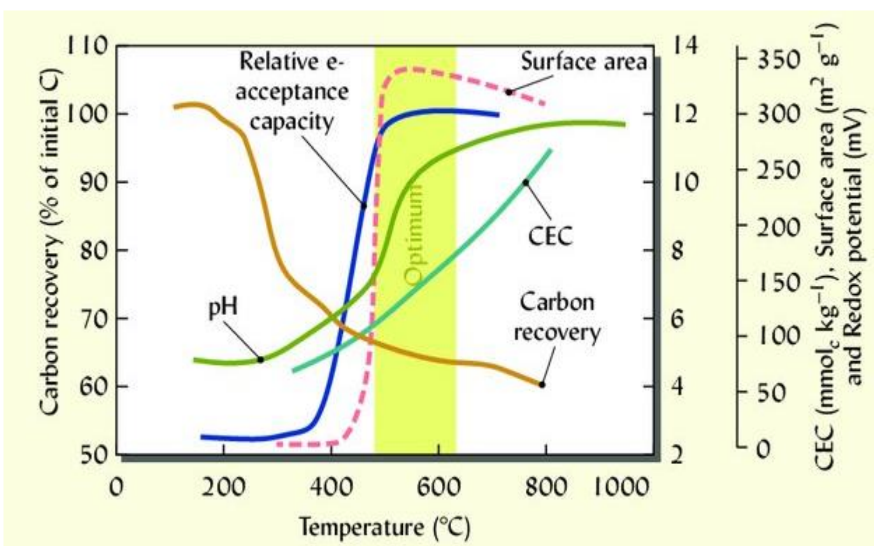

FIGURE 6: COMPARISON OF VARIOUS BIOCHAR PROPERTIES COMPARED TO THE TEMPERATURE OF PRODUCTION. CONSEQUENTLY 500-600ºC IS THE TEMPERATURE MOST CHAR IS FORMED DURING A WILDFIRE (WEIL AND BRADY, 2017).

of 500-600ºC (*Figure 5*) are ideal for maximizing surface area while retaining functional groups and producing an adequate yield (Weil and Brady, 2017). That said, the ideal temperature depends on the feedstock and the desired use. It is critical to consider feedstock and production temperature when assessing the impact, efficacy, and precautions of any given biochar.

In addition to standard production methods, biochars are often 'modified' to enhance certain properties and functional capacities depending on the desired use. There are many methods of biochar modification. The goal of such alterations is to generally increase surface area or enhance the chemical capacity of the material. There now exist innumerable methods, but the most common modification methods include activation with steam, magnetization, alkali/acid solutions, or additions of minerals, organic functional groups, and nanoparticles (Li et al., 2017). The modification of biochar can lead to significantly improved efficacy. For example, compared to unmodified biochar which showed no reduction in NH_3, biochars modified with sulfuric acid to a pH of 2.0 resulted in a linear reduction of NH_3 volatilization in poultry litter (Ritz et al., 2011). The use of modified biochar often improves desired results, but such modifications add cost and complexity to an already expensive product. Therefore, modifications should be chosen critically in relation to the target end use.

Biochar properties change over time as they age. The surface of fresh biochar surface can be hydrophobic, and the volatile carbon can tie up available nutrients present when applied, leading to negative initial results (Mia et al., 2017). A critical review by Mukherjee and Lal (2014) outline many of the potential adverse results from biochar application along with hypothesized mechanisms. One of most common mechanisms mentioned is the abrupt change pH in the soil. Some of the issues associated with a highly alkaline biochar include micronutrient deficiencies, increased heavy metal mobility, and harm to soil bacteria and fungi (Mukherjee and Lal, 2014; Joseph, 2021). As biochar ages, improvements in both physical and chemical properties are generally observed (Mia et al., 2017). Aged biochars develop surface functional groups and have increased cation exchange capacity (Mukherjee and Lal, 2014; Mia et al., 2017). This process of ageing important to reduce potential hydrophobicity and load the pores with nutrients and microbial life.

There are substantial limitations which must be assessed when considering the suitability of biochar application. One of the most obvious challenges is the wide variability of the properties of biochar. Incorporating biochar with animal bedding, manure compost or liquid manure is an excellent way to enrich biochar and mitigate the potentially adverse effects of fresh biochar (Sarkhot et al., 2012; Mia et al., 2017). For this reason, applying biochar to soil which has been used in animal agriculture may be the best method of use.

BIOCHAR IN ANIMAL AGRICULTURE

Most research has focused applying biochar as a soil amendment, but the use of biochar in animal agriculture is rapidly expanding in both research and practice (Graves et al., 2022; Schmidt et al., 2019). When applied properly to animal agriculture, biochar is an excellent manure and nutrient management tool. It has the capacity to mitigate ammonia and GHGs, reduce leaching of nutrients, increase resource circularity, and improve animal health and barn conditions. On top of these benefits, incorporating biochar with animal waste improves the properties of biochar desired for soil application (Kammann et al., 2017). For these reasons the incorporation of biochar into animal agriculture can provide cascading benefits.

The soil application of animal enriched biochar may have even greater potential for temperate regions, which have recorded mixed results from biochar application. In a global meta-analysis, regions with a mean annual temperature less than 10ºC were found to have no yield increase from biochar (Schmidt et al., 2021). It is of no coincidence that most commercial biochar sold in Europe is used as an input in animal agriculture before making its way into the soil (Kammann and Schmidt, 2014; Kammann et al., 2017).

Biochar is a versatile puzzle piece that can fit into many aspects of animal agriculture. The six most common uses of biochar in animal agriculture are:

1. Animal bedding
    - Sorbent for both gasses and animal excrement, capturing N from leaching or volatizing
2. Manure co-composting
    - Regulation of air and moisture content. Increase composting temperature, speed, and compost quality while decreasing the associated GHG emissions
3. Anaerobic digestion enhancement
    - Increase methane production and decrease gas impurities
4. Feed supplement
    - Improve animal health, digestion efficiency, and weight gain
5. Manure slurry management
    - Reduce ammonia gas and odors, adsorb plant available nutrients

6. Biochar production with manure as a feedstock

    - High macronutrient availability compared with other biochars

ANIMAL BEDDING

IMAGE 2: BIOCHAR AND STRAW BARN BEDDING (COURTESY OF KANSAS FOREST SERVICE)

The management of barn bedding to improve animal health and manage manure is ever evolving. In addition to disease mitigation and animal comfort, decisions are often based on resources that are locally abundant and inexpensive. Incorporating biochar (5-10% by volume) into bedding materials such as sawdust, woodchips or straw can provide numerous benefits including nutrient retention, ammonia adsorption, reduced hoof disease and odor control (O'Toole et al., 2016). The addition of biochar to barn bedding captures excess N which is either leached or volatilized into potent GHGs; furthermore, creating a more N:P balanced manure/compost material (Wilson Biochar Associates, 2019). Often, manure or composted manure is overapplied to meet crop N demands. Over time this generates a buildup of P as it is quickly immobilized rendering it unavailable to plants. This excess P, often referred to as legacy P, is a risk to environment leaching and algal blooms in freshwater ecosystems. By retaining more N, farmers can apply less manure, not only reducing eutrophication risk, but lowering operational costs of spreading.

Modifying the pH of biochar greatly improves its capacity as a bedding material. Urolytic bacteria, which convert urea into NH_3, are most effective in conditions around pH 8.5-9.

Therefore, most fresh biochars, which are alkaline (pH>9), are less effective and can even contribute to the volatilization of ammonia (Wilson Biochar Associates, 2019; Ritz et al., 2011). Biochars can be acidified with several agents including citric acid, lactic acid, sodium bisulfate, sulfuric acid or even wood vinegar (a pyrolysis by-product) to improve the function as a bedding material. Another method of acidifying biochar relies on the incorporation of lactobacillus bacteria (Wilson Biochar Associates, 2019). This example speaks to the importance of biology as a key partner with biochar for managing animal bedding.

Recommendations:

1. Incorporate at a rate of 5-10% of bedding by volume
2. Acidify biochar to reduce ammonification
   And/or
3. Inoculate bedding with lactobacillus bacteria

Resources:

- How to Use Biochar in Barns – Umpqua Biochar Education Team
- Poultry Manure Biochar – Wilson Biochar Associates

CO-COMPOSTING WITH BIOCHAR

Co-composting with biochar was determined to be one of the first agronomically and economically feasible uses of biochar in temperate climates (Schmidt et al., 2021). Co-composting with biochar can reduce associated GHGs, while increasing microbial activity, temperature, compost maturity rate and nutrient retention (Godleska et al., 2017). In general, industry experts agree that adding biochar to compost is one of the best ways to incorporate biochar into soil (Antonangelo et al., 2021). Applying biochar to compost can also help reduce some of the ill-effects (e.g. rapid pH change, hydrophobicity and nutrient immobilization) encountered when fresh biochar is applied to soil. During composting, functional groups, CEC and hydrophilicity of biochar are improved leading to increased water and nutrient holding capacity (Antonangelo et al., 2021). Increased compost efficiency, GHG mitigation and improved biochar properties exemplify potential for cascading benefits.

Co-composting with biochar has been shown to increase retention of both C and N while improving moisture and aeration, which are crucial for thermophilic composting (Hestrin et al., 2020; Malinowski et al., 2019; Jang et al., 2018). The ability of biochar to absorb ammonia emissions not only reduces odors and emissions from composting but yields a finished compost with greater available N (Hestrin et al., 2020; Steiner et al, 2010). Due to disease concerns and existing infrastructure, it may be challenging to incorporate biochar into bedding systems of some operations. In which case it makes more sense to include biochar to the composting manure. Although much of the N may have already been lost, adding biochar to composting can reduce further losses of nutrients, GHG emissions and increase the speed of the composting process ((Wilson Biochar Associates, 2019).

Many studies validate the efficacy of biochar as a co-composting ingredient (Antonangelo et al., 2021). Steiner et al. (2010) saw a 64% increase of N retention with an addition of 20% pine biochar to composting poultry litter. At a lower yet still impressive rate, Janczak et al. (2017) measured a 30% and 44% decrease in NH_3 when 5% and 10% biochar was applied to composting litter. These results are confirmed by Agyarko-Mintah et al. (2017), who found that poultry litter composted with biochar resulted in cumulative N_2O emissions 65-70% lower than the control.

Not only are there substantial environmental benefits, increased speed in composting and reduced days to maturity is an economic benefit to both farmers and compost facilities

(Antonangelo et al., 2021). When composting swine manure with biochar, Wang et al. (2018) found a 12% decrease in total compost time. While trialing biochar at an operational compost facility Malinowski et al. (2019) documented no increase in composting speed, noting the importance for further studies at an operational scale.

When incorporating biochar into a composting operation, it is important to consider how it will affect the C:N ratio. The total C:N ratio of biochars can vary widely from 10:1 to 639:1 (Bonanomi et al., 2017). Though much of the C in biochar is unavailable for microbes making the effective C:N much lower (Bonanomi et al., 2017). Biochar can be an effective compost ingredient at just 3% (by weight), but for high N materials such as manure, application rates in the range of 10-20% are recommended (Camps and Tomlinson, 2015; Antonangelo, 2021). Unless there is an accurate understanding of the C:N ratio of your biochar, start slow and monitor the compost regularly.

Recommendations:

1. Use a biochar with a high SA, CEC, water-holding capacity, and functional groups. Likely this will be best if produced between 400°C – 700°C
2. 10-20% application rate by mass, start small until C:N ratio balance is understood.

Resources:

- On-Farm Production and Use of Biochar for Composting with Manure – (Wilson Biochar Associates, 2018)

LIQUID MANURE MANAGEMENT

Manure lagoons and tanks are used to capture and store animal waste until field application. Although such systems may be effective at reducing leaching potential, uncovered lagoons are a significant source of CH_4, CO_2, and N_2O gases. Not to mention the intense odor created by NH_3 and other volatile compounds. The incorporation of biochar to manure slurry can improve both odor and nutrient retention (Dougherty et al., 2017; Schmidt, 2014). Like animal bedding, the addition of lactic acid producing bacteria can reduce pH and the associated ammonia volatilization.

IMAGE 3 DAIRY MANURE SLURRY MIXED WITH BIOCHAR.

An experiment conducted by Dougherty et al. (2017) compared the efficacy of a manure lagoon cover with biochar produced from Douglas Fir hog fuel via slow pyrolysis at 600ºC vs biochar from Douglas Fir chips gasified at 650ºC. The biochar produced with slow pyrolysis led to a 72-80% decrease in NH_3 in the headspace; meanwhile, the gasified provided no significant benefit to ammonia reduction. It was hypothesized that the higher pH, 9.32 of gasified biochar vs. 7.28 of pyrolyzed biochar, aided to the conversion of NH_4^+ to NH_3. Additionally, the pyrolyzed biochar was more hydrophobic, leading to greater gas insulation. Considering the feedstock materials were similar, these results speak to the importance of production process and the vital differences of the physico-chemical properties of biochar. This reiterates the point that all biochars are not created equal and the known properties must be considered before any application. The same study measured odor reductions over 12 weeks with a panel of judges (since odors are subjective) who deemed that all biochars provided odor reduction compared to the control (Dougherty et al., 2017).

Instead of using biochar as a lagoon cap designed to reduce ammonia and odors, liquid manure can simply be mixed with biochar for soil application. The main benefit of adding biochar with liquid manure before soil application is the reduction of nutrient leaching or volatilization (Ghezzehei et al., 2014). Liquid manure mixed with 1% biochar applied to soil reduced nitrification (68%), ammonification (221%), CO_2 flux (67%), and N_2O flux (26%) (Sarkhot et al., 2012). Within 24 hours, biochar can adsorb up to 43% NH_4^+ and 65% PO_4^{3-} in liquid manure (Ghezzehei et al., 2014). In addition to reducing nutrient leaching, biochar gains agronomic potential as a fertilizer. To extrapolate to a landscape scale, Ghezzehei et al. (2014) estimated that biochar mixed with liquid manure from California dairy farms could reduce the demand of 57,000t NH_4 and 4,600t P_2O_5 chemical fertilizer per year in California alone.

Recommendations: *(Adapted from the practical guide by Schmidt (2014))*

1. Drain manure lagoon, leaving a max of 25cm of material.
2. Inoculate the lagoon with 0.2-0.5% sauerkraut juice (or other lactobacillus)
3. Add 1% molasses as food source for growing lactic acid bacteria population
4. Mix in 2% biochar (Ideal properties are a high SA and CEC with a low pH)
5. With each manure deposit add 0.1% biochar and sauerkraut juice

Resources:

- Treating Liquid Manure with Biochar (Schmidt, 2014)

ANAEROBIC DIGESTION

Applications of manure, liquid manure, and compost on crops or pasture are a circular use of animal waste to return fertility to soil. But regions with high concentrations of animals often accumulate a surplus of animal waste leading to degraded local air and water. An alternate solution to manure management is the production of biogas from anaerobic digestion (AD) of manure or manure slurry. Biochars derived from manure and incorporated with manure AD can help close the loop and drastically reduce the volume of manure to manage (Pan et al., 2022).

Anaerobic digestion relies on the microbial decomposition of biomass in an oxygen limited environment. Gases produced during the anaerobic digestion of biomass include CH_4 (50-75%), CO_2 (25–50% v/v), N gases (2-8%) and trace amounts of hydrogen sulfide (H_2S), NH_3, hydrogen and other volatile gases (Li et al, 2019). The goal of biogas production is to effectively capture and utilize CH_4 to produce energy which would otherwise be emitted into the atmosphere. CO_2 and H_2S are considered impurities in the production process, decreasing the quality of biogas, and in the case of H_2S, causing degradation and corrosion to the system's equipment (Blackline Safety, 2017). Biogas production may not have capacity to revolutionize the energy grid, it can play a role in the abatement of potent CH_4 to the atmosphere, strengthen regional energy independence, and provide income to farmers.

Emerging scientific evidence shows promising synergies when biochar is added to anaerobic digestion. A recent review by Tang et al. (2020), concluded that additions of biochar improved the efficiency of AD by improving conditions for microorganisms and enzymes responsible for biogas production. The exception was large application rates (>20% biochar). In a study by Jang et al. (2018), it was found that when biochar produced from dairy manure was added to AD at a rate of 10g L^{-1}, there was a 27-35% increase in methane yield and a decrease in the lag time of microbial activity. Yang et al. (2020), found even more promising results with corn straw biochar, which increased methane production by 70%. Pan et al. (2022), measured an 81% increase in methane production with cow manure biochar pyrolyzed at 400°. These results demonstrate the feasibility to find synergy and close loops in manure management with biochar. Additionally, biochar added to AD has been shown to decrease the concentration of impurities such as CO_2 and H_2S. Wang (2018) observed a 76% decrease in H_2S with the addition of poplar biochar.

Efficiencies in anaerobic digestion have been statistically linked to feedstock type, pyrolysis temperature and application rate, with no statistical effect form pH, size, or surface area (Xiao et al., 2021). In their statistical meta-analysis, Xiao et al. (2021) found Sewage and municipal sludge biochar to be the best feedstock for improving anaerobic digestion by providing nutrients for microbial activity. While all other feedstocks provided benefits there was no statistical difference. However, manure biochars did have a trend above other plant feedstock likely due to higher nutrient contents. One clear observation from the meta-analysis was that biochars produced at >700°C were substantially less effective than lower temperature pyrolysis (Xiao et al., 2021), likely due to the loss of surface functional groups. Nearly all the experiments with biochar in AD have been in small batch, lab scenarios. Scaling observed at a commercial or field production would be an excellent contribution to our understanding and potential expansion in industry application.

Recommendations:

1. Begin by adding small quantities and monitor response.
2. Avoid excessive application rates >20% by volume.
3. Biochars with greater nutrient content, functional groups and electrical conductivity may be more effective.

MANURE AS BIOCHAR FEEDSTOCK

IMAGE 4: VOLUME REDUCTION OF DRIED MANURE TO MANURE BIOCHAR (SOURCE: SANFORD ET AL., 2022)

Just like any other biomass, manure can be used as a feedstock to produce biochar and there may be good reason to do so. The first reason is on-farm production is a fraction of the price commercially available options. In a series of on-farm case studies in Oregon, USA, Wilson (2018) found that on average farmers were able to produce biochar (from a variety of feedstocks) for $100/yd^3 compared to the market price of ~$250/yd^3. Secondly, the mass and volume of manure make it an expensive material to transport, limiting the range of manure distribution and management (Ghezzehei et al., 2014). Pyrolyzing manure into biochar can reduce the volume and mass of the material, increasing the range of transportation and agricultural use. Mass reductions of dried manure after pyrolysis are in the range of 42-86% (Sanford et al., 2022). Additionally, manure derived biochar has a higher nutrient content, providing more fertility than other biochars. In their review, Sanford et al. (2022) concluded that P retention was in the range of 93-99% whereas N was more volatile with retention between 18-62%. Thus, the authors conclude that manure derived biochar can act as an effective slow-release P fertilizer.

Although the nutrient content of manure biochar is much higher than other feedstocks, it also ranks as some of the lowest surface area (Joseph et al., n.d.). This is an important consideration when determining the end use of manure biochar. Due to the low surface area, manure biochar lacks sorption capacity, but the medium-term availability of nutrients makes it appealing to use a soil amendment. Another benefit from pyrolyzing manure is that pyrolysis >400°C can eliminate antibiotic residuals (Draper and Sweet, 2020).

One important consideration of manure biochar is the potential accumulation of heavy metals such as Zn and Cu which are often used as feed additives. Although such metals are concentrated in the pyrolysis process, it has been found that they also become less bioavailable (Zuo et al., 2020; Draper and Sweet, 2020). The most challenging limitation of creating biochar from manure is the low moisture requirement (Wilson, 2018). For optimum biochar production and energy use efficiency, biomass feedstock should be below 30% moisture content (Sanford et al., 2022). Thus, a manure-based biochar system would require additional procedures to separate and dry the solids before pyrolysis. This adds additional cost and complexity to the operational function of manure-based biochar production. Another potential option of manure biochar production would be through hydrothermal conversion, which is a suitable method for feedstocks with high moisture content.

Recommendations:

1. Consider if and how manure solids can be separated and dried in the operation.
2. Manure should have a moisture content <30%.

Resources:

- Biochar Production through Slow Pyrolysis of Manure (Sanford et al., 2022)
- Feasibility Assessment of Dairy Biochar as a Value-Added Potting Mix (Enders et al., 2018)
- On Farm Production and Use of Biochar in Composting (Wilson Biochar Associates

FEED

IMAGE 5: BIOCHAR AS A FEED ADDITIVE FOR COWS. (SOURCE: BBC)

Feeding charcoal to animals to mitigate and treat illness has been a known practice for centuries. Prize winning dairy farmers even considered it an essential ingredient for increasing butterfat content and quality of milk (Savage, 1917). Since 2010, the use of biochar as supplementary animal feed has been growing in popularity with farmers and researchers alike. From a review of 112 scientific publications Schmidt et al. (2019) concluded that the use of biochar as animal feed is effective in improving animal health, feed efficiency, barn conditions, manure quality, and soil health while decreasing GHG emissions and nutrient loss. Nearly all the publications reviewed found positive results, albeit some were non-significant.

Although biochar can be costly, incorporating biochar into animal feed has shown its financial viability (Joseph et al., 2015; Kammann et al., 2017). A three-year study on an Australian cattle ranch demonstrated soil and pasture improvement from incorporating biochar into feed (Joseph et al., 2015). In the living experiment, the farmer replaced fertilizers and insecticides used on the pastures with a daily feed supplement of 0.33kg of wood biochar mixed with 0.1kg molasses daily. Biochar was enhanced by nutrients from the gut and incorporated into the soil profile by dung beetles. Not only were soil properties and pasture health improved, but profitability was increased (*Figure 7)*. 90% of commercial sold biochar in Austria, Germany, and Switzerland was used in animal agriculture, mainly as feed (Kammann et al., 2017). In addition to improved soil health, Kammann et al. (2017) noted that farmers interviewed in Germany have found biochar pays for itself by improving animal health (i.e. reducing the need of antibiotics and veterinary services). Biochar is generally added at rate of 1% to feed (Kammann et al., 2017).

Property	2011	2015
Electrical conductivity (dS m^{-1})	0.063	0.124
pH (H_2O)	5.9	5.9
pH ($CaCl_2$)	4.9	5.2
Total N (g kg^{-1})	NM[a)]	4.7
Total C (g kg^{-1})	NM	58.1
Total P (mg kg^{-1})	NM	938
Colwell P (mg kg^{-1})	49	102
Colwell K (mg kg^{-1})	55	205
KCl-extractable NH_4^+-N (mg kg^{-1})	21	10
KCl-extractable NO_3^--N (mg kg^{-1})	15	33
Total organic C (g kg^{-1})	41.7	46.7
Al (cmol(+) kg^{-1})	< 0.100	0.168
Ca (cmol(+) kg^{-1})	5.10	6.78
K (cmol(+) kg^{-1})	0.17	0.50
Mg (cmol(+) kg^{-1})	0.63	0.76
Na (cmol(+) kg^{-1})	0.10	0.18

FIGURE 7: CHANGE IN SOIL PROPERTIES IN PASTURE AFTER INCORPOATING BIOCHAR AND MOLASSES INTO CATTLE FEED REGIME FOR 3 YEARS. (SOURCE: JOSEPH ET AL., 2015)

One of the main mechanisms associated with biochar in feed is adsorption. For centuries charcoal has been used an emergency treatment for acute poisoning for both humans and other animals. It has a high adsorption capacity for a variety of toxins which livestock may encounter such as plant toxins, mycotoxins, pesticides, or pathogens (Schmidt et al., 2019). Considering the abundance of insecticides and herbicides found on animal feed today, adsorption of such chemicals is of clear value. Although the high adsorption capacity may be one of biochar's most important mechanisms, there is more at play to explain such results.

In addition to adsorption, improved feed efficiency has been credited to the electrical conductivity of biochar. Biochar is considered to function as a *geobattery* or *geoconductor* as it accepts, stores, and moves electrons through its extensive surface (Sun et al., 2017). This contributes to redox activity by facilitating electron transfers in the digestion of feed. Digestion is mediated by microbes which require an electron receptor to take excess electrons which build up during decomposition of organic molecules. Naturally, these microbial reactions will transfer electrons to biofilms which have very low electrical conductivity. Activated charcoal and other humic substances have approximately 100-1000x greater electrical conductivity than biofilms which greatly enhances redox activity (Schmidt et al., 2019). Furthermore, an electron mediator such as biochar is a beneficial feed ingredient which has been shown to increase the digestion efficiency of feed. As noted by Schmidt et al. (2019), the understanding of biochar's electrochemical reactivity in animal digestion is a science in its infancy but based on what is known, the electrical conductivity and presence of surface functional groups for a given biochar are important factors when considering the efficacy of biochar as a feed additive.

Related to energy conversion efficiency, a growing field of research has been examining the potential for biochar to reduce methane emissions via it's improved redox activity. Promising results came from Leng et al. (2012), who found methane reductions of 10% (0.5% biochar feed) and 12.7% (1% biochar feed). A more recent study by Saleem et al. (2018) found that biochar acidified to a pH of 4.8 and added to feed at 0.5% decreased methane by 34%. Although reduced enteric fermentation is often cited as a benefit from feeding biochar, it is very much an emerging field of research with limited scientific consistency. Although it has a legacy of use and is allowed in the EU, biochar is not an FDA approved feed (Schmidt, 2019).

Recommendations:

1. Ensure biochar is free of any potential contaminants (e.g. heavy metals or toxins)
2. Choose a biochar with moderate electrical conductivity and a large surface area (Characteristics associated with Biochar produced at higher temperatures).
3. Incorporate into feed at 1% rate and monitor response.

Resources:

- The Use of Biochar in Animal Feeding – Schmidt et al. (2019)
- Biochar Cattle Feed Background Paper – (Wilson Biochar Associates)

CONCLUSION

Biochar has been a divisive topic in the science community. A thorough analysis of the literature conveys that there are sound scientific arguments backing both positive and negative stances on biochar. The alteration of soil properties from biochar application is dependent upon a complex combination of biochar characteristics, soil conditions, and climate. The properties and mechanisms of biochars are complex, but so must be regenerative agricultural systems and soil health management. The reduction of agriculture to cash crops and feedlots has stripped resiliency from the system. As nature shows, a certain level of complexity and chaos is essential to balanced and resilient ecosystems.

Much of biochar research to date has been reductionist in nature as the scientific community strives to hone the understanding of specific properties and mechanisms. In other words, there is a desire to understand how each individual property of biochar influences a given application. This is a valuable inquiry but the myriad variables impacting the outcome of biochar application make such reductionism challenging. Such variability makes it difficult for an agronomist or a farmer to make an informed decision on biochar applications. Additionally, widespread adoption of biochar is hindered by relatively high-cost barrier, which further limits farmers' willingness to trial a new input with unknown, variable results.

For any given application, biochar must go through holistic planning principles. By investigating the environmental, economic, and social impacts of biochar for a given end use, practitioners should determine if biochar is a good fit for their system. In some instances, when regional biomass is scarce or nutrients are sufficiently managed, biochar may not be a worthwhile option. While in others, where nutrient and biomass management are a serious challenge, it may provide some of the synergistic co-benefits and resource circularity mentioned in this document.

The use of biochar in animal agriculture can increase nutrient retention, productivity, animal health, resource circularity, while mitigating GHGs and environmental pollution. By considering the interaction of biochar between animal and cropping systems further synergies begin to emerge. Integrating biochar into animal agriculture can improve the physical, chemical, and biological composition of biochar which may buffer some of the potential negative aspects associated with fresh biochar. When these animal enriched biochars are applied to the soil, they can increase soil carbon, and water and nutrient holding capacity, enhancing agricultural resilience to climate change (Joseph et al., 2015). Prioritizing soil health is key to climate smart agriculture.

Most published research has been conducted within labs or highly controlled environments. The value of well documented citizen science and partnerships between academia and farmers is essential to progress. Applied research at farm scale is a crucial next step to better understanding biochar within the complexities of an operational animal agricultural system.

Biochar is simply one piece of the puzzle which may fit into many different puzzles; therefore, it must not be viewed or studied in a silo but applied and researched amongst a suite of tools. Just like animals should be reintegrated into our agricultural systems, biochar should also be applied within holistic resource management, not simply as a solitary, linear input. From this review, the scientific evidence shows great potential for biochar in animal agriculture to reduce environmental impacts, increase resource circularity and create cascading benefits.

RECOMENDATIONS

1. Increase farm-scale research on integrating biochar into animal agriculture and then soil. Measuring the life cycle of biochar from production to animal to soil will help identify potential synergies, shortcomings, and the most impactful applications.
2. Give thoughtful consideration to the properties of the biochar and how those may affect the function for the targeted use(s).
3. Include lactobacillus bacteria to reduce the pH when aiming to reduce ammonia gas, otherwise alkaline biochar may not help.

SUMMARY MATRIX OF APPLICATION RECOMMENDATIONS:

	Anaerobic Digestion	**Bedding**	**Biochar Feedstock**	**Co-composting**	**Feed**	**Liquid Manure Management**
Application	- Start slow and monitor - Do not exceed 20% biochar	- 5-10% by volume - Inoculate bedding or biochar with lactobacillus to reduce pH	- Separate solids, dry to <30% moisture, and pyrolyze manure	- 3%-20% (by weight) depending on C:N ratio - 10-20% is common for manure composting	- 1% biochar added to feed regiment	- Inoculate lagoon with 0.2-0.5% sauerkraut juice (sj) - Add 1% molasses - Add 2% biochar - Add 0.1% biochar and SJ with manure addition
Optimal Biochar Properties	- High nutrient content - Functional groups - EC	-Low pH -High SA and functional groups	- High nutrient content -Low SA	- High SA, CEC, functional groups, water holding capacity	- No heavy metals or other contaminants - Moderate EC - High SA	- High SA, CEC, AEC - Low pH
Biochar Production Guidelines	-Temp: <700°	N/A	- Manure needs <30% moisture content	-Temp:400-700° C	- Higher temperature (to increase SA + EC)	N/A
Considerations	- Quantities >20% can be detrimental	- Lactobacillus or acidifier is key - How to adapt with current bedding system	- Cost to separate and dry manure - Is there better biomass available in the region?	- Biochar has a wide range of total and effective C:N ratio	-Contamination of biochar - Potential to reduce nutrient availability - Regulations	-Optimal properties differ depending on use as a Lagoon cap OR liquid manure-biochar mix for fertilizer

*Biochar properties vary widely, take these recommendations as suggestions, and see what works within your system.

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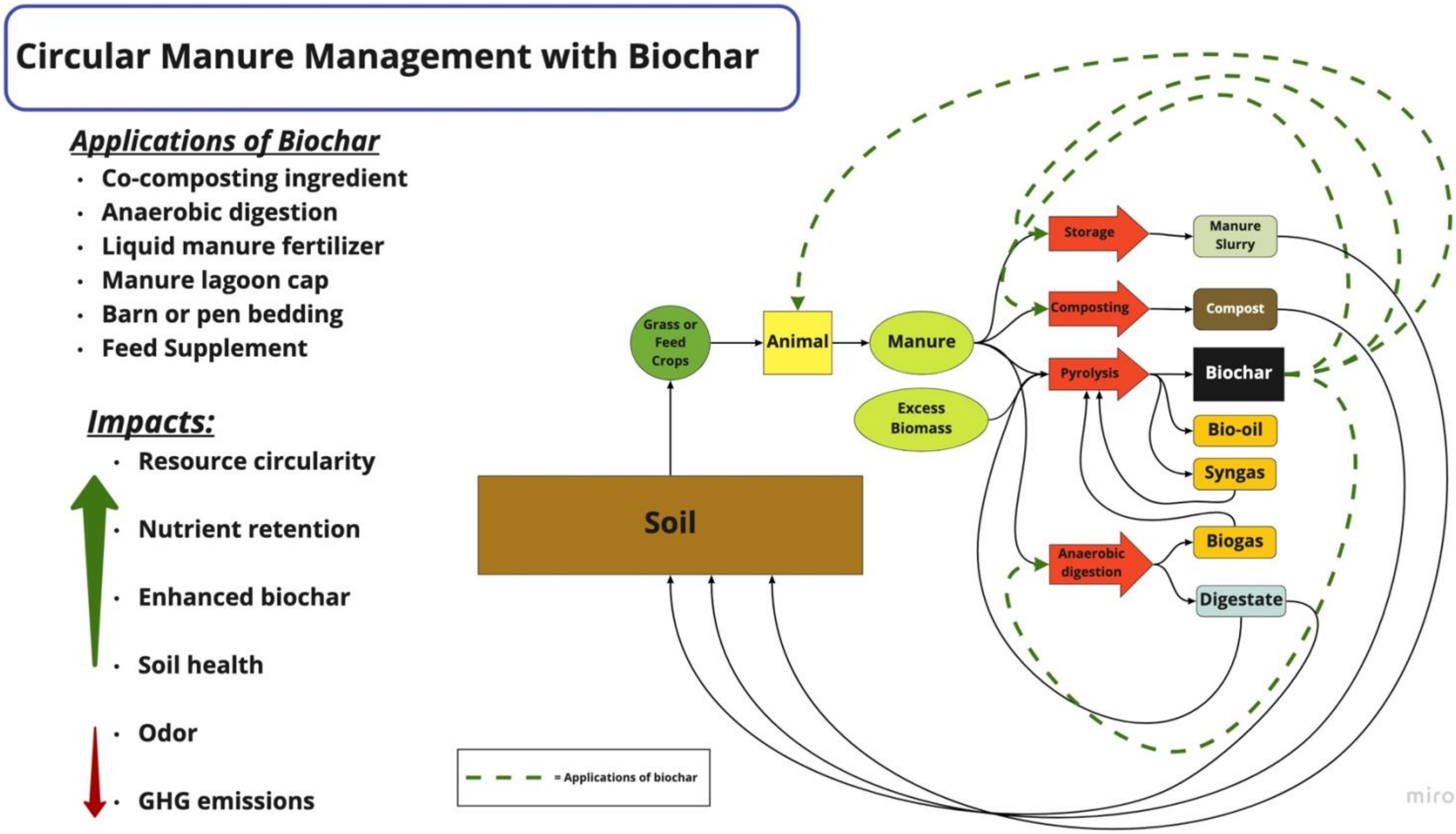
APPENDIX

1. *Flowchart*



2. *Open access resource list*

- The Use of Biochar in Animal Feeding – Schmidt et al. (2019)
- Biochar Cattle Feed Background Paper – (Wilson Biochar Associates)
- Biochar Production through Slow Pyrolysis of Manure – (Sanford et al., 2022)
- Feasibility Assessment of Dairy Biochar as a Value-Added Potting Mix – (Enders et al., 2018)
- On Farm Production and Use of Biochar in Composting – (Wilson Biochar Associates)
- Treating Liquid Manure with Biochar – (Schmidt, 2014)
- On-Farm Production and Use of Biochar for Composting with Manure – (Wilson Biochar Associates, 2018)
- How to Use Biochar in Barns – Umpqua Biochar Education Team
- Poultry Manure Biochar – Wilson Biochar Associates