Enrichment of Biochar and its Application for Wheat Production In Atlantic Canada

by

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Dedication

This thesis is dedicated to my partner Amy and son Rowan who provided a strong foundation which without I surely would have cracked. Amy's constant support, words of encouragement, and keen eye were immeasurable. Rowan's contributions of unhindered joy and life provided just the right kind of distractions, and the thought of his future kept me inspired and motivated to fulfill this commitment.

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Abstract

Interest in the use of biochar in agricultural systems is increasing with both producers and researchers studying how best to implement this technology into cropping systems. Atlantic Canadian soils are characterized as being acidic, low in organic matter, and prone to nutrient leaching during the fall and spring. Previous research has shown that biochar can improve crop growth whilst also addressing these challenging soil parameters. However, there is little research with Atlantic Canadian soils or cropping systems. This research investigated how biochar can be incorporated into spring wheat production in Atlantic Canada, with the objective of evaluating the effect of biochar with and without nutrient enrichment on plant growth and development and soil characteristics. An enrichment characterization (for inorganic nitrogen sorption), a soil column leaching experiment (for inorganic nitrogen loss), germination experiments, pot-based greenhouse experiments, and field trials were conducted to determine differences in two types of biochar (wood, crab) and varying rates of application (seed coating, 3 t ha^{-1}, 5 t ha^{-1}) in comparison to conventional inorganic fertilizer application. Enrichment characterization demonstrated that wood-based biochar more readily sorbed inorganic nitrogen at a rate four-fold to the crab-based biochar. Soil column leaching experimentation showed that both biochar types significantly reduced inorganic nitrogen leaching compared to both conventional fertilizer application and control soil. Germination results showed that wood based biochars increased seedling vigour as rates were increased, while crab-based biochar negatively impacted initial plant growth. The pot-based greenhouse trial showed significant benefits to crop growth and vigour with the seed coated treatment performing as well as the broadcast application (5 t ha^{-1}); however, these benefits were not observed in the field trials. This research suggested that the seed coating of biochar could provide significant crop benefits at a far lower application rate than broadcast applications. Each biochar behaved differently, with the wood based biochars having the most significant impact on crop growth and mineral sorption. The biochar treatments produced crops of comparable vigour and yield to the conventionally fertilized treatments. This research suggests that there are promising applications for wood based biochars in spring wheat systems. Further research into optimum seed coating rates as well as studies over multiple years will be required before a holistic understanding can be reached.

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Chapter 1: Introduction

Agricultural soils in the Atlantic provinces are generally low in soil organic matter (SOM), acidic, and prone to leaching of nutrients during the non-growing season (November – April). Recent research into SOM levels in Prince Edward Island (PEI) shows that 56% of its land base has an average loss from soils (and subsequent volatilization into the atmosphere) of 0.5 tonnes of C ha^{-1} y^{-1} (Burton, 2019). This trend is present in most Atlantic Canadian soils and is caused mainly by current tillage and rotation practices. The loss of SOM decreases the soils' productivity and ability to hold nutrients and minerals and negatively impacts waterways, aquifers, and air quality. These negative impacts compound agriculture's net environmental impact. Globally, agriculture contributes 10-12% of total anthropogenic greenhouse gas (GHG) emissions and is the primary contributor of both methane and nitrous oxides (NO_x) 50% and 60% of total emissions respectively (Hillier et al., 2011). Much of the carbon dioxide (CO_2) emissions contributed by agriculture are from fertilizer and mechanical equipment use. The current North American carbon footprint to produce ammonium nitrate (33.5-0-0) is 6.7 kg CO_2 per 1 kg N (Hoxha & Christensen, 2018). Methane emissions are prevalent in animal agriculture systems and poorly drained soils low in SOM, where matter decomposes in an anoxic (or oxygen deprived) environment. The nitrous oxide emissions are often generated through the microbial processes of nitrification and denitrification which is most prolific when excess labile nitrogen (N) is available within the soil.

My project seeks to address this suite of problems at the level of fertilizers and soil, by evaluating the agronomic potential and rhizosphere impacts of the soil application of biochar, a form of carbon created when biomass feed stocks undergo pyrolysis (Weber & Quicker, 2018). This thesis will investigate how the addition of enriched and unenriched biochar affects wheat's growth and physiology in comparison to amendments used on their own or conventional NPK fertilizers.

1.1 Literature review

For this project to be relevant to Canadian farmers, wheat has been chosen as a model crop. Wheat, including both spring and winter varieties, is the largest cereal crop grown in Canada, representing 35.1% of the area seeded with cereals and oilseeds, with a total production of 31.9 million tons. Regionally, Atlantic Canadian provinces cropped 18,000 hectares with a harvest of 21.6 million tonnes of wheat in 2023 (Atlantic Grains Council, 2023). Wheat is a C3 crop that performs well in cool temperate areas and is widely adapted to growth in Canada (Acevedo et al., 2002). It is sensitive to both abiotic and biotic factors which can have significant effects on yield. There are several key factors which biochar may influence that can affect wheat growth, including moisture, pH, SOM content, nutrient availability/soil mineral composition, and microbial communities (Carew et al., 2009).

Moisture is essential for plant growth and development, with water deficits negatively affecting yield. These moisture requirements change based on growth stages of plants. Initially, a certain amount of soil moisture is required for the seed to imbibe water and initiate germination. For the plant to successfully complete its vegetative growth, at least 100 mm and closer to 125 mm of rainfall is required; however, crop requirements vary each year due to spring and early summer temperatures as less moisture is required for transpiration in a cool spring compared to a warmer one (Mckenzie & Woods, 2011). Once at the reproductive growth stage, wheat will use 7 to 8 mm of water per day, with research showing that for each 25 mm of water used, wheat produces 136 to 191 kg ha^{-1} in total. Wheat plants require between 420 – 480 mm of water throughout the growing season (both vegetative and reproductive growth cycles) (Mckenzie & Woods, 2011). Moisture deficiencies initially present themselves as a slowed growth rate of leaves and stems; as plants fail to take up enough moisture for transpiration, their stomata close, and leaves wilt in mid-day heat. Further moisture stress results in older leaves and tillers being aborted; eventually plants will senesce and die (Mckenzie & Woods, 2011).

Soil pH has a direct effect on the ability of plants to obtain nutrients from the rhizosphere. The optimal pH range for wheat is between 6.0 and 7.0. When wheat is grown at a pH below 6.0 there can be magnesium deficiencies, slower mineralization of organic N, reduced phosphorous availability, and increased risks of aluminum and manganese toxicity (Vitosh, 1998). Soils in Atlantic Canada are generally acidic (in the range of 4.0 – 5.5) due to the coniferous and boreal forests that populate these lands

(Burton, 2019). In addition, many common farming practices can increase soil acidity, such as mouldboard & disc plowing; and applications of inorganic fertilizers (Vitosh, 1998). To achieve adequate yields on these soils, liming agents are used to bring soil pH into the 6.0 – 7.0 range.

Soil organic matter (SOM) is a key component of soils, the decomposed biological plant and microbial residues present within the uppermost layers of soil (Lehmann & Kleber, 2015). This matter stabilizes soil structure, regulates soil moisture levels, provides a haven for microbes, and facilitates the storage and exchange of nutrients through charged functional groups attached to its structure (Lehmann & Kleber, 2015). Soil organic matter's main beneficial function in the soil is that of buffering and regulation of abiotic growth factors as well as facilitating nutrient exchange with, and refuge for beneficial microbes. Many modern farming practices erode SOM, leading to the loss of carbon stores to volatilization and runoff. Agriculture needs to develop methods to both reduce carbon loss from soils and replace what has already been lost.

Nutrient requirements of plants vary depending on developmental growth stages. The germinating seed can initially mobilize nutrients from endosperm seed reserves; however, shortly after shoot emergence, roots need to absorb nutrients from the soil in order to maintain growth. Wheat requires nitrogen, phosphorous, potassium, and sulphur in larger amounts, with smaller amounts of micronutrients required for optimal growth. Nitrogen is essential due to its presence in protein structures and chlorophyll. Phosphorous is initially important for early growth and root mass development, and potassium plays an essential role in improving the efficiency of photosynthesis, aiding with disease resistance, and improving water use efficiency. Sulphur is required as a building block of proteins as well as in the formation of chlorophyll (Pandey et al., 2020). Recent estimates suggest that for every 1000 kg of grain produced, there is a need for 22.8 kg N, 4.4 kg P, and 19.0 kg K; this corresponds to an NPK ratio of 5.18:1:4.32 (Chuan et al., 2013).

Microbes play an important role in plant growth through mineralization of soil organic matter and nutrients within the soil. Wheat readily associates with arbuscular mycorrhizal fungi (AMF) and develops symbiotic relationships which allow for easier acquisition of nutrients - primarily phosphorous and others immobile in the soil strata (Tkacz et al., 2020).

While the idea of plant-microbe symbiosis is not new—Albert Bernhard Frank introduced the term “mycorrhizae” in 1885 and *Rhizobia* in 1889—there has been renewed interest lately in understanding plant microbe interactions and soil carbon cycling. This interest arises in part from challenges related to addressing climate change. One of the key recent developments in understanding how plants and microbes interact with SOM was described by Paungfoo-Lonhienne et al. (2010) when they showed evidence for a mechanism of direct transfer of nutrients from symbiotic microbes to plant roots. Free-living microbes are internalized into plant roots, where the microbes appear to be degraded over time. Paungfoo-Longienne et al. termed this process rhizophagy. More recent investigation by White et al (2018) showed this process to occur in many plant species, wheat being one of them, and with wide ranging families of microbes (White et al., 2018). They further built our understanding of rhizophagy by describing its cyclic nature and developed this concept into what they call the rhizophagy cycle. This is the process by which symbiotic microbes, often seed transmitted, alternate between an intracellular/endophytic phase and a free-living soil phase (White et al., 2018). This cycle connects the ideas of soil priming with direct nutrient acquisition via plants. It proposes that plants engage in the process of ‘microbivory’ and have developed mechanisms to ‘farm’ microbes as needed in response to soil nutrient levels–highlighting the importance of soil microbial communities in plant growth. The intricacies of this cycle vary between plant species. White et al (2018) have developed a framework to describe it: [1] Microbes mineralize nutrients within the SOM of the rhizosphere; [2] Microbes then enter the root through the root cap and shed their cell wall turning them into protoplast structures; [3] Nutrients are then extracted from the microbes through reactive oxygen species; [4] Once nutrients have been extracted, microbes exit the root through root hairs and begin anew the cycle of foraging for nutrients.

Due to increasing populations and reducing arable land areas, there is a need to develop fertilizers and fertilizing modalities that better meet the demands of crops, the microbes that interact with them, and the current state of our soils.

Biochar

Biochar's lattice carbon structure is inert and remains sequestered within the soil for hundreds, if not thousands, of years. Agricultural soils created by indigenous peoples in South America over 500 years before colonization remain highly productive to this day (Briones, 2012). Similar soils have been found in Europe, suggesting that these highly stable black soils can be established in a variety of climactic conditions and may be an efficient way to sequester CO_2 while increasing soil fertility (Wiedner et al., 2015). Further, Wiedner et al. (2015) suggest biochar's agronomic benefits could help to mitigate the negative impact of climate change, due to its carbon sequestration mechanism; capacity to reduce leaching and soil borne GHG emissions; and its ability to provide liming as well as slow-release fertilizer mechanisms.

Biochar's ability to improve soil's nutrient retention and reduce nutrient leaching is due to its structural and chemical composition (Hagemann et al., 2017). It is highly porous, has an abundance of functional groups, and high exchange capacities, both cation (CEC) and anion (AEC). These result in excellent water, nutrient, and air retention within the biochar matrix and allow it to act as a buffer for these characteristics within the soil, positively impacting the rhizosphere. In addition to improving abiotic soil characteristics, the high surface area and pore spaces present in biochar also provide a haven for, and promote, beneficial bacterial and fungal microbes.

A recent meta-analysis (Shakoor et al., 2021) regarding the effects of biochar application on GHG emissions and crop growth showed that GHG emissions, notably NO_x volatiles, were reduced while crop yields significantly increased. Several factors determine biochar's efficacy, including soil pH, the biochar's C/N ratio, and the application rate. A separate meta-analysis comprising 129 publications from 38 countries (Schmidt et al., 2021) showed that application rates <10 tonnes ha^{-1} had the greatest effect on reducing NO_x volatilization whilst most increasing crop yield of 'wheat', 'maize', 'rice', 'vegetable', and 'other'. Methane and CO_2 levels did increase slightly under biochar application, perhaps due to increased microbial activity (a positive soil health metric) within the soil. However, net carbon capture greatly outweighed these slight increases. The yield curve follows a weighted bell curve with its maximal increase at rates of 2 - 4 tonnes ha^{-1}. Across application rates and crops, mean yield increased from 17 Mg ha^{-1} to 22 Mg ha^{-1} (an increase of 29%). The authors caution that when biochar is applied at rates of >10 tonnes ha^{-1} its porous structure can act as a sponge, immobilizing nutrients within soil profiles and restricting plant roots' access to required nutrients.

Biochar as a nutrient carrier matrix

The observed immobilization of nutrients can be negated, and biochar's positive impacts increased, by 'enriching' or saturating biochar with nutrients before it is applied to the soil (Joseph et al., 2013). In essence, biochar can act as slow release 'nutrient carrier matrix' for fertilizer. A paper published by the journal 'Nature Communications' describes the mechanism of biochar's slow-release properties. They posit that this function of biochar is facilitated by an organic coating that covers the outer and inner surfaces of the material when it is created during raw feed stock pyrolysis (Hagemann et al., 2017). This coating provides hydrophilicity, redox-active moieties, and additional mesoporosity that enhance nutrient retention and water holding capacity.

Biochar use signifies a 'new paradigm' in fertilizer application, with the matrix being considered a tool for the slow-release application of mineral and organic fertilizers (Schmidt et al., 2017). In trials carried out on 'typical mid-western soils' (Clarion, fine-loamy, mixed, superactive, Mesic Type Hapludolls) by researchers at Iowa State University, biochar enriched with conventional fertilizers applied at rates of 5 & 10 g per kg of soil increased water retention by 15%, CEC by 20% and pH by 1 unit, with significant increases to nutrient and mineral retention: total N increased by 7%, organic C by 69%, and Mehlich III extractable P, K, Mg, & Ca levels were also increased. The article states that biochar could significantly improve the quality and fertility status of mid-western soils (Laird et al., 2010). It is worth noting that this projection has been made on soils that are already consistently rated as some of the most fertile soils in the world (Paul et al., 2001).

Schmidt et al. demonstrated that biochar enriched with cow urine and applied to the root zone substantially increased yields of a variety of crops (13 crops across 21 trials) when compared to traditional organic fertilization and inorganic NPK fertilizer (Schmidt et al., 2017). This trial suggests that there are synergistic properties associated with biochar and organic substrates that may meet or exceed yields obtained with optimized conventional practices. If similar findings could be realized within Atlantic Canada, it would provide a boon to farmers, consumers, and our shared ecosystem.

Biochar as a promoter of soil microbial activity

In addition to the fertility benefits that biochar provides, research into the ability for biochar to positively impact soil microbial activity shows promise. A meta-review of 265 datasets and 49 published studies on this subject showed that the addition of biochar to soil increases microbial biomass and in turn promotes nutrient cycling which facilitates a greater availability of nutrients to roots throughout the growing season (Zhang et al., 2018). While the addition of biochar increased both fungal and bacterial microbes, it changed the ratio of fungal to bacterial microbes, with fungi becoming more predominant. Many of the fungi that increase when biochar is applied are beneficial mycorrhizal fungi (both arbuscular mycorrhizae (AMF), and ectomycorrhiza) (Warnock et al., 2007). There are four main mechanisms suggested that promote this increase in beneficial microorganisms, including (1) an alteration of soil physico-chemical properties, (2) indirect effects on mycorrhizae through effect on other soil microbes, (3) plant-fungus signaling interference and detoxification of allelochemicals by biochar, and (4) provisions of refugia from fungal grazers (Warnock et al., 2007).

Wheat readily associates with AMF with a significant positive effect on yield and growth (Pellegrino et al., 2015). While the mechanism that produces these increases is not fully understood, many factors have been suggested, such as fungi's ability to mine phosphorous (an essential macronutrient that is often inaccessible to plants). Others have gone further, with an article published in the journal *Agronomy* suggesting that AM fungi cause wheat to up-regulate enzymes associated with energetic metabolism, embryo development, nucleotide metabolism, and stress response (Ganugi et al., 2019).

Biochar is uniquely suited to help agricultural industries transition towards a low carbon future. Not only is its production carbon negative, but its highly porous non-labile structure can hold liquid amendments, preventing volatilization and easing stress during drought conditions. This same structure increases beneficial mycorrhizal fungi within the soil, positively affecting a wide range of crops grown in a variety of different climactic situations (Bona et al., 2016).

This research aims to increase these benefits by charging biochar with either of two amendments: cow urine or seaweed. Schmidt et al. showed that when biochar is enriched with cow urine there is a dramatic increase in crop yield and productivity (Schmidt et al., 2017). Additionally, biochar increases microbial activity within the soil, positively impacting plant growth by increasing nutrient cycling and plant available nutrients.

Amendments

Cow urine

Cow urine is rich in macro and micro-nutrients, having NPK values of 6.8 – 21.1 g N L^{-1}; 0.35 g P_2O_5 L^{-1}; 11.0 g K_2O L^{-1} (Schmidt et al., 2017). In addition to its nutrient profile, researchers have found that cow urine inhibits the growth of plant pathogenic fungi (*Fusarium oxysprum, Rhizoctonia solani,* and *Sclerotium rolfsii*) and can promote plant growth through biostimulant properties (Jandaik et al., 2015). The application of cow urine greatly increases the growth rate of wheat and other crops from the *Poaceae* family (Ganesapillai & Simha, 2015).

Modern confined dairy operations separate cow faeces from urine to reduce ammonia volatilization and limit GHG emissions. Volatilization occurs when the urease enzyme present in faeces mixes with the urea present in urine (Vaddella et al., 2010). Faecal manure is readily applied to fields as a crop amendment; however, urine rapidly degrades when surface applied, and storage is challenging due to the volume produced in a typical animal feeding operation (AFO). When applied directly to the soil, urine quickly undergoes volatilization, with studies showing that within a few days of application 50% of the applied N has been emitted into the atmosphere (Ganesapillai & Simha, 2015). In addition, liquid amendments are prone to run-off and leaching, potentially causing eutrophication and other environmental damage.

If cow urine's lability could be negated by being captured within a biochar fertilizer matrix, then it could be used by farmers to increase crop yields while further reducing nutrient losses through volatilization and nutrient degradation.

Seaweed extract

Recent research into the application of seaweed extracts to plants and soil indicate that the compounds contained can act as plant growth promoters (due to their ability to stimulate microbial activity in the soil), as a source of enzymes and growth promoting hormones, and can reduce abiotic stress response (Battacharyya et al., 2015). There is potential for seaweed extracts and biochar to work synergistically to dramatically increase the microbial activity of the soil; however, this is a novel concept and has not been thoroughly researched.

Many seaweeds have been shown to possess plant-growth promoting potential and are being used as an organic amendment by agricultural and horticultural operations. Commonly, the brown seaweed *Ascophyllum nodosum* undergoes a proprietary extraction process before being made available as a commercial product for farming operations. This extract contains both macro and micro-nutrients (N, P, K, Ca, Fe, Mg, Zn, Na, S) and a number of growth promoting compounds that have been shown to improve plant growth, yield, stress response, and quality (Battacharyya et al., 2015).

Liquid dairy manure

Commonly in dairy and AFOs manure is stored in concrete pits until it is applied to crop lands (Johannesson et al., 2017). This manure can vary widely based on animal type and feed, contamination from bedding and raw milk, as well as residence/storage time and controlled factors such as agitation and aeration. Typically, however, this amendment is rich in nitrogen (in the ammonia form), phosphorous, potassium, magnesium, sulfur, organic matter, and a diversity of microbes (Johannesson et al., 2017).

Ammonia volatilization and nitrogen losses begin immediately when the manure is produced and continue through lagoon storage and field application. Typical liquid manure nitrogen losses are in the 40 to 70% range (Meisinger & Jokela, 2000) but they can be as high as 95% under certain conditions, such as LDM being surface applied in warm dry conditions. This loss is a major economic cost to farmers, as cereal nitrogen demands are high and there is very little carry-over of nitrogen through the winter and spring from the previous year. Additionally, this volatilization of nitrogen into the atmosphere causes significant pollution to the surrounding environment. Globally, the dairy sector accounts for 3 to 5% of GHG emissions from mainly enteric and manure management (Petersen, 2018).

While there is research to suggest that cow urine and biochar could work synergistically (Schmidt et al. 2017), there is little research on the use of enriched biochar as a nutrient carrier matrix on a field scale. Much of the existing research is based on potted greenhouse experiments.

1.2 Research goals and objectives

Research statement

The overall objective of this project was to evaluate the effect of wood and crab based biochars with and without nutrient enrichment on the growth, development, and yield of wheat. This project seeks to answer the following three research questions.

Research questions (Q) and hypotheses (H)

Q1. Will biochar's nutrient carrier matrix and high pore density allow for a more sustained release of nutrients than conventional fertilizer?

H: The properties of biochar will allow for nutrients to be released for a greater duration of time than conventional fertilizers or liquid amendments.

This question was addressed via a soil leaching experiment where nitrogen (nitrate and ammonium) leaching was assessed across six leaching events, using 0.01M $CaCl_2$ to replicate rain events. The leachate was then analyzed for inorganic nitrogen after each rain event to determine the longevity of the nutrients supplied by each fertilizer/amendment (biochar versus conventional fertilizers).

Q2. Will plants react differently to biochar applied as a seed coating over typical broadcast and incorporation?

H: Biochar applied as a seed coating will maximize initial plant to biochar contact, improving germination and growth over biochar applied conventionally (broadcast and incorporated).

This was evaluated through both growth-pouch based germination experiments as well as pot-based greenhouse experiments. Data collected included days to germination, root and shoot lengths, relative chlorophyll content (measured using a Soil Plant Analysis Development (SPAD) meter), as well as above and below-ground biomass weight (indicators of plant vigour).

Q3. Will enriched biochar increase seed yield and quality over conventional fertilizer, or over each of the other treatments applied on their own?

H: Plants that receive enriched biochar will produce greater yields and improved grain quality, such as thousand kernel weight (TKW) and test weight (TW), over the other treatments.

This was evaluated through two field trials, with spring wheat seeded in the spring of 2024 at two locations (Truro and Kentville, NS). Over the course of the growing season, plant growth metrics (height, SPAD, disease ratings) were recorded. The trials were harvested at maturity and seed yield and quality data taken (kg ha^{-1}, TKW, kg HL^{-1}).

Chapter 2: Evaluation of Soil Nitrogen Dynamics and Early Wheat Growth from the Application of Wood- And Crab- Based Biochars Enriched with Cow Urine or Liquid Seaweed Extract

2.1 Introduction

Biochar provides several agronomic benefits that could reduce the negative impact of climate change in agricultural production (Yadav et al. 2023). This is mainly due to its recalcitrant carbon fraction (Bakshi et al., 2018), its capacity to reduce leaching and soil-borne greenhouse gas (GHG) emissions (Chataut et al., 2023), its provision of liming and its slow-release fertilizer mechanisms (Joseph et al., 2013). However, there have been contradictory results in the field, with some research showing reductions in crop yield and immobilization of nutrients (Purakayastha et al., 2019). This immobilization was due to biochar's porous structure and charged organic coating which led to sequestering nutrients in the soil (Hagemann et al., 2017).

Other researchers have shown that enriching biochar with nutrients can reduce this immobilization and sorption of soil minerals, instead biochar can act as a slow-release fertilizer (Karim et al., 2022). Schmidt et al. (2017) demonstrated that biochar enriched with cow urine and applied to the root zone substantially increased yields of various crops (13 crop species across 21 trials) when compared to organic fertilization or inorganic fertilizer (Schmidt et al., 2017). Other trials carried out on 'typical mid-western soils' (Clarion, fine-loamy, mixed, superactive, Mesic Type Hapludolls) by researchers at Iowa State University used biochar enriched with conventional fertilizers applied at rates of 5 and 10 g per kg of soil and incubated in soil columns for 500 days (Laird et al., 2010). They found biochar enrichment increased water retention by 15%, cation exchange capacity (CEC) by 20%, and increased pH by 1 unit, with significant reductions in nutrient leaching. Total nitrogen (N) increased by 7%, organic C by 69%, and Mehlich III extractable P, K, Mg, and Ca levels were also elevated when compared to unamended soils.

Previous research has shown that enriched biochar can enhance soil health and plant growth metrics (Schmidt et al., 2021). However, there is little information on how effectively the recommended enrichment process can increase extractable nitrate (NO_3^-)

and ammonium (NH_4^+) levels in crab (whose shells represent a significant waste product in Nova Scotia) and wood biochars. Further, due to the variable nature of biochar products (such as source material and pyrolysis temperature), biochar products require a large and rigorous body of evidence, if biochars are to be incorporated into modern agricultural practices.

Once biochar products are enriched, the organic coating that covers the outer and inner layers of the surface provides nutrient and water retention properties (Hagemann et al., 2017). Laird et al. (2010) showed that by incorporating enriched biochar products into already highly fertile mid-western soils, many of these soils' agronomic attributes could be greatly enhanced. In comparison, Atlantic Canadian soils are more acidic, have substantially less organic matter, and are less fertile, with a climate conducive to NO_3^- leaching (heavy rains, freeze/thaw events) (Burton, 2019). Due to current poor nitrogen management practices in Atlantic Canada, residual soil nitrogen has been increasing to 'very high' state of > 40 kg ha^{-1} inorganic nitrogen in the top 60 cm of soil after crop harvest (Clearwater et al., 2016). Biochar could be an effective tool in preventing this nitrogen from leaching out of the soil system during the non-cropping season. There is little research to show how Atlantic Canadian soils may perform when amended with biochar. With significant room for agronomic improvement of these soils, they are excellent sites for study.

When raw (unenriched) biochars have been studied in soil columns, they have shown highly significant reductions in NO_3^- leaching. Clough et al. (2013) showed leachate from biochar amended soils had 25% - 34% less nitrates than unamended soils, all containing 40 kg N ha^{-1} of $(NH_4)_2SO_4$. Similarly, many studies have shown reductions in NH_4^+ emissions after the application of biochar. NH_4^+ readily adheres to biochars irrespective of feedstock and pyrolysis temperature (Yao et al., 2012). However, there is little research conducted on enriched biochars and their ability to both reduce leaching and slowly release N to the soil strata. This is especially pertinent for biochars that are enriched with highly nitrogenous products such as animal urines or manures.

In addition to changing soil and nutrient dynamics, biochar has been shown to modulate plant growth and physiology (Agarwal et al., 2022). Many studies have shown significant field scale changes to yield, as referenced above; other researchers have noted changes to germination success and speed (Ali et al., 2021). This suggests that there are phytohormonal interactions at play between plants and biochar products. These interactions could be beneficially optimized by changing how the biochar product is applied. If, for example, a biochar product can reduce the time taken for germination, then applying it as a seed coating instead of typical broadcast and incorporation methods may provide further benefit, maximizing the quantity of biochar in contact with the seed and subsequent radicle. Similarly, these phytohormonal effects may inhibit or be deleterious to germination and initial growth, in which case applying biochar products in a manner such as the banding of nutrients typically applied when corn is seeded may be more appropriate.

The objective of this study was to evaluate two locally produced biochar products for inorganic nitrogen sequestration and then assess their effects on soil leaching dynamics and initial spring wheat germination and vigour, in an enriched and unenriched form.

The hypotheses of this study were:

- Wood and crab-based biochars could sequester significant quantities of nitrogen that would benefit initial plant growth.
- Both enriched and unenriched biochars would significantly reduce inorganic nitrogen leaching compared to a control or conventional fertilizer application.
- Direct seed to biochar contact would quicken germination time and enhance initial seedling vigour.

To test the above hypotheses and evaluate the possible benefits of biochars, three experiments were undertaken:

(1) An analysis of the potential nutrient sequestration that could occur with two locally produced biochars enriched with liquid cow urine or a liquid seaweed extract;

(2) a leaching experiment to assess how effectively those nutrients could be retained in the root zone; and

(3) a germination experiment using spring wheat to determine the effect of biochar rate of application as well as biochar type and enrichment status.

2.2 Materials and Methods

The following tables (2.1 & 2.2) describe the analysis of the cow urine and biochars used in this chapter.

Table 2.1 Cow urine nutrient characteristics analysis

Cow urine characteristics	
pH (pH units)	6.12
EC (dS m^{-1})	27.80
Nitrogen (%)	0.30
P_2O_5 (%)	0.170
K_2O (%)	0.220
Ca (meq L^{-1})	23.71
Mg (meq L^{-1})	49.92
S (%)	0.066

Table 2.2 Biochar characteristics analysis

	Wood biochar	Crab biochar
BET surface area testing (m^2 g^{-1})	65	43
Ash (%)	2	5
Carbon (min %)	58	24.5
Total Nitrogen (%)	0.18	1.23
P_2O_5 (%)	0.15	0.53
K_2O (%)	0.22	0.98
Ca (%)	0.25	60.22
Mg (%)	0.06	0.09
S (%)	0.02	0.03
Maximum moisture (%)	5	7

Brunauer-Emmett-Teller (BET)

Biochar preparation and enrichment

Both crab and wood biochars were created at Cape Breton University (CBU) via a small batch pyrolization unit (Faculty of Chemistry, Sydney, Canada). Wood feedstocks came from mixed forestry waste and crab feedstock came from processing residues from the harvest of snow crabs on the Atlantic Canadian coast. Both feedstocks were pyrolyzed in a zero-oxygen environment. The temperature inside the pyrolysis reactor increased by 20 °C every hour until reaching 400 °C and then was maintained at 400 °C for four hours before cooling back to room temperature.

The biochars were ground with a Wiley mill until they passed through a 1 mm screen, then enriched; the enrichment process is graphically illustrated in Figure 2.1. The biochars were combined with pre-prepared liquid amendments: a liquid seaweed extract prepared at the recommend dilution of 15 mL L^{-1} distilled water (Seaboost™ 0.3-0.3-4); or freshly collected cow urine from a dairy herd diluted with distilled water at a ratio of 1:1 with distilled water. Four glass beakers (4 L each) were filled with the liquid amendment (2 with cow urine, 2 with liquid seaweed extract). Fifty grams of each biochar was placed in fine-mesh filter bags then suspended in the glass beakers, each containing 4 L of prepared liquid containing either seaweed extract or cow urine, so that both biochars could be enriched with both amendments separately. A 20 cm air stone - providing 7.5 L of air per minute to each mixture - was placed into each beaker to ensure constant mixing and enrichment for 48 hrs.

After 48 hrs, the suspended biochars were removed from the vats and the vat liquids were passed through filter paper to capture any biochar that had escaped the filter bags. The biochars were then dried in commercial drying ovens at 40 °C for 72 hrs. After this time, the biochars were placed in storage containers and frozen at -20 °C until they were analyzed for extractable nitrogen (both NO_3^- and NH_4^+).

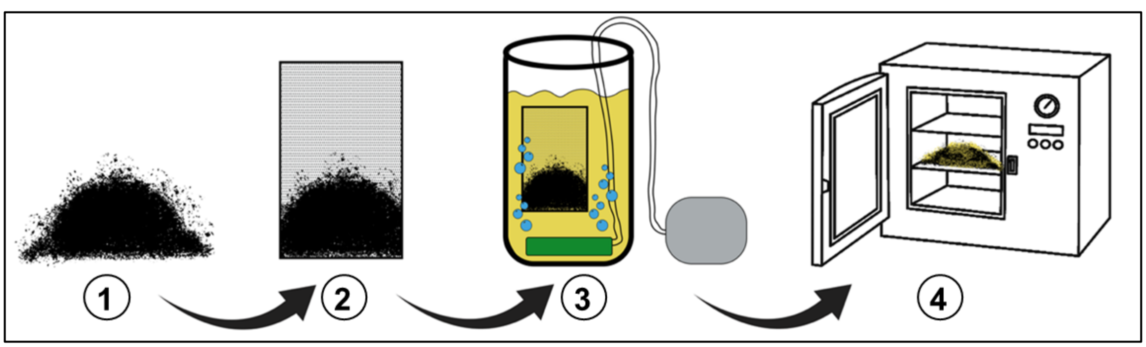

Figure 2.1. Enrichment process for ground biochars. (1) Biochar was ground to < 1mm; (2) biochar was placed in a fine-mesh bag; (3) the bag was placed in enrichment liquid and constantly aerated; (4) enriched biochar was dried to 40 °C for 72 hrs.

Unenriched biochars, enriched biochars, and the liquid amendments (both pre and post enrichment) were analyzed to quantify inorganic nitrogen sorption. A standard inorganic nitrogen extraction method using 2 M KCl was used (Smith & Li, 1993). Liquids were then passed through 1 mm filter paper (Fisherbrand™ P4 grade) before an aliquot was analyzed for inorganic nitrogen via a Technicon AutoAnalyzer.

Soil column leaching experiment

A factorial treatment matrix comprised of two factors – (1) solid fertilizer: wood biochar, crab biochar, urea, and none; and (2) liquid fertilizer: cow urine (1:1 ratio with distilled water, 10 t ha^{-1}), liquid seaweed extract (15 mL L^{-1} distilled water), and none (distilled water). This created a matrix of 12 treatments with the biochars being enriched with the liquid amendments when combined. For non-biochar treatments the solid and liquid treatments were simply applied together in their raw form. The biochars were applied at rates of 1.4 g per soil column (equivalent to 5 t ha^{-1}) to match previous research recommendations (Schmidt et al., 2021). Urea (46-0-0) was applied at a rate of 0.046 g per soil column (equivalent to 75 kg N ha^{-1}), determined from previous research (Nass et al., 1996). A standard soil column leaching experiment was set up for this experiment (Owens et al., 1996). Air dried field soil (sandy loam, Woodville, NSWOV3~A soil type) was first sieved through a 1 mm screen and then mixed with Ottawa sand at a rate of 100 g sand per 1 kg soil to ensure adequate drainage. 50 g of soil was then placed inside soil columns measuring 10 cm deep with a diameter of 6 cm that had Fisher Scientific P4 filter paper covering the drainage holes. Once soil columns were set up and soil rehydrated, treatments were applied and surface mixed into the soil using a clean spatula. Treatments were arranged in a Completely Randomized Design (CRD) with 4 replications.

Application rates per soil column were calculated based on bulk density. The field soil's bulk density was assessed, as well as that of the Ottawa sand amended field soil used within the columns. The increased bulk density of the Ottawa sand amended soil modified the application rates based on the weight of a hectare of soil to a depth of 15 cm. These application rates were then calculated for the weight of soil added to each column (50 g).

The initial leaching event occurred directly after the application of each treatment. Each soil column was placed on a vacuum flask and 20 mL of 0.01 M $CaCl_2$ was poured into each column and subsequently collected into and frozen in a -80 °C freezer. This process was repeated five times at intervals of 14 days before sub-samples were analyzed for NO_3^- and NH_4^+ using a Technicon Auto Analyzer. After leachate collection and analysis for NH_4^+ and NO_3^-, concentrations were analyzed both in absolute terms (quantity of compound collected in the leachate) as well as relative terms (percent loss from each event compared to total treatment loss). These concentrations were analyzed through repeated measures analysis to include the temporal factor (leaching event).

Germination experiments

To determine the effects of enriched and unenriched biochar on the germination of spring wheat seeds (cv. AAC Scotia), two separate germination experiments were conducted in growth chambers. The first experiment investigated the optimal rate of raw (unenriched) biochar application. The second experiment compared the biochars (both enriched and unenriched) to their liquid enrichments and at various ratios within those categories. The setup for both experiments was similar with the only difference between techniques being the rates and compositions of the biochar used. A Conviron CMP3244 germination chamber was used for all experimentation with a light cycle of 16 hours at 23 °C with temperatures reducing to 18 °C for the 8-hour night cycle. The experiment duration was 8 days with humidity maintained at 98% relative humidity for the duration of the experiment.

Rate of biochar experiment

A two-factor experiment was run, with one factor being biochar type (crab, wood, none) and the other being rate of biochar application. Treatments received either 0.10 g, 0.25 g, 0.50 g, or 1.00 g of biochar per germination pouch. This created 9 separate treatments arranged in a completely randomized design (CRD) with 4 replications. Eight spring wheat seeds (cv. AAC Scotia) were placed into growth pouches (Mega International LLC), measuring 18 cm by 16.5 cm, before the biochar treatment was added uniformly on top of the seeds. Each pouch received 30 mL of distilled water before the setup was placed inside the germination chamber. This comprised 'day 0' of the experimental setup. From day 2, growth pouches were monitored daily for germination; and from day 4, shoot lengths were measured daily. Shoots and roots were harvested on day 8 and measured for biomass weights both wet and dry.

Effects of enrichment experiment

A two-factor experiment was run with one factor being enrichment type (seaweed extract, cow urine, none) and the other being wood:crab biochar ratios with treatments of 100:0, 75:25, 50:50, 25:75, 0:100, and 0:0. This created 18 treatments that were replicated 4 times following a CRD as with the rate experiment above. Eight spring wheat seeds (cv. AAC Scotia) were placed into Mega International LLC growth pouches before the biochar treatment was added uniformly on top of the seeds at a rate of 1.00 g per pouch. Each pouch received 30 mL of distilled water before the setup was placed inside the germination chamber. This comprised 'day 0' of the experimental setup; from day 2, growth pouches were monitored daily for germination and from day 4 shoot lengths were measured daily. Shoots and roots were harvested on day 8 and measured for biomass weights, both wet and dry.

Statistical analysis

For the germination, application rate, and enrichment effects experiments, data was analyzed using Minitab Statistical Software (Minitab LLC, State College, PA, USA). The significance level was set at 0.05 and the ANOVA assumptions of independence, constant variance, and normality of the residuals were met. When significant differences in the mean were detected, the Fisher LSD test was used to establish significant value ranges.

For the soil column leaching experiment, both NH_4^+ and NO_3^- were analyzed using SAS v9.4 Proc mixed repeated measures analysis to determine each factor's singular and interactive effects. For each nitrogen compound, the repeated measures analysis compared the effect of solid and liquid fertilizer across the six temporal events to determine significance.

2.3 Results

Biochar enrichment characterization

Changes to enrichment liquids pre- and post-enrichment

Cow urine and seaweed both contained varying levels of nitrate (NO_3^-) and ammonium (NH_4^+) at the pre-enrichment stage (Figure 2.2). The cow urine had levels below the reporting limit for NO_3^- (<0.001 mg L^{-1}) but had a significant concentration of NH_4^+ (25.6 mg L^{-1}). The seaweed extract had measurable values of both NO_3^- and NH_4^+, 0.110 mg NO_3^- L^{-1} and 7.73 mg NH_4^+ L^{-1} respectively. The enrichment process significantly changed the N content of both enrichment liquids, suggesting that the biochars affected liquid N concentrations. During liquid seaweed extract enrichment, the concentration of

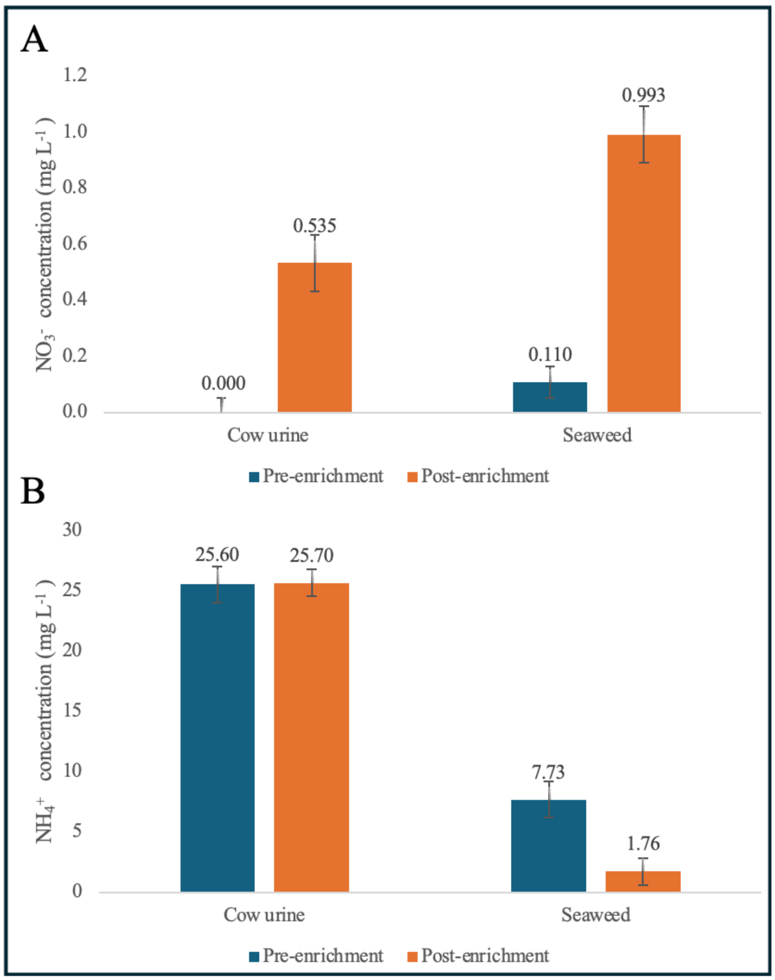

Figure 2.2. Nitrogen content of enrichment liquids pre- and post-enrichment. Each bar represents the mean value of four replications.

NH_4^+ was reduced from 7.73 mg L^{-1} to 1.76 mg L^{-1}, but the concentration of NO_3^- increased from a starting concentration of 0.110 mg L^{-1} to 0.993 mg L^{-1} post enrichment. On the other hand, the enrichment process had no effect on NH_4^+ concentration in cow urine, but NO_3^- content in cow urine significantly increased from <0.001 mg L^{-1} to 0.535 mg L^{-1} post-enrichment.

Changes to biochar post-enrichment

The effect of enrichment methods (cow urine and seaweed extract) on inorganic N content in biochar varied depending on biochar type (Figure 2.3 A & B). After conversion from concentration to absolute quantity, unenriched wood biochar contained minimal NH_4^+ (2.14 mg L^{-1}) and NO_3^- (0.002 mg L^{-1}). The unenriched crab biochar contained significantly more NO_3^- than the wood biochar (1.286 mg L^{-1}) (Figure 2.3 A). However, NH_4^+ levels were not significantly different between the two unenriched biochars (Figure 2.3 B). These levels of both NO_3^- and NH_4^+ increased statistically when enriched with cow urine but not when enriched with seaweed.

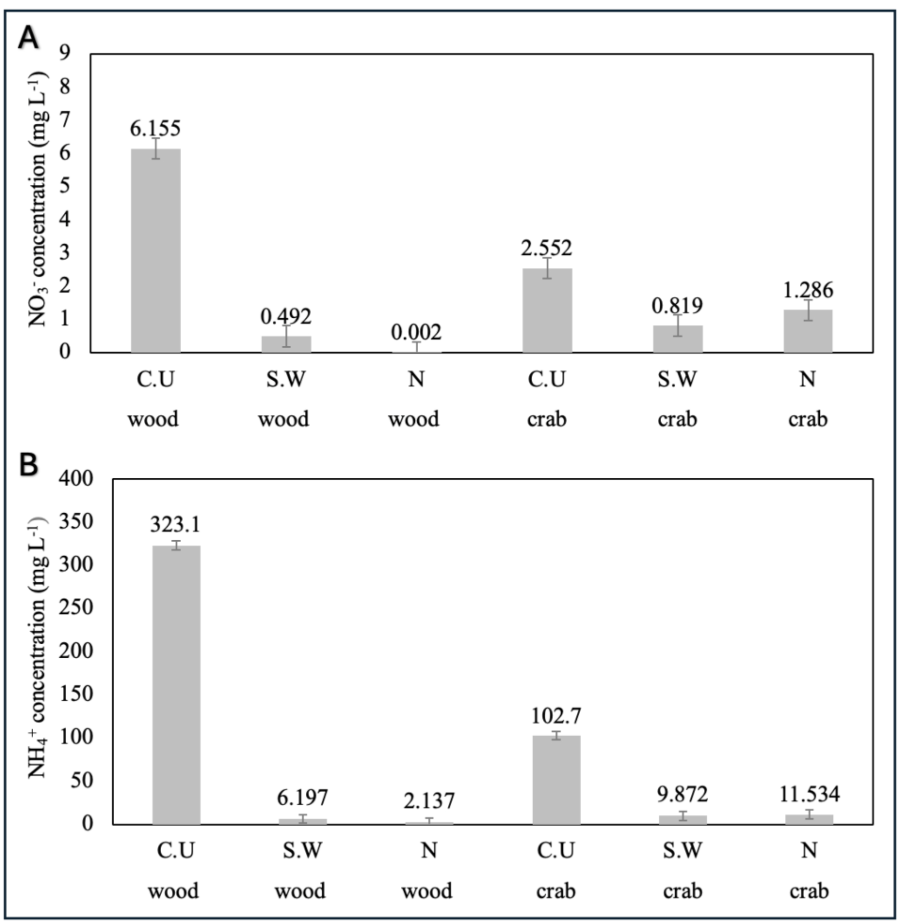

Figure 2.3. Effects of biochar types (wood vs crab) and enrichment liquid (cow urine, C.U., seaweed, S.W., and non-enrichment, N) on the concentration of (A) NO_3^- (mg L^{-1}) and (B) NH_4^+ (mg L^{-1}).

Concentrations of both NO_3^- and NH_4^+ significantly changed for both biochars after enrichment. Wood biochar enriched with cow urine showed significantly higher levels of both NO_3^- and NH_4^+ over the other treatments. There was an increase in NO_3^- levels from 0.002 mg L^{-1} to 6.16 mg L^{-1} and of NH_4^+ from 2.14 mg L^{-1} to 323 mg L^{-1} (Figure 2.3). This was the most effective enrichment combination. Following this, the enrichment of crab biochar with cow urine significantly increased NO_3^- and NH_4^+ concentrations in the biochar. Nitrate concentrations increased from 1.29 mg L^{-1} to 2.55 mg L^{-1} and concentrations of ammonium from 11.5 mg L^{-1} to 103 mg L^{-1}. The liquid seaweed extract enrichment did not significantly change the NO_3^- and NH_4^+ concentrations of either biochar type post enrichment.

Soil column leaching experiment

Table 2.3 and Figure 2.4 present the results of a repeated measures analysis examining the effects of solid and liquid fertilizers and leaching events on NO_3^- and NH_4^+ concentrations in leachate. Initial NH_4^+ and NO_3^- concentrations in the leachate were significantly changed by the addition of the treatments. Cow urine dramatically increased initial NH_4^+ concentrations collected in the leachate. There were significant interactive effects for either NH_4^+ or NO_3^- in every leaching event except for the fourth. However, no event had significant interactive differences for both NH_4^+ and NO_3^- in the same event. In the event that either NH_4^+ or NO_3^- had a significant interactive event, the other compound had a significant single factor difference in the opposite direction. For example, in the second leaching event, the greatest amount of NH_4^+ leached was from the urea solid fertilizer factor; this corresponded with the significantly least amount of NO_3^- leached for urea in that second leaching event. This trend continues for the majority of the leaching events. This interplay between NH_4^+ and NO_3^- quantities is seen not just with urea but across the other treatments also. The fourth leaching event, the only one without significant interactive effects, shows significant differences for both NH_4^+ and NO_3^- across both liquid and solid fertilizer factors. Cow urine produced significantly lower NH_4^+ and NO_3^- concentrations compared to the none and seaweed treatments. In terms of the solid fertilizer factor, urea produced the significantly highest NH_4^+ concentrations and the lowest NO_3^- concentrations. The wood biochar, crab biochar, and none treatments produced similar relative concentrations of both NH_4^+ and NO_3^-.

Table 2.3. P-values from repeated measures of analysis of variance (ANOVA) analysis for the effects of solid fertilizer, liquid fertilizer, and leaching events on mineral nitrogen. $MSE^{-0.5}$ = the square root of the mean squares error (MSE), which estimates the common standard deviation (σ).

Treatment	NO_3^-	NH_4^+
Solid fertilizer	<0.001	<0.001
Liquid fertilizer	<0.001	<0.001
Leaching event	<0.001	<0.001
Solid fertilizer * Liquid fertilizer	<0.001	<0.001
Solid fertilizer * Leaching event	<0.001	<0.001
Liquid fertilizer * leaching event	0.053	0.023
Solid fertilizer * Liquid fertilizer * Leaching event	0.009	0.007
$MSE^{-0.5}$	0.031	1.49

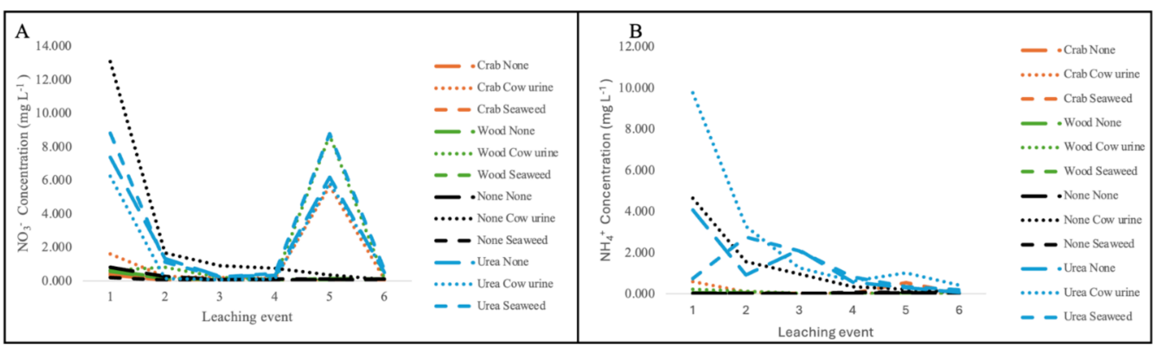

Fig 2.4. Interaction of solid and liquid fertilizer on (A) NO_3^- concentration and (B) NH_4^+ concentration by leaching event.

Figure 2.5 illustrates the effect of fertilizer types on NH_4^+ and NO_3^- concentrations within each event, as well as their percentage loss per event relative to the total treatment loss. The relative values allow for comparison between treatments as the quantity of N added couldn't be matched across treatments (unenriched wood biochar containing near undetectable NO_3^- levels for example). To determine relative percent leached for each treatment, the total nitrogen for each treatment and replication was summed and the amount of nitrogen leached during each event for each treatment was then presented as a percentage of that sum. As can be seen in Figure 2.5, each factor strongly affected nitrogen release, which was significantly different across leaching events. The greatest mean N release was from the combinations of urea and liquid cow urine. Across treatments, nitrogen capture from the first three leaching events was primarily in the NH_4^+ form; the last three events were in the NO_3^- form.

Figure 2.5 A and B detail the NH_4^+ release from solid fertilizer by leaching event as well as the relative release based on total release over the leaching events. Both the "Urea" and "None" factors released significantly greater total NH_4^+ than either of the biochars, which only provided minimal amounts across all leaching events. When comparing the relative NH_4^+ release from each compound, they all followed a similar trend with greater percent release in the initial leaching events and subsequently less in the later events. Both biochars did, however, release significantly greater relative amounts in the 5th and 6th leaching events than the urea or none factors. Figure 2.5 C and D detail the NH_4^+ collected in leachate from the liquid fertilizer factor by leaching event. The cow urine factor contained the greatest quantity of NH_4^+ and the majority (60%) of this was released in the first leaching event. While cow urine released significantly more NH_4^+ in the second event as well, each subsequent event entailed no significant difference in NH_4^+ for any of the factors. There was an immediate release of NH_4^+ from the cow urine treatment but this quickly leached through the columns and provided no additional residual nitrogen when compared to the other treatments. The release of NO_3^- was delayed until the 5th and 6th leaching events where both the Urea and None factors released significantly greater quantities than either of the biochars (Figure 2.5 E and F). When comparing relative release, the biochars provided significantly greater NO_3^- in the first two events, with wood biochar providing relatively greater quantities in the first event and crab biochar providing more in the second event. Similarly to the solid fertilizer, the liquid fertilizers released the majority of their NO_3^- in the 5th leaching event (Figure 2.5 G and H). Cow urine released a significantly greater quantity of NO_3^- than the other factors, followed by seaweed; however, all treatments followed a similar trend.

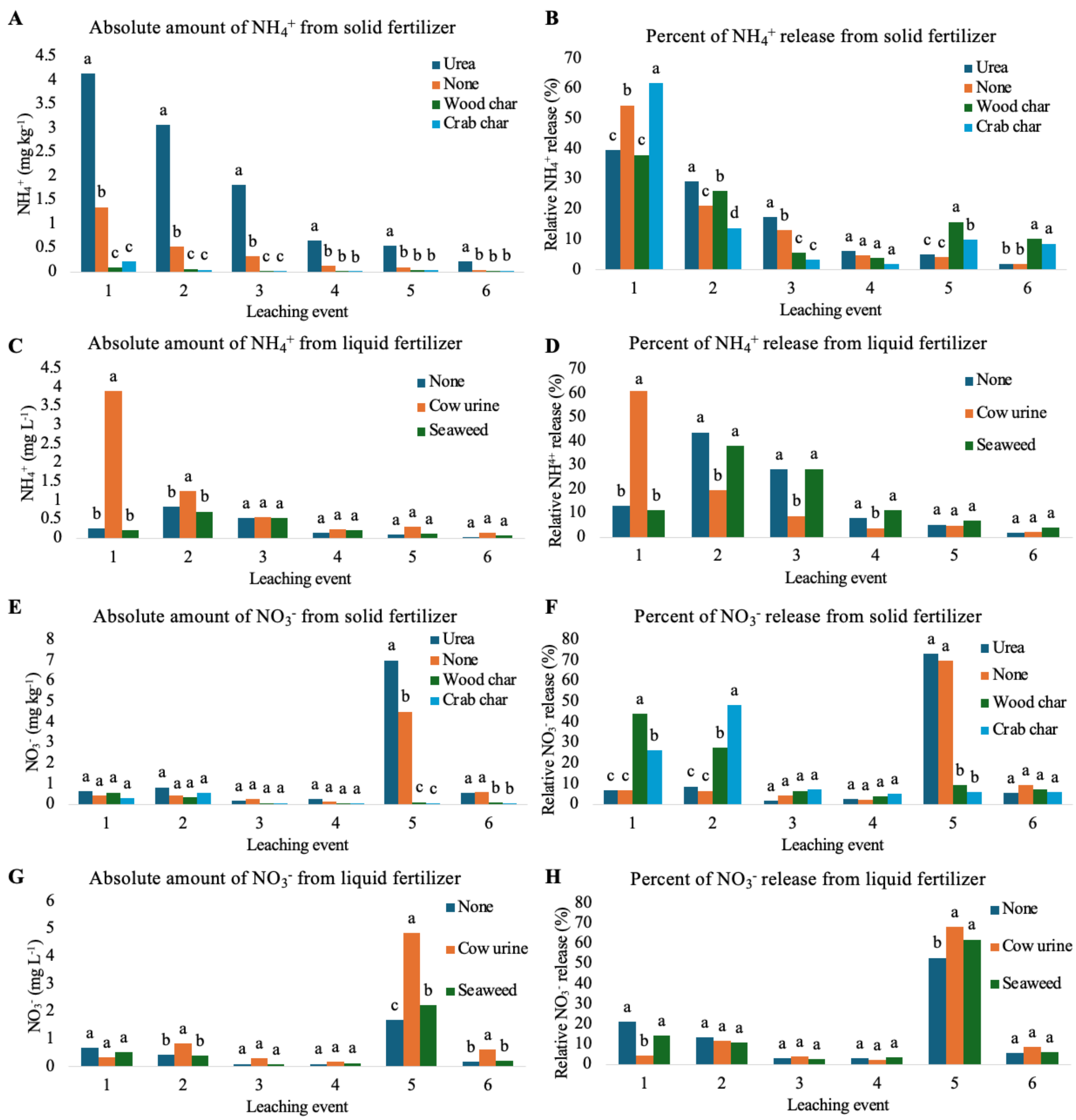

Figure 2.5. Effects of fertilizer types and leaching events on the quantity of NH_4^+ collected in leachate from solid fertilizer (A) and liquid fertilizer (C) and the concentrations of NO_3^- collected in leachate from solid fertilizer (E) and liquid fertilizer (G). Effects of fertilizer types and leaching events on the percent loss from each event compared to total treatment loss of NH_4^+ collected in leachate from solid fertilizer (B) and liquid fertilizer (D) and the concentrations of NO_3^- collected in leachate from solid fertilizer (F) and liquid fertilizer (H). Means with a common letter within each leaching event did not differ at $p < 0.05$.

Initial spring wheat growth experiment

To understand the effect that both biochar type, rate, and enrichment had on initial spring wheat growth, two experiments were conducted. The first experiment investigated the effects that biochar type and rate (grams per germination pouch) had on initial wheat growth (Figure 2.6). The second experiment investigated the effects that biochar enrichment and ratio, from 100% wood (100:0) to 100% crab (0:100) had on wheat seedlings at a set rate of 1.00 g of biochar per pouch (Figure 2.6). Seven days after the experiment initiation, biochar type, enrichment, and biochar rate had significant effects on spring wheat growth, shoot lengths, root and shoot biomass weights, and root to shoot ratios. Both biochar type and application rate had significant effects on the mean shoot length seven days after experiment initiation (Figure 2.6). The crab biochar produced a negative response as the rate was increased. Rates of 0.10 g and 0.25 g per growth pouch produced greater shoot lengths than the 1.00 g application rate. None of the crab applications produced shoot lengths that were greater than the control treatment of distilled water. The wood biochar behaved in an opposite manner to the crab; as the rate of wood increased, so too did the mean shoot length. The 1.00 g application rate of wood biochar produced shoots that were significantly greater than the control. The other rates (0.10 g, 0.25 g, 0.50 g) were not significantly greater that the control of 10.5 cm, as can be seen from the Fisher significance grouping in Figure 2.6.

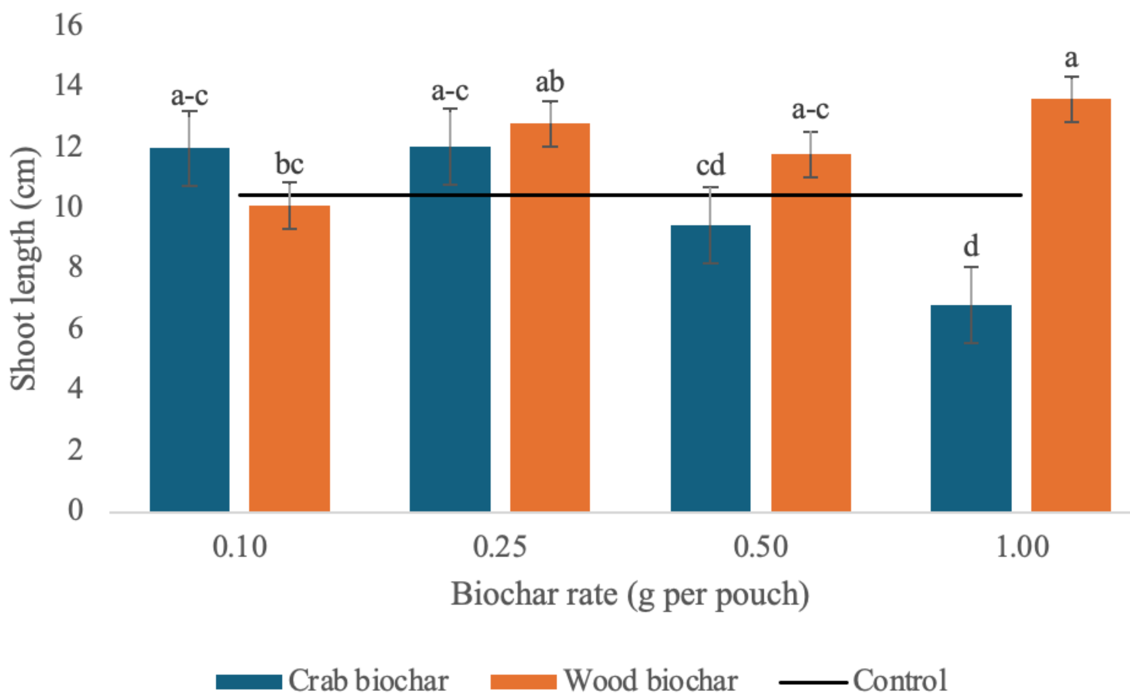

Figure 2.6. Shoot length (cm) of spring wheat (cv. AAC Scotia) in response to varying biochar rates and types (two-way interaction p-value = 0.001). Means sharing a common letter are not significantly different at $p < 0.05$.

Table 2.4 describes the results of comparing the enriched biochars (cow urine, seaweed) with differing ratios of each biochar. A ratio of 0:0 represents the enrichment liquid on its own (placed in the bottom of the germination bag at the recommended dilution). A ratio of 100:0 represents only wood biochar; and a ratio of 25:75 represents a mixture of 25% wood to 75% crab. Each biochar treatment was applied at a rate of 1.00 g per germination pouch. All shoot lengths were measured on day seven of the experiment. Liquid cow urine on its own (diluted 50:50 with distilled water) prevented germination completely; however, biochar enriched with liquid cow urine produced some of the longest shoot lengths. Both enriched biochars produced shoots of greater lengths than the unenriched biochars or the control (None – 0:0). This suggests that the application of an enriched biochar is preferable to an unenriched or control in terms of shoot lengths. However, the liquid seaweed extract treatment matched the enriched wood biochar cow urine treatment to produce shoots of the greatest length. All biochars enriched with seaweed extract produced shoots that were significantly shorter than the liquid seaweed extract treatment on its own.

Table 2.4. Effect of enrichment and biochar ratio on shoot length of spring wheat cv. AAC Scotia

Enrichment type	biochar ratio (wood:crab)	Shoot length (cm)
Cow urine	00:00	0 g
	100:00	15.5 g
	75:25	13.4 cd
	50:50	13.2 de
	25:75	13.6 cd
	00:100	14.4 a-c
Seaweed	00:00	15.4 ab
	100:00	13.6 cd
	75:25	14.1 cd
	50:50	13.3 c-e
	25:75	14.1 cd
	00:100	13 d-f
None	00:00	12.2 ef
	100:00	13.2 de
	75:25	14 cd
	50:50	12.2 ef
	25:75	14.3 bc
	00:100	11.6 f
p value		
Enrichment		<0.001
Biochar ratio		<0.001
Enrichment * Biochar ratio		<0.001

Means with a common letter did not differ at p <0.05.

2.4 Discussion

These three experiments were built on one another to assess the effectiveness of the described technique for biochar enrichment; and the effectiveness of enrichment itself, including how effectively enriched biochar can retain nutrients in the soil profile, and positive or negative effects on germination and initial vigour. There were several notable results from this study.

Enrichment

Whilst the quantity of biochar added to each enrichment vessel was relatively small in comparison to the quantity of liquid (50 g to 4 L), a reduction in ammonia and/or nitrate levels was expected due to the porous and charged structure of the biochars (Egyir et al., 2022). However, nitrate concentrations increased during the enrichment process. This may be due to the aerobic bubbling environment, conducive to nitrifying bacteria proliferation, present during enrichment; in combination with the capacity of biochar to stimulate microbial activity (He et al., 2019). These properties may have facilitated the oxidation of ammonia to nitrite, then nitrate during the enrichment process via microbial metabolism (Zhang et al., 2018).

Initially, the wood biochar contained nitrate levels below detection, and the crab biochar had minimal nitrate levels of 1.286 mg/L. The low concentrations of nitrates present in the biochars could not have influenced the concentration of the liquids enough on their own to account for this increase of nitrate in the liquid solutions. In a recent paper examining the volatilization of ammonia from soils amended with modified and nitrogen-enriched biochars, the authors noted similar results; however, they did not analyze their soils for NO_3^-. They found that the biochars reduced ammonia emissions by 57% to 83% depending on whether they had been enriched or not. This suggests that the ammonia emission reduction was due to increased oxygen-containing surface functional groups present on and within biochar, which produced an environment conducive to bacterial nitrification (Egyir et al., 2022).

The crab biochar sequestered less NO_3^- and NH_4^+ from the liquids than the wood biochar. This may be in part due to the high concentration (60%) of $CaCO_3$ in the crab biochar in combination with extremely high pH, reducing the biochars' affinity for the charged nitrogen compounds. This was also most likely due to make-up of functional groups present on the organic coatings of the biochar products (Hagemann et al., 2017). Each biochar product behaved uniquely in the enrichment of liquids even when exposed to identical processes. This aligns with other researchers' findings that biochar compositions and properties are dramatically changed by feedstock type, as well as pyrolysis process and temperature. However, there are similar characteristics exhibited across biochar types, namely the ability to adhere charged molecules to the intricate surface of the biochar product. The uniqueness of these characteristics could allow for bespoke biochar products to be developed to address certain crop or soil situations.

Leaching

All factors within this experiment significantly affected both the quantity and timing of NO_3^- and NH_4^+ release. A repeated measures analysis showed significant changes to the release of inorganic nitrogen over time, especially when a slightly acidic extractant was used (0.01 M $CaCl_2$). NH_4^+ release steadily declined from the 1st leaching event to the 6th while NO_3^- started at an initial low which peaked at the 5th leaching event. This dramatic rise in NO_3^- was likely due to the microbially mediated nitrification process (Joseph et al., 2013). The field soil used in the experiment was unsterilized, allowing for this process to occur as it would in a field.

While the general trend of NH_4^+ release and oxidation to NO_3^- was expected, there were notable differences in how this process occurred based on both the solid and liquid fertilizers and their interactions with each other. Urea and cow urine both provided high initial quantities of NH_4^+ that were then converted to NO_3^- and leached in the 5th event. These highly nitrogenous inputs behaved as would be expected by a soluble fertilizer. Conversely, both biochars dramatically reduced the quantity of nitrogen compounds in the leachate compared to the control. This suggests that both biochars sequestered/adsorbed the soil nitrogen compounds.

The general pattern of nitrogen leaching followed an expected pattern with high initial NH_4^+ availability facilitating the nitrification process whereby ammonium is converted through nitrite to nitrate. NH_4^+ concentrations generally reduce over time. Some of this reduction in NH_4^+ concentration is microbially mediated, producing a substantial release of NO_3^- over time. This nitrification process has been well documented by other researchers such as Beeckman et al. (2018).

Both biochars contained significant quantities of nitrogen when they were added to soil columns. As applied to the soil columns, the cow urine enriched wood biochar contained 0.452 mg of NH_4^+ and 0.009 mg of NO_3^-. The cow urine enriched crab biochar contained 0.144 mg of NH_4^+ and 0.004 mg of NO_3^-. When these quantities of N were added to the base N rates from the control soil, they would have contained significantly greater nitrogen compounds than the control soil. However, unlike with the control, nitrogen was maintained within the soil profile through all the leaching events. This suggests that biochar is extremely effective at preventing inorganic nitrogen leaching. Whether plants can extract this nitrogen from the biochar amended soil requires further research.

Other researchers investigating biochar's nutrient retention and soil fertility stimulating potential (Hagemann et al., 2017b) have found similar results to those of this chapter. Their raw or 'pristine' biochar contained relatively minimal quantities of NO_3^-. Once enriched, in their occasion co-composted, the biochar retained roughly 2,000 mg NO_3^- kg^{-1}. While they managed to enrich their biochar product with substantially more NO_3^- than in this experiment, they found that conventional methods of extracting and assessing NO_3^- capture were insufficient to quantify the total nitrogen captured by the biochar. A conventional extraction technique like the one used here, using 2 M KCl, was only able to extract 43% of the nitrogen that had been captured by the biochar (Hagemann et al., 2017a). This suggests that the enriched biochar products used in this experiment could contain considerably more nitrogen than the initial extraction suggested. It is not likely, however, that plants are able to extract all the nitrogen that biochars can retain.

The application of biochar to the soil columns resulted in a drastic reduction in inorganic nitrogen compounds within the collected leachates. This reduction in both NO_3^- and NH_4^+ has been well documented from multiple angles, some beneficial, and some deleterious (Schmidt et al., 2021). Clough et al. (2013) demonstrate that the addition of biochar to composts and manures can drastically reduce NH_4^+ volatilization and nitrogen leaching, enhancing the efficiency of composting systems and reducing losses of nitrogen from raw manures. When biochar was applied to soils at rates higher than 5 – 10 t/ha, a similar effect occurred, where plant available nutrients were sequestered/adsorbed by the biochar, reducing yields and preventing plants' access to the nutrients they require. This 'locking up' of nutrients by biochar has not been well documented in pre-enriched biochars. However, the leaching experiment results suggest that biochar may be sequestering nutrients to such a degree that plants may have less access in the biochar-applied soils than in the control soil. The prevention of leaching does not necessarily mean that plants would not grow in these soils; further experimentation with plants will be needed to better understand these nitrogen dynamics. If plants can access the nitrogen held by the biochar while it is prevented from leaching to the degree that the soil column experiments suggest, then these enriched biochars would prove to be highly efficient and effective slow-release fertilizers.

Early plant growth

The effects of biochar rate, type, and enrichment all significantly altered the germination and growth of spring wheat (cv. AAC Scotia). These results highlighted the wide range of effects that biochar can elicit. Wood and crab biochars elicited almost opposite reactions in the rate experiment, with wood biochar producing a positive growth response to the rate of biochar addition. By contrast, crab biochar produced a negative growth response, as the lowest rates of crab biochar produced the greatest shoot lengths. Wood biochar, however, produced the greatest shoot lengths at the greatest rate, with the possibility that even higher rates could have further increased the wheat shoot length. None of the crab biochars produced shoot lengths significantly greater than the control; only the maximum rate of wood biochar (1.00 g) did. Other studies investigating the effects of biochar on germination found no differences in germination rate; and greater spring wheat shoot lengths on biochar amended soils as opposed to a non-amended soil (Kataya et al., 2024). Investigations into the effect that biochar has on wheat gene expression suggest that biochar can be rich in gibberellins (GA), auxins (IAA), and abscisic acid (ABA), which can all positively affect plant growth and vigour (Racioppi et al., 2020).

Interestingly, when wood and crab biochars were mixed in varying ratios, the negative effects of the crab biochar were reduced and the resulting mixes all performed similarly, suggesting that the presence of wood biochar somewhat masked the negative effects of the crab. Both enriched biochars performed significantly better on average than unenriched biochars, with only a few of the unenriched biochar treatments being significantly similar to the enriched ones. The two treatments that produced the greatest shoot lengths were the 100% wood biochar enriched with cow urine; and the liquid seaweed extract on its own.

Previous research has shown that, as with biochar, liquid seaweed extracts contain a wide range of phytohormones such as GA, IAA, and ABA (Ghaderiardakani et al., 2019). The charged organic coating on the biochars could have reduced the plants' ability to interact with the phytohormones present in seaweed when the biochar was enriched with it. The enrichment process may also have influenced phytohormone availability or effectiveness, which could explain why the liquid seaweed extract treatment on its own produced greater shoot lengths than any of the seaweed enriched biochars. In other research, biochar and liquid seaweed amendments have shown beneficial effects to tomato dry matter, yield, and soluble sugars (Ghaderiardakani et al., 2019). These changes seem to occur later in the plant's growth, at which point the biochar/seaweed amendment produces significant changes to the soil's microbiome. The limitations of this germination experiment prevent these possible benefits from showing themselves.

2.5 Conclusion

The biochars were able to be successfully enriched with inorganic nitrogen which, when applied to the soil columns, significantly reduced the quantity of nitrogen leached out of the system. Additionally, cow urine enriched wood biochar enhanced initial wheat seedling growth compared to a control. These findings suggest, promisingly, that cow urine enriched biochar may prove to be an effective 'nutrient carrier matrix' and be extremely efficient at retaining nutrients in the soil profile, where plants have access to them. There are limitations to the conclusions that can be drawn from this study. Further investigation should include a longer time factor.

Biochar comprises mainly recalcitrant carbon that will remain in the soil for many years. This may be invaluable to farmers in climactic conditions where multiple freeze-thaw events happen every year as considerable leaching and pollution is occurring routinely under conventional practices.

Chapter 3: Evaluation of the Effects of Raw- or Liquid Dairy Manure Enriched-Biochar on Spring Wheat Growth and Yield

3.1 Introduction

Humans have intentionally and unintentionally been farming with biochar-based products for thousands of years. There are highly publicized instances such as the *Terra Preta* soils of South America, which comprise highly fertile soils rich in biochars and animal wastes that were farmed thousands of years ago (Glaser & Birk, 2012). Less intentional instances of biochar application come in the form of the historic and current application of wood ash to agricultural fields. Ash samples often contain biochar particles due to incomplete combustion, and these particles may be partially responsible for the benefits that wood ash provides (Mahmood & Kamal, 2022). Biochar has several agronomic benefits that producers could capitalize on to improve crop growth, increase nitrogen use efficiency, and beneficially alter soil physio-chemical properties (Upadhyay et al., 2024). However, due to the inherently variable nature of biochar feedstock and production (pyrolysis), a robust and varied body of evidence is required for researchers and producers to make educated and informed choices on its use.

Biochar catalyzes immediate and long-term changes to soil physical and chemical properties, as well as microbial communities. Soil aggregation is positively affected by the application of biochars, which have been shown to improve wheat yield (Yang et al., 2024). These aggregates are a key soil health metric that can help to improve drainage as well as stabilizing and shielding soil organic matter (SOM) from erosion or loss. This improved aggregation may be in part why soil organic carbon (SOC) levels remain elevated for many years after biochar application (Ding et al., 2023). Long-term experimentation (11 years) by Ding et al (2023) showed that after 11 years, soils that had biochar applied to them still had 39 – 51 % of the biochar in the top 30 cm of soil and additionally had increased levels of SOC, dissolved organic carbon, and microbial biomass carbon. Their research shows that even single applications of biochar can have long-term benefits to soil carbon cycles and stores.

In addition to benefitting soil carbon dynamics, biochar, due to its highly reactive carbon coating (Hagemann et al., 2017a), can sequester and act as a source of fertility for highly labile nutrients such as ammonium (NH_4^+) and nitrate (NO_3^-). Long-term experimentation on the application of inorganic nitrogen and biochar shows that there are significant interactive effects between biochar and inorganic nitrogen fertilizer (Hematimatin et al., 2024). In this study, the availability of inorganic nitrogen to crops increased except when the highest rate of 20 t ha^{-1} of biochar was applied. At this highest application rate, yields of a seven-year crop rotation comprising spring barley, maize, spring wheat, and field peas were reduced due to the sequestration of nutrients in the soil profile (Hematimatin et al., 2024). When applied at lower rates, this sequestration or "capture" of nitrogen can provide a mechanism for labile inorganic nitrogen to be captured when available in the soil profile, and extracted by plants when needed (Haider et al., 2020a). Haider et al. (2020a) show that plants can extract nearly all the NO_3^- sequestered by 'field-aged biochar' and uptake similar levels of nitrogen from the biochar as from inorganic fertilizer applied as $CaNO_3$. In a field study, Schmidt et al. (2017) demonstrated that biochar enriched with cow urine could produce comparable crop yields to inorganic fertilizers across 21 field trials and on 13 crops.

Biochar has a direct effect on soil microbial life and antagonistic pathogens in addition to modulating soil characteristics and physical properties (Tikoria et al., 2023). The high surface area, organic coating, and charged functional groups provide a refuge for microorganisms as well as a surface for mineralization and chemical reactions to occur (Warnock et al., 2007). In addition to promoting 'beneficial' microbial soil networks, biochar has shown antagonistic effects on a variety of disease-causing plant pathogens as well as deleterious soil organisms such as plant-parasitic nematodes (Edussuriya et al., 2023; Kumari et al., 2024; Yu et al., 2024). Of particular interest to this research study, biochar applied with or without fertilizer significantly increases the colonization of wheat plants roots by mycorrhizal hyphae (Blackwell et al., 2015; Solaiman et al., 2010). This increased colonization allows the wheat plant to uptake greater quantities of nitrogen, phosphorous, potassium, sulfur, zinc, and water than wheat plants in soils not amended with biochar (Blackwell et al., 2015). These beneficial microbial associations and improved soil properties when biochar is applied enhance crops' ability to respond to environmental stresses (Chi et al., 2024; Haider et al., 2020b).

Early research in this area has shown that throughout the wheat plants' lifecycle, biochar can cause significant physiological and morphological changes to the crop. Research into this area began with the findings that the application of wood smoke enriched water, or smoke applied directly to the soil surface, significantly increased germination of a wide range of plants (Crosti & Dixon, 2001). Subsequent research on the germination of wheat seeds to different biochar types grown in petri-dishes, as well as 10 different soil types, showed a significant increase in germination (%) as well as root lengths 10 days after sowing (Solaiman et al., 2012). These beneficial effects were observed at the 10, 20 and 50 t ha^{-1} rate; both 0 t ha^{-1} and 100 t ha^{-1} showed significantly lower root growth and germination percentages across most biochar treatments. The authors of this study suggested that in-vitro experimentation with wheat seeds and biochar was an effective pre-field tool to assess compatibility. Other researchers have shown that enhanced root growth continues throughout the crop's life-cycle, increasing nutrient use efficiency: crops grown with 25% less inorganic nitrogen had yields equal to full nitrogen application rates of 120 kg N ha^{-1} (Zhu et al., 2023). These beneficial attributes can vary depending on the cultivar of wheat grown; Italian researchers' investigation of the differences in gene expression of an ancient wheat cultivar, "Saragolla", in comparison to a widely grown commercial cultivar, "Svevo" showed significant differences in gene expression related to Gibberellic Acid (GA) pathways, which significantly stimulated germination ability and further growth of the plant (Racioppi et al., 2020).

Regardless of slight wheat cultivar differences, the application of biochar has been shown to increase wheat yields, protein content, and nitrogen uptake (Shahzad et al., 2018). The greatest yield increases with biochar treatments were observed when the crop experienced environmental stresses such as salinity or drought (Chi et al., 2024; Haider et al., 2020b; Shahzadi et al., 2024). This increased adaptability to environmental stress suggested that biochar applications could be an invaluable tool to help farmers, and their soils, become more resilient to the challenges that we face in a time of erratic climate changes.

In light of this, this study was guided by the following hypotheses:

- Biochar, in both raw and enriched forms, increases initial vigour and growth of the spring wheat cultivar ‘Optimum’.
- The combination of biochar and inorganic fertilizer maximizes the increase in grain yield and quality.

To test these hypotheses, this study aimed to investigate the agronomic potential of locally produced biochar in improving spring wheat growth and development. Three experiments were performed to address this objective: (1) germination experiments to assess germination and compatibility of the biochar to the wheat; (2) pot-based experiments to assess initial plant vigour; and (3) field experiments to assess grain yield and quality.

3.2 Materials and Methods

The experiments used the following source material amendments:

- Biochar, obtained from a local supplier (RDA Atlantic Inc) in the spring of 2024 comprising hardwood woodchips at 45 % moisture. Wood chip composition was roughly 90 % ash and 10 % hornbeam with pyrolysis temperature reaching 400 °C for 210 seconds.
- The pyrolysis of biochar occurred at a low temperature resulting in a relatively low Brunauer-Emmett-Teller (BET) surface area (65 m^2/g) compared with a high temperature product (up to 453 m^2/g) (Weber & Quicker, 2018); however, the low temperature means the organic coating of the biochars’ surfaces is retained.
- Liquid dairy manure (LDM) collected from an aerated manure lagoon attached to a conventional dairy operation at Dalhousie University’s Agricultural Campus.
- Liquid seaweed extract (SeaBoost 0.3–0.3–4) derived from *Ascophyllum nodosum*
- Enriched biochar was created following the stated methods described in Chapter 2, section 2.2.

Tables 3.1 and 3.2 detail the biochar and liquid dairy manure characteristics.

Table 3.1. Biochar analysis as received from supplier (RDA Atlantic Inc)

Biochar characteristics	
BET surface area testing ($m^2\ g^{-1}$)	65
Ash (%)	2.00
Carbon (min %)	58.00
Total Nitrogen (%)	0.18
P_2O_5 (%)	0.15
K_2O (%)	0.22
Ca (%)	0.25
Mg (%)	0.06
S (%)	0.02
Maximum moisture (%)	5.00

BET, Brunauer-Emmett-Teller

Table 3.2. Liquid dairy manure amendment analysis performed by Nova Scotia Department of Agriculture Analytical Laboratory

Liquid dairy manure characteristics (as received)	
Dry matter (%)	0.11
pH (pH units)	7.20
Nitrogen (%)	0.30
Carbon (%)	2.65
P_2O_5 (%)	0.129
K_2O (%)	0.304
Ca (%)	0.168
Mg (%)	0.041
Na (%)	0.066
Cu (ppm)	2.34
Fe (ppm)	80.29
Mn (ppm)	22.56
Zn (ppm)	9.29

Germination experiment

To determine compatibility and initial effects of the enriched and unenriched biochar with spring wheat (cv. Optimum), a germination experiment was conducted. The experiment was arranged in a Completely Randomized Design (CRD) with four replications and repeated twice to create a robust data set for analysis. There were four treatments, including (1) biochar enriched with liquid dairy manure (0.5 g per pouch); (2) liquid dairy manure (LDM) (20 mL 1:1 ratio with distilled water); (3) unenriched bichar (0.5 g per growth pouch); and (4) none (40 mL distilled water) as control. Each experiment was run over eight days in a growth chamber (Sanyo MLR-350) at a constant humidity of 98% and an 18/6 hr day/night photoperiod at 21/18°C day/night temperatures with a light intensity of 192 umol m^{-2} s^{-1} PPFD. Ten spring wheat seeds were placed in standard 18 cm by 16.5 cm germination pouches (MEGA International LLC); treatments, detailed below, were then added to the pouches. Each pouch was topped up with distilled water to a total of 40 ml of liquid added to each pouch.

After 3 days, pouches were monitored for germination; shoot lengths were measured at the termination of the experiment (day 8). Once the experiment was terminated, three plants from each pouch were randomly selected and roots scanned with WinRHIZO software (Regent Instruments, 2000) to determine root lengths.

Pot-based experimentation

To assess initial plant vigour under similar biochar treatments, a six-week pot-based greenhouse experiment was conducted. Field soil (60 kg) was collected from a farm in the "Truro" soil class (NSTUO3~A), representing a sandy loam soil found in Nova Scotia. This soil was then air-dried for 2 weeks in a greenhouse before being sieved through a 2 mm screen. After being sieved, perlite was added to the soil at a ratio of 4 parts soil to 1 part perlite (by volume) to reduce compaction issues throughout the lifecycle of the experiment. Nursery pots (20 cm diameter) were used for this experiment with each containing roughly 1 kg of the perlite amended soil.

Experimental units were arranged in a Completely Randomized Design (CRD) with four replications. This experiment was a two-factor factorial design with 12 treatments (see

Table 3.3 for more information). Factor 1 was fertilizer application method - (1) biochar broadcast and incorporated into the pot soil; (2) biochar applied as a seed coating; (3) inorganic fertilizer (24-12-12) broadcast and incorporated into the pot soil; (4) no fertilizer application as control. Factor 2 comprised liquid fertilizer application: (1) liquid seaweed extract (LSE); (2) cow urine; (3) none as control. In instances where liquid fertilizers were combined with biochars, the biochar was first enriched with the liquid fertilizer. In other instances, liquids were applied at recommended rates: cow urine diluted 1:1 with distilled water and applied at a rate of 10 t ha^{-1}; LSE diluted at 15 ml LSE in 1 L distilled water and applied at a rate of 4 L ha^{-1}.

Table 3.3. List of treatments for the pot-based experiment

Factors	**Broadcast biochar**	**None**	**NPK (24-12-12)**	**Seed coated biochar**
None	Biochar applied at 5 t ha^{-1}	Control	24-12-12 applied at rate equivalent to 75 kg N ha^{-1}	Seeds coated with 50 mg of unenriched biochar each
Liquid seaweed	Seaweed enriched biochar applied at 5 t ha^{-1}	Liquid seaweed applied at 4 L ha^{-1}	Liquid seaweed applied at 4 L ha^{-1}; 24-12-12 applied at rate equivalent to 75 kg N ha^{-1}	Seeds coated with 50 mg of seaweed enriched biochar each
Cow urine	Cow urine enriched biochar applied at 5 t ha^{-1}	Cow urine applied at 10 t ha^{-1}	Liquid cow urine applied at 10 t ha^{-1}; 24-12-12 applied at rate equivalent to 75 kg N ha^{-1}	Seeds coated with 50 mg of cow urine enriched biochar each

Nursery pots (20 cm) were filled with soil then rehydrated to holding capacity before the dry fertilizer treatments were mixed into the surface of the soil. Eight wheat seeds were then added to each pot before liquid fertilizer treatments were applied. Pots were placed in a temperature-controlled greenhouse (21 °C) with supplemental lighting (600 W HPS) on April 3, 2024, and terminated on May 15, 2024. From day 4 of the experiment initiation, pots were monitored for germination. Total germination rates were calculated on day 10, at which time pots were thinned to four plants per pot for the remainder of the experiment.

During the remainder of the experiment, plant heights as well as relative chlorophyll content (Minolta SPAD-502Plus) were measured. At the end of the experiment, Zadoks growth stage of GS34, shoots were harvested at soil level and measured for biomass weights. The soil from pots was then removed and roots were isolated then washed before being weighed for biomass.

Field experiments

Two field experiments were conducted to investigate the effects of this locally produced biochar on the spring wheat cultivar (cv. Optimum). The two field sites were in different regions and soil types within Nova Scotia. Each site represents a key agricultural area of the province; the first was in Kings County (KC), on a typical sandy soil (Cornwallis, NSCNW2~A, 45°05'40.1"N 64°36'57.5"W); the second site was in Colchester County (CC), on a sandy loam (Woodville, NSWOV3~A, 45°22'20.8"N 63°15'17.1"W). Table 3.4 details the pre-plant soil conditions at both locations.

Table 3.4. Pre-plant soil characteristics for field sites Kings County (KC) and Colchester County (CC). Samples collected May 17, 2024.

Site	Soil texture	OM	pH	CEC	P_2O_5	K_2O	Ca	Mg	Na	S	Al	B	Cu	Fe	Mn	Zn
		%		meq 100 g^{-1}	kg ha^{-1}						mg kg^{-1}					
KC	sandy	2.7	6.1	7.4	243	265	4505	274	5	23	1438	<0.50	0.49	198	15	0.73
CC	sandy loam	3.3	6.4	10.3	1288	167	3072	190	10	19	1190	<0.50	1.13	174	58	3.06

OM, organic matter; CEC, cation exchange capacity.

Both field sites were prepared before planting with conventional tillage practices with phosphorous and potassium applied at 75 kg ha^{-1}. Nitrogen was applied the day before seeding as determined by treatment factors. Where inorganic nitrogen was used, urea was applied at 75 kg N ha^{-1} and incorporated. Weather summaries including the monthly rainfall, growing degree days (base 5 °C), and mean temperature are listed in Table 3.5.

Table 3.5. Weather statistics (2024) for field sites Kings County (KC) and Colchester County (CC) using Environment Canada weather station data for Kentville, NS and Truro, NS respectively

	Precipitation		GDD (base 5)		Mean temperature	
	KC	CC	KC	CC	KC	CC
	mm				°C	
May	29.8	46.7	227	200	12.3	11.4
June	78.9	124.0	375	336	17.5	16.2
July	201.8	172.2	506	463	21.3	19.9
Aug.	30.0	109.6	461	430	19.9	18.9
Sept.	80.3	67.6	326	279	15.9	14.3
Total	420.8	520.1	1895	1708	-	-

GDD, growing degree days.

The treatment design comprised two factors with factor 1 being biochar application method (broadcast 3 t ha^{-1}, seed coated, none); factor 2 comprised additional fertility (LDM, urea, none). Where treatments comprised of biochar LDM, the biochar had been previously enriched with the LDM. This totaled 9 separate treatments; treatments were replicated four times in a randomized block design with plot sizes of 6.25 m^2.

Table 3.6. List of treatments for the field-based experiment

Factors	**None**	**Broadcast (t ha^{-1})**	**Seed coating**
None	None (control)	Unenriched biochar applied at 3 t ha^{-1} and incorporated	Seeds coated with unenriched biochar
Liquid dairy manure (LDM)	LDM applied at 10 t ha^{-1} and incorporated	Biochar enriched with LDM applied at 3 t ha^{-1} and incorporated	Seeds coated with biochar enriched with LDM
Urea	Urea applied at 75 kg ha^{-1} and incorporated	Unenriched biochar applied at 3 t ha^{-1}; urea applied at 75 kg ha^{-1} both incorporated together	urea applied at 75 kg ha^{-1} and incorporated; seeds coated with unenriched biochar

The KC site was seeded on May 21, 2024, and the CC site was seeded on May 23, 2024. From day 4, sites were monitored daily for emergence until day 10. Stand counts (two 1 m rows per plot) for each site were measured on June 10 at KC and June 12 at CC. Plant heights and relative chlorophyll (Minolta SPAD 502Plus) measurements were taken on June 28 at KC and July 2 at CC; at this point in the season the crop was at the Zadok's growth stage of GS29. Plant heights were measured again at the Zadok's GS 70 stage in early August. The CC trial was harvested August 27, 2024, with a Zurn plot combine and the KC trial was harvested September 10, 2024. Harvest bags were dried using a forced-air dryer before cleaning, and grain moisture content was adjusted to 13% for yield reporting. Yield, thousand kernel weights (TKW), and test weight (TW, kg HL) were then collected for each plot. Soil tests were collected at early milk development (Zadok's GS 73).

Statistical Analysis

The collected data were analyzed for variance in Minitab V21, after the assumptions of normal distribution of residuals and constant variance were confirmed and met. A different type of test was used for each experiment depending on its specific requirements. The germination experiment used a one-way ANOVA; the pot-based experiment used a two-way ANOVA; the field experimentation used a mixed-effects ANOVA with experimental treatments as fixed effects and blocks as random effects. If statistical differences were found ($p < 0.05$), these were then assessed using Fisher's LSD test to evaluate treatment effects.

3.3 Results

Germination experiment

In addition to developing an understanding of the initial growth characteristics that these biochars and liquid amendments would elicit in the spring wheat, this experiment aimed to ensure that there were no inhibitory effects caused by the enrichment liquid or the biochars before further experimentation was carried out. The results showed significant changes to both shoot and root characteristics that were brought about by the different treatments (Table 3.7). The liquid dairy manure (LDM) and unenriched biochars significantly increased mean shoot length when compared to the control or enriched biochar treatments. Root lengths were significantly shorter for the LDM treatment in comparison to both the biochars and the control, which were not significantly different from one another. No significant difference in root area was observed. These results showed that both the enriched and unenriched biochars produced wheat of equal or greater initial growth characteristics than the control (they were not antagonistic in comparison to the control).

Table 3.7. Effects of enriched or unenriched biochar and liquid dairy manure on shoot lengths, root lengths, and root area for spring wheat, cv. Optimum. Analyzed using a one-way ANOVA with Fisher's LSD test for significance. √MSE = the square root of the mean squares error (MSE), which estimates the common standard deviation (σ).

	Shoot length (cm)	Root length (cm)	Root area (cm^2)
None	16.6 b	20.1 a	11.2
Enriched char	18.5 b	19.6 a	11.6
Nonenriched char	21.2 a	19.4 a	11.3
Liquid dairy manure	21.5 a	17.9 b	10.2
p value	<0.001	0.009	0.255
√MSE	5.51	2.01	20.3

Means that do not share a letter are significantly different from one another within each column.

Pot-based experiment

Shoot biomass was significantly altered by both biochar application methods as well as the NPK application, as can be seen in Table 3.8. The two biochar treatments, as well as the NPK treatment, increased shoot biomass weights by 1.7 to 1.9 times the control treatment. Root biomass was significantly altered by solid fertilizer treatments. Both biochar application methods, broadcast and tilled into the pot or applied as a seed coating, significantly increased root biomass over the 'none' or 'NPK' treatments. Similarly to the root biomass results, the shoot-to-root ratios were significantly different between solid fertilizer treatments. Both seed-coated biochar and the broadcast biochar resulted in a shoot-to-root ratio that was significantly lower than the NPK treatment. The none and NPK treatments had similarly high shoot-to-root ratios, following the general trend observed in the shoot and root results.

The number of tillers per plant was significantly affected by the liquid fertilizer treatment. The application of cow urine significantly increased tiller quantity per plant over the control. The liquid seaweed application was not significantly different from either the control or the cow urine treatments. Solid fertilizer did not meet the 0.05 significance threshold but was close to this threshold with a value of 0.058. Similarly to the LF treatments, the SF treatment with the greatest labile nitrogen (NPK) was trending towards significantly increasing the number of tillers over the other SF treatments.

Table 3.8. Effects of solid and liquid fertilizers in a pot-based experiment on spring wheat cv. Optimum's shoot, root and tiller development. Analyzed using a two-way ANOVA with Fisher's LSD test for significance. $MSE^{-0.5}$ = the square root of the mean squares error (MSE), which estimates the common standard deviation (σ).

	Shoot biomass (g per pot)	Root biomass (g per pot)	Shoot to root ratio	Tillers per plant (#)
Solid Fertilizer (SF)				
Broadcast biochar	64.0 a	26.3 a	0.41 b	3.2
None	34.4 b	20.0 b	0.58 a	2.8
NPK	59.4 a	18.5 b	0.59 a	4.3
Seed coated biochar	67.0 a	26.1 a	0.39 b	2.8
Liquid Fertilizer (LF)				
Cow urine	61.5	25.5	0.48	4.3 a
None	52.7	22.0	0.53	2.3 b
Seaweed	55.7	21.3	0.51	3.1 ab
SF * LF				
Broadcast char * Cow urine	70.7	25.2	0.36	3.7
Broadcast char * None	60.3	23.9	0.40	3.2
Broadcast char * Seaweed	62.9	22.6	0.36	3.0
None * Cow urine	69.9	22.9	0.33	3.3
None * None	39.5	20.5	0.52	3.2
None * Seaweed	54.71	24.6	0.45	3.3
NPK * Cow urine	57.6	21.6	0.38	3.2
NPK * None	66.34	18.5	0.28	3.5
NPK * Seaweed	63.5	20.1	0.32	3.3
Seed coated char * cow urine	69.9	22.6	0.32	3.0
Seed coated char * None	56.6	22.0	0.39	3.2
Seed coated char * seaweed	61.2	23.2	0.38	3.4
P values				
SF	**<0.001**	**0.001**	**0.009**	0.058
LF	0.167	0.062	0.493	**0.008**
SF * LF	0.121	0.062	0.264	0.856

MSE$^{-0.5}$	0.534	1.230	0.087	0.964

Means that do not share a letter are significantly different from one another.

Field experiment

Tables 3.9 and 3.10 display the results from these trials, showing plant characteristics as well as soil test results collected from both sites on September 5th, 2024. Plants at both sites reacted similarly to the treatments, showing similar significant differences to plant height and SPAD measurements; however, there were unique differences at each site as well.

Table 3.9 describes the plant characteristics at both sites. Both plant height and SPAD results showed significantly similar changes, with the NPK treatment having plants with the greatest heights as well as "greenest" leaves. Both metrics strongly correlate with plant vigour. The other significant difference in plant metrics for the CC site was TKW. The NPK treatment resulted in significantly lower TKW's than the none or LDM treatments. While not quite passing the significance threshold of 0.05, TW had a P-value of 0.063 at the CC site and showed a similar trend with NPK, test weights for the NPK treatments being lower than those of the LDM or none treatments. Both TKW and TW are correlated with the "quality" of the wheat kernels with lower values representing smaller kernels of lower quality (such as lower flour yield for a lower TW). While not passing the significance threshold, the interaction of factors in the yield metric was close to showing significance with a P-value of 0.077. The interaction of biochar seed coating and inorganic fertilizer (N-P-K) produced the highest yield across treatments.

Table 3.9. Field trial results for spring wheat cv. Optimum for field sites Kings County (KC) and Colchester County (CC). Analyzed using a Mixed-effects ANOVA with Fisher's LSD test for significance. √MSE = the square root of the mean squares error (MSE), which estimates the common standard deviation (σ). Means that do not share a letter are not significantly different at significant *p*-value of 0.05

	Stand count (#/m^2)	Plant height (cm)		SPAD		Yield (t/ha)		TKW (g)		TW (kg/hL)
	KC	KC	CC	KC	CC	KC	CC	CC	KC	CC
Fertility application method (FA)										
Broadcast	517	17.7	36.6	40.80	38.6	1.26	1.19	26.2	24.2	69.0
Seed coating	570	17.0	37.1	40.19	37.1	1.31	1.20	25.7	24.2	69.2
None	570	17.7	36.6	41.86	38.4	1.33	1.21	25.8	24.3	69.0
Fertility Substance (FS)										
NPK	549	19.0 a	38.4 a	44.91 a	40.6 a	1.30	1.21	24.6 b	24.3	68.3
LDM	560	16.9 b	36.8 ab	38.91 b	37.0 b	1.30	1.21	26.8 a	24.4	69.7
None	538	16.5 b	35.0 b	39.03 b	36.6 b	1.29	1.17	26.3 a	24.0	69.2
FA * FS										
None * NPK	614	19.1	40.0	46.69	41.4	1.13	1.30	25.8	24.3	68.4
Broadcast * NPK	484	19.1	38. 4	43.12	41.0	1.27	1.13	24.0	24.3	67.9
Seed coating * NPK	560	18.8	36.8	44.92	39.3	1.51	1.22	24.0	24.3	68.5
None * LDM	560	17.1	35.7	38.51	46.8	1.41	1.18	25.8	24.0	69.2
Broadcast * LDM	549	17.4	36.9	39.89	37.2	1.18	1.36	28.0	25.0	69.8
Seed coating * LDM	581	16.4	37.7	38.33	37.0	1.32	1.09	26.8	24.3	70.2
None * None	538	17.0	33.9	40.39	37.2	1.46	1.15	26.0	24.8	69.5
Broadcast * None	517	16.7	34.4	39.38	37.6	1.33	1.08	26.5	23.3	69.3
Seed coating * None	570	15.8	36.7	37.32	35.1	1.09	1.28	26.3	24.0	68.8
P values										
AM	0.127	0.144	0.832	0.126	0.306	0.783	0.982	0.789	0.943	0.956
FS	0.743	<0.001	0.005	<0.001	0.001	0.995	0.891	0.014	0.757	0.063
FA * FS	0.365	0.870	0.121	0.098	0.839	0.077	0.303	0.286	0.467	0.796
√MSE	6.22	1.49	2.75	3.63	3.05	0.49	0.31	1.39	1.99	1.49

Plant height was measured at Zadok's growth stage of GS29.
SPAD, soil plant analysis development, a device that measures relative chlorophyll content.
Means that do not share a letter are significantly different from one another.

Table 3.10 describes the soil characteristics for both sites. There were significant differences for the minerals potassium (K_2O), magnesium (Mg), and sulfur (S) at the CC site and significant differences to calcium (Ca) at the KC site. Sulfur levels in the soil were significantly higher with the NPK factor over the LDM or none factors. Both potassium and magnesium showed slight significant interactive effects. Biochar did not show any direct effects on its own; however, its interactive effects with the other treatments influenced the changes to soil cations.

The KC site showed significant differences for interaction and fertility substance (FS) for both pH and calcium (Ca). The biochar treatments (broadcast, seed coating) interacting with the none factor had the highest trending pH values out of all the interactions; however, the significantly lowest pH rating also included a biochar treatment (seed coating * LDM). In terms of Ca, there were significant interactive effects; however, these did not follow a clearly discernable pattern.

Table 3.10. Changes to soil characteristics at Zadok's 73 growth stage for the Kings County (KC) and Colchester County (CC) sites. Analyzed using a Mixed-effects ANOVA with Fisher's LSD test for significance. √MSE = the square root of the mean squares error (MSE), which estimates the common standard deviation (σ). Means that do not share a letter are not significantly different at significant p-value of 0.05.

	N (%)		pH		OM (%)		P_2O_5 (kg/ha)		K_2O (kg/ha)		Ca (kg/ha)		Mg (kg/ha)		S (kg/ha)	
	KC	CC	KC	CC	KC	CC	KC	CC	KC	CC	KC	CC	KC	CC	CC	KC
Fertility application method (FA)																
Broadcast	0.16	0.17	6.13	6.18	3.3	3.3	1388	1467	131	132	2993	3018	220	239	22	2
Seed coating	0.16	0.17	6.14	6.14	3.2	3.3	1392	1420	123	128	3029	2990	227	249	21	2[illegible]
None	0.16	0.17	6.21	6.18	3.3	3.3	1333	1330	126	127	3079	2955	227	246	21	21
Fertility Substance (FS)																
NPK	0.16	0.17	6.13 b	6.12	3.2	3.3	1373	1399	127	124	2934 b	2986	219	249	21.9 a	21
LDM	0.16	0.17	6.12 b	6.17	3.4	3.2	1424	1405	125	132	3023 ab	2977	227	242	21.0 b	21
None	0.16	0.17	6.23 a	6.21	3.3	3.2	1318	1413	128	130	3144 a	3001	230	242	21.1 b	22
FA * FS																
None * NPK	0.16	0.18	6.10 c-e	6.12	3.3	3.3	1383	1358	130	123 ab	2829 c	2968	217	251 ab	22	21
Broadcast * NPK	0.16	0.16	6.11 b-e	6.17	3.3	3.3	1371	1531	130	125 ab	2990 bc	3048	224	231 b	22	21
Seed coating * NPK	0.16	0.18	6.19 a-d	6.06	3.2	3.3	1363	1307	121	126 ab	2983 bc	2941	214	267 a	22	21
None * LDM	0.16	0.17	6.10 c-e	6.12	3.4	3.2	1338	1346	127	137 ab	3188 ab	3019	230	241 b	21	21
Broadcast * LDM	0.16	0.16	6.09 de	6.13	3.3	3.3	1466	1403	124	147 a	2984 bc	2930	218	249 ab	22	21
Seed coating * LDM	0.16	0.17	6.00 e	6.18	3.4	3.2	1466	1466	123	113 b	2898 c	2983	232	236 b	21	22
None * None	0.16	0.16	6.25 ab	6.20	3.3	3.2	1277	1286	121	122 ab	3220 a	2879	235	246 ab	20	21
Broadcast * None	0.16	0.17	6.20 a-d	6.25	3.4	3.3	1329	1466	138	122 ab	3006 a-c	3076	219	237 b	21	21
Seed coating * None	0.15	0.17	6.23 a-c	6.18	3.1	3.2	1348	1486	126	146 a	3207 ab	3047	234	243 b	22	22
P values																
AM	0.649	0.542	0.122	0.500	0.344	0.283	0.410	0.066	0.551	0.816	0.393	0.705	0.346	0.254	0.205	0.085
FS	0.896	0.150	0.025	0.085	0.325	0.531	0.126	0.967	0.860	0.537	0.012	0.950	0.124	0.342	0.024	0.085
FA * FS	0.813	0.298	0.018	0.441	0.718	0.837	0.732	0.203	0.729	0.049	0.031	0.533	0.275	0.047	0.143	0.183
√MSE	0.001	0.023	0.251	0.221	0.266	0.204	324	305	21.1	2405	450	390	12.6	20.1	1.21	1.14

3.4 Discussion

The three experiments described in this chapter aimed to develop an understanding of the spring wheat cultivar Optimum's reaction to enriched and unenriched biochar at three key stages: germination, vegetative growth, yield, and other agronomic and soil characteristics.

Germination experiment

The germination experiments were intended to both explore the positive effects that the treatments may have on the spring wheat seed, as well as ensure that there were no inhibitory effects of the treatments on the germinating seed. This experiment successfully met both of those objectives.

After the eight days of the experiment, both the unenriched biochar and LDM produced shoot lengths greater than the control (none) and the enriched biochar. These results suggest that within the first week of growth, enriched biochar was not as beneficial to growth as the unenriched biochar. In a similar experiment where various biochars were created and tested for wheat germination potential (Kataya et al., 2024), the authors found that the germination rate was enhanced by 'washing' the biochar prior to its use. They found that unwashed biochars may contain inhibitory elicitors. The combination of LDM and biochar may contain slight inhibitory compounds that slow initial growth. Unlike the previous research conducted by Kataya et al. (2024), this experiment had 100% germination across all treatments.

Root growth also slightly differed across treatments with the LDM treatment producing shorter roots than the other treatments. The control, enriched, and unenriched biochars all produced similar root lengths. Other authors have found root length-enhancing properties when biochar was used (Xiang et al., 2017). However, the increased root length (by 32%) was observed in mature plants rather than seedlings. The root analysis showed, in this study, that the only difference between treatments was the slight reduction in root lengths for the LDM treatment. This reduction in root lengths may be due to the high levels of labile nutrients available within the germination pouches of the LDM treatments, reducing plants' need to extend roots in scavenging for nutrients.

Pot-based experiment

The increase in root biomass caused by both biochar factors (broadcast, seed coated) represented a roughly 36% increase in root biomass over the none and NPK treatments. This increase in root biomass closely matches a meta-analysis on the effects of biochar application on root traits (Xiang et al., 2017). They cited an average observed root increase of 32% across several crops. The increase in root biomass was likely due to increases in root length as opposed to width or number, as was observed in the germination experiment. Other researchers (Olmo et al., 2016) have noted that biochar tends to increase the proliferation of long and fine root structures that are better equipped to increase the total area of the soil in the plant's rhizosphere (a narrow region of soil in the vicinity of plant roots), maximizing the plant's ability to uptake water and nutrients. This increase in exploratory fine and long root structures has been suggested by Olmo et al. (2016) as the reason for the increase in fertilizer use efficiency that biochar amendments have shown. Indeed, in the present study, minimal application rates such as those used when biochar is applied as seed coating proved to be as effective as the broadcast rates of 5 t ha^{-1} in promoting root proliferation and potentially enhanced nutrient acquisition.

Field trials

Both field sites had delayed planting dates of May 21 for the KC site and May 23 for the CC site. These delays reduced the potential GDD's that the plants experienced and the precipitation they received, negatively impacting crop growth and yield. This resulted in roughly 200 fewer GDDs than was possible from the 2024 season, with totals of 1735 GDD at the KC site and 1532 at the CC site.

Plants at both sites behaved similarly in response to the treatments, showing significant differences in plant height as well as relative chlorophyll content (SPAD). In both cases, the NPK treatment most increased plant height as well as chlorophyll content. LDM also significantly increased plant height but not relative chlorophyll content. These both correlate with plant vigour, suggesting that nutrient availability was greatest in the LDM and NPK treatment factors at the Zadoks GS 29 stage.

Interestingly there were no significant differences to yield across treatments at either site. The additional fertility provided by the treatments was expected to increase yields over the control; however, this was not the case. The KC site had severe cereal leaf beetle predation across all treatments and both trials had severe outbreaks of fusarium head blight (FHB) due to high precipitation in July (200 mm) combined with mean temperatures of roughly 25 °C for the month. Fungicides and insecticides were not used at either location, to maximize our ability to measure potential inhibitory or beneficial effects that any of the treatments would have on growth and yield of the crop. Other researchers (Chen et al., 2019) found that applications of biochar promoted the silicon content of wheat plants, which significantly reduced predation by herbivorous insects. Similarly, researchers have shown reduced prevalence and injury from pathogens such as FHB when biochar is applied (Arshad, 2024; Guo et al., 2024). In this trial, there were no significant differences between plots for either biotic or abiotic diseases. This may be due to the relatively low application rates (3 t/ha) of biochar used in this experiment compared to those the authors describe. Both Arshad (2024) and Guo et al. (2024) showed that biochar feedstock and application rate play critical roles in biochars potential stress and disease mitigating ability.

At both locations, soil characteristics were changed slightly by the treatments. At the CC site magnesium and potassium were significantly different. At the KC site calcium was significantly different. Magnesium, calcium, and potassium are all cations with which biochar has been shown to interact (Nkoh et al., 2021). Soil nitrogen testing did not differentiate between nitrate and ammonium. Ammonium is also a base cation that may have shown interactive effects. There were no changes to total soil inorganic nitrogen across treatments or sites; similarly, there were no changes to organic matter levels. This is also most likely due to the low application rates of biochar used in these field trials.

There were interactive soil pH changes to the research plots at the KC site. The combined effect of biochar’s cation exchange capacity and its high pH of 13 most likely promoted chemical changes in the soil profile, as other researchers have noted (Zhang et al., 2019).

The relatively low rates used in these field trials contributed only slightly to changes in soil pH.

There was a notable lack of soil and crop responses across treatments at both sites. This lack of response was due in part to several anomalous weather events that caused excessive precipitation at both sites, leaching nutrients out of the trial area as well as into neighboring plots. These events likely diminished the inherent differences between plots that the treatments may have elicited under normal conditions.

3.5 Conclusion

This chapter investigated the agronomic potential of the spring wheat cultivar Optimum to wood biochar enriched with liquid dairy manure or unenriched; and applied as a typical broadcast method or as a seed coating. Both enriched and unenriched biochars significantly affected plant growth and development. Both the germination experiment and pot experiment showed positive interactions with enriched and unenriched biochars applied as both a seed coating or broadcast and incorporated into pots. Because of delayed seeding and heavy disease pressures, these results did not follow through to the field experiment. The spring wheat cultivar did not show inhibitory growth or yield when grown in combination with the biochar, but in fact positive growth metrics for much of the experimentation.

Further field experimentation with a wider range of application rates may better allow Optimum's yield characteristics, when amended with biochar, to be understood. Importantly, this study demonstrates that when biochar was applied as a seed coating or broadcast, the wheat cultivar responded as well or better than NPK or control treatments in all three of the experiments. Further investigation to optimize the best rate and combination with other fertilizers or amendments is required.

Chapter 4: General Discussion and Conclusions

Atlantic Canadian soils are generally low in soil organic matter, acidic and prone to leaching of nutrients (such as nitrates, NO_3^-) during the non-growing season (November to April); in addition, there is a current trend of 0.5 t ha^{-1} of carbon loss from agricultural soils in the region every year (Burton, 2019). The challenges these soils face in terms of nutrient leaching, acidity, and carbon loss are all challenges that biochar has been shown to directly ameliorate.

This research project aimed to address these local challenges by investigating the potential incorporation of biochar into current cropping systems using a model crop, spring wheat, currently grown on over 44,000 acres across the Atlantic Canadian provinces of Nova Scotia, New Brunswick, and Prince Edward Island (Atlantic Grains Council, 2023).

Previous research has shown mainly positive but also contradictory results from the inclusion of biochar into agricultural cropping systems (Schmidt et al., 2021). There are few investigations of how biochar might be incorporated into Atlantic Canadian soils.

To investigate biochar's inclusion into current cropping systems, an overall objective of evaluating the effect of biochar with and without nutrient enrichment on the growth, development, and yield of wheat was developed, encapsulating three different biochar types as well as three enrichment liquids in combination with two spring wheat cultivars over six separate experiments. This wide-ranging scale and scope provided a thorough and promising set of initial insights into the ways in which enriched and unenriched biochars behave with Atlantic Canadian spring wheat cultivars. This research project points to exciting possibilities and lays the groundwork for future research. Further investigation is essential, as biochar is inherently variable with slight changes to feedstock or pyrolysis time and temperature significantly changing the final product.

Before experimentation with spring wheat was initiated, it was important to quantify biochars' ability to sequester and subsequently release nutrients. This was achieved through an enrichment process and then a subsequent soil column leaching experiment – both were detailed in Chapter 2. These experiments found that wood-based biochar was able to sequester significant quantities of inorganic nitrogen (6.16 mg NO_3^- L^{-1}, 323 mg NH_4^+ L^{-1}), substantially more than crab-based biochar. However, as other researchers have demonstrated, the actual quantity of inorganic nitrogen adsorbed may have been significantly more, as current standardized extraction techniques may only extract ~ 40% of the total nitrogen (Hagemann et al., 2017b).

Subsequent investigation into biochars' soil dynamics and nutrient release were undertaken in a soil column leaching experiment using field-dried unsterilized soils. The addition of either crab or wood-based biochar significantly reduced NO_3^- and NH_4^+ leaching in comparison to a urea amended soil and a control soil. This suggested that both biochars were able to significantly reduce soil leaching even when they had been previously enriched with inorganic nitrogen. This may suggest an immobilization of soil nutrients as the mild extractant (0.01 M $CaCl_2$) was only able to release minimal amounts of nitrogen from the soil. This immobilization, while important in reducing nitrogen loss and pollution, must not hinder plant growth or yield if this technology is to be incorporated into current cropping systems. Therefore, it is imperative to develop an understanding of the most efficient application rates and soil dynamics.

To investigate the direct effect that enriched and unenriched biochar had on spring wheat growth and development, three separate germination experiments were conducted, testing three different biochars as well as three separate enrichment liquids on two different spring wheat cultivars. These experiments quantified the optimum rate of biochar application; if there were benefits to combining different types of biochars (crab and wood); and if enriched and unenriched biochars improved initial growth over the control or each enrichment liquid on its own. Across these experiments, the enriched wood biochar significantly increased initial shoot growth with a positive relationship to rate of application. The crab biochar, however, had inhibitory effects as the rate of application was increased, significantly reducing shoot growth in comparison to a control. These results were in accordance with other studies (Kataya et al., 2024; Solaiman et al., 2012; Zhang et al., 2022): across a variety of crops, biochar often enhanced germination speed as well as initial shoot and root growth. However, at excessively high biochar application rates (> 50 t ha^{-1}) biochar would inhibit germination, growth, and yield.

Following germination experimentation, greenhouse pot-based experiments and field scale experiments were conducted to determine if the initial benefits to crop growth could be observed and tracked across the lifecycle of the spring wheat crop and its subsequent grain yield. After six weeks, the pot experiment was terminated with biochar amended soils producing wheat plants with significantly greater root biomass (36 %) than pots which received inorganic fertilizer (24-12-12 at 300 kg ha^{-1} equivalent rate). Shoot biomass weights were equal to the inorganic fertilizer treatment. This increase in root mass suggests that the biochar amended pots had wheat plants better prepared to handle stress and better able to uptake nutrients and water than the control or inorganic treatment.

The field experiments, due to heavy disease, herbivory pressure, and inhibitory weather conditions showed only slight differences between the biochar, inorganic fertilizer, and control treatments with no observed differences to yield across treatments. There were significant differences in crop vigour (plant heights and relative chlorophyll content at ZG 29), with the inorganic fertilizer treatments most positively affecting those metrics. However, these initial growth differences did not significantly influence yield. There were changes to the soil profile across treatments, with pH and the soil cations K_2O, Ca and Mg being influenced by the interactions of biochar and inorganic fertilizer. Biochar is most often negatively charged and so reacts strongly to positively charged cations (Munera-Echeverri et al., 2018).

These experiments, in combination with contemporary research, suggest that biochar could be an effective amendment in current wheat cropping systems and have widescale benefit to Atlantic Canada in terms of significant reductions in nitrogen leaching. While there were no quantifiable differences to yield in the field experiments, there were clear benefits to plant growth and vigour in the other experiments. Other researchers have suggested that enriched biochars are most effective as a soil amendment after three years (Chia et al., 2014) and have an estimated half-life of 104 years in clayey soils. If indeed biochars effectiveness were to increase in the three years following application and contribute positively to the soil for many years; even a slight increase to yield would have significant economic and environmental benefits.

A minimally researched, but exciting prospect was the possibility of applying enriched biochar as a seed coating instead of the conventional broadcast/incorporation methods currently used. In the greenhouse pot experiment, this technology provided plants of comparable vigour to the broadcast application rate (5 t ha^{-1}) at a far lower rate (roughly 700 kg ha^{-1} depending on seeding rate). The application of biochar through a seeder when the crop is sown would eliminate multiple field passes by the producer and require less equipment use, thus reducing input costs as well as pollution.

A controlled greenhouse based experiment where wheat plants are grown directly in soil columns could directly compare the different effects that enrichment, seed coating, and broadcasting of biochar have on wheat plant and soil composition. This approach is recommended for future study, with Chard & Bugbee (2005) providing an example of how such a column could be constructed and used.

The experiments in this thesis provide an excellent resource for further study and experimentation that can be used to most optimize the incorporation of biochar into Atlantic Canadian soils. Suggested further areas of research would include enhanced enrichment techniques to ‘charge’ the biochars with higher quantities of nutrients, further investigation into seed coating technologies, as well as further field-scale experimentation to develop multiple site years of data.

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