Biochar Production, Applications, and Waste Management for Enhancing Sustainability Benefits across Food-Energy-Water Systems

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Authorization to Submit Thesis

This thesis of Benjamin D. Hersh, submitted for the degree of Master of Science with a Major in Mechanical Engineering and titled "Biochar Production, Applications, and Waste Management for Enhancing Sustainability Benefits across Food-Energy-Water Systems" has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

The future of food-energy-water resources is an ever-increasing global concern due to a growing standard of living and population. Particularly, a global increase in demands for food requires substantial land, energy, and water resources to address the future need and mitigate negative environmental impacts. Reusing or recycling resources is one of the promising approaches to reduce the negative impacts of the food system on the agro-ecosystem. A comprehensive literature review of food-energy-water (FEW) nexus and the applications and advantages of pyrolysis-char (biochar) to FEW-related issues is conducted in this study, including narrative and systematic reviews. Biochar production from biomass feedstocks can be accomplished in different ways and is beneficial for organic and sustainable soil amendment and several other FEW-related applications. This study proposes a mixed, portable fast and slow pyrolysis conversion pathway to facilitate biochar production process near the feedlot or drylot areas and address major challenges in the biochar industry infrastructure. According to the International Biochar Initiative classification approach and obtained results from physiochemical properties analysis, biochar produced in this study characterized as a Class 1 fertilizer due to its properties. Additionally, a gate-to-gate life-cycle assessment is provided to evaluate energy consumption, heat loss, and environmental emissions across biomass-to-biochar conversion processes and systems. These analyses are essential in understanding the process intricacies and determining optimization opportunities for future work. It is concluded that the proposed approach in this study is capable of reducing the handling, transportation, and storage costs by producing and transferring high-quality biochar instead of transferring low-energy density biomass feedstocks.

Acknowledgements

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Dedication

This thesis is dedicated to my parents and Hannah, who continuously supported me and pushed me along in this journey.

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Statement of Contribution

Chapter 2 of this thesis was coauthored by Amin Mirkouei, John Sessions, Behnaz Rezaie, and Yaqi You. The review of literature was completed by me Benjamin Hersh with constructive collaboration from each of the co-authors in their respective areas of study. The determination of relevant material was accomplished with the assistance of Amin Mirkouei. The original draft was prepared by myself Benjamin Hersh, and initially edited by Amin Mirkouei, further review and editing was completed as a joint effort between Amin Mirkouei, John Sessions, Behnaz Rezaie, and Yaqi You. Funding for the completion of the project was acquired by Amin Mirkouei through the IDeaL research group, as well as the Idaho State University Developing Collaborative Partnerships Grant.

Chapter 1: Introduction

1.1 Research Challenges and Motivation

Access to food, clean drinking water, and energy is the basis of modern society, and the research at the nexus of food-energy-water (FEW) attempts to both identify and quantify the national and global needs and to address resource and development challenges. The challenges facing FEW are preserving the synergies and limiting the trade-offs in the nexus of the three branches. As society progresses and the population steadily grows, the strain on FEWS has stimulated research efforts to find FEW beneficial products that can address current FEW needs without compromising the future generation's ability to meet their needs.

Prior studies reported the significant effects of biomass-based char (biochar) to address the food-energy-water systems (FEWS) challenges, as well as mitigate greenhouse gas (GHG) emissions and the environmental impacts. Biochar production from agricultural wastes and leftovers, forest harvest residues, and animal manure, using thermochemical technologies (e.g., pyrolysis or gasification), is a sustainable approach for waste management. However, biomass collection, transportation, and conversion operations have been identified as major cost drivers to produce market-responsive biochar. Therefore, biomass pretreatment and conversion process at collection sites can address the upstream and midstream challenges and stimulate biochar industry. In addition, standard procedures, metrics, and instruments for biochar characterization and quality classification have not been developed yet.

The motivation behind this thesis lies in developing a sustainable production process for the purpose of creating FEW beneficial bioproducts, and provide a framework for the production, characterization, and analysis of biochar. This will be accomplished by discussing prior research of the existing interlinkages of FEW nexus, as well as the benefits of biochar-derived products to meet sustainability goals across FEWS. The application to a real-world system will be accomplished through the analysis of our small-scale portable refinery unit, and how improvements in the production process can positively affect the applications and sustainability of biochar.

1.2 Research Objectives and Tasks

This thesis focuses on the pyrolysis system located at the Center for Advanced Energy Studies in Idaho Falls, Idaho, USA. The pyrolysis system is a thermochemical biomass conversion system that creates primarily bio-oil and biochar. The main objective of this reactor is to create a novel production process that can create a cost effect and sustainable product. This thesis focuses on the optimization of the process for biochar production, and the analysis of the biochar produced to show the potential FEW nexus benefits of biochar production.

To accomplish the primary objectives, five research tasks have been pursued in this thesis, which are as follows:

1. Review prior studies and determine the FEW challenges, as well as benefits of the production and application of biochar.
2. Develop and optimize the biochar production process with the assistance of a programmable automation controller and other new inventions.
3. Analyze the production data, and process yield and biochar quality obtained from the process.
4. Develop life cycle assessment models of the conversion process and biomass-to-biochar system based on the input and output data.
5. Provide recommendations for improvement of the biochar production process, and future applications of the biochar product.

Reviewing prior research provides a framework for decision making in the handling of FEW nexus. By comparing existing FEWS methodologies, along with exploring the potential impacts of biochar-derived products to FEWS, the benefits of biochar-derived products to FEWS is identified and discussed. The systematic review was conducted, using both quantitative and qualitative methods for studies, with the purpose of determining the flow of research and the research communities contributing most to the field.

The experimental data was obtained through the production of biochar, bio-oil, and syngas from pine wood sawdust, using the updated CFP and SP reactors. Then the analysis of biochar yield was performed by a mass to mass comparison, and the quality analysis was performed based on data from laboratory results. The results of the experimental data and analysis are used to determine the effectiveness of the system changes.

The development of life cycle inventory (LCI) of this analysis included the data collection from the literature to estimate and approximate emission of our system. The data collected and approximated is used to develop a product system in OpenLCA software in order to perform a life cycle impact assessment (LCIA) of the product system. Additionally, an evaluation of energy used through the heat loss to the environment is calculated to determine the opportunities for energy optimization.

1.3 Research Scope

Recent interest in FEWS has stimulated research efforts to address current and future environmental challenges and FEW shortage crises in the United States (U.S.) and world. The modernization of FEWS will provide enhancements, such as promoting FEW security, climate change solutions, and the livelihood of affected communities. Also, there is a need for research into the development of potential products that do not strain any of the FEW branches.

With the current research into the benefits of unblended and blended biochar-based products, it is evident that biochar could be a viable product to ease pressure on the FEWS. Biochar is the solid byproduct obtained through the carbonization or thermal decomposition of biomass feedstocks. This thermal decomposition can be accomplished through various conversion processes, such as pyrolysis, gasification, and hydrothermal carbonization. The sustainability and life-cycle assessment of a unique conversion process has been conducted to understand biochar-based product effect as a soil amendment across FEWS, particularly organic farming.

The developed and empirically verified small-scale pyrolysis process in this study can reduce the environmental and economic impacts of biochar production. Biochar quality and yield of each process are dependent on various parameters, such as feedstock type, temperature, pressure, and exposure time of biomass to the heating source. Further research is necessary for developing a holistic approach for the biochar characterization for its application to FEWS and analysis of biochar sustainability.

The scope of this research is to study the biomass pyrolysis process in the laboratory environment and offer an investigation into the optimization and sustainability of biochar-based products. To accomplish this, a mass-to-mass analysis is conducted and compared to energetic input into the pyrolysis system, and the calculated heat loss and emissions of the production process. The goal is to show the sustainability and benefits of biochar to the FEW nexus, and assist future research in bioenergy applications.

1.4 Thesis Outline

This thesis is reported in manuscript format and comprises five chapters and an appendix. Chapter 1 provides the research challenges, motivation, and scope, as well as research objective and tasks.

Chapter 2 focuses on reviewing the current state of research into the FEW nexus, the applications and advantages of biochar, and the benefits of biochar products to the FEW nexus. This is accomplished through both narrative and systematic reviews. This Chapter is an article submitted to the *Journal of Cleaner Production* and titled “A review and discussion on biochar-related prospects for enhancing sustainability benefits across food-energy-water systems.”

Chapter 3 focuses on biochar production and characterization. The advantages of biochar production processes, using a unique conversion process are explored to determine how to produce high-quality biochar. The goal of this paper is to show the effects of the addition of a programmable-logic-controller, several separate heating units, and a slow pyrolysis (SP) bed reactor. The effects of the additions are analyzed by the characterization and analysis of the byproduct produced using the standards set forth by the International Biochar Initiative and the European Biochar Certificate.

Chapter 4 centers on sustainability assessment (gate-to-gate LCA) of the built in-house conversion pathway for biomass-based biochar production. A real case study is conducted to collect the experimental data for the input and output analysis, such as material, energy, and emission flows. This Chapter is an article submitted to ASME-IDETC and Computers and Information in Engineering Conference and titled “Life cycle assessment of pyrolysis-derived biochar from organic wastes and advanced feedstocks.”

Chapter 5 provides a summary of the results, contributions, conclusions, and recommendations for addressing research questions discussed in this research. The goal of these recommendations is to provide insight on possible ways to enhance sustainability benefits across biomass-to-biochar life cycle by improving production processes and reducing the emissions and losses. The future work discusses subjects and pitfalls found during this research, each subject discussed in this thesis showed potential in additional research, and expanded upon ideas previously discussed in this study.

In addition, Appendix A is a Studio 5000 manual developed to describe how the coding was accomplished for the pyrolysis system. This manual includes the following:

- Establish a connection to the controller
- Add modules
- Develop ladder logic
- Develop scaled values
- Designate controller tags
- Develop a human-machine interface (HMI)

The purpose behind this manual is to leave the university with a guide to the thought and work behind the programmable automation programming, as well as help future students with ladder logic development. This manual is complete with examples from the working project, and describes the thinking behind the ladder logic and control of each of the system aspects.

Chapter 2: A review and discussion on biochar-related prospects form enhancing sustainability benefits across food-energy-water systems

Benjamin Hersh[1], Amin Mirkouei[1, 2,]*, John Sessions[3], Behnaz Rezaie[1], and Yaqi You[4]

2.1 Abstract

The future of food-energy-water resources is an ever-increasing global concern due to a growing standard of living and population. This study presents opportunities for sustainable growth based on the previous research and developments across food-energy-water systems through biomass-based products (bioproducts), such as biochar, an emerging by-product of biofuel production. Bioproducts are in a nascent phase, but are growing steadily with improvements in production technologies and other cost-reducing strategies. Perspectives on solutions and opportunities that can promote the socio-economic resilience and ecological integrity of regional food-energy-water resources are identified through narrative and systematic literature reviews. These solutions are examined within the context of the environmental and economic parameters that influence stakeholders' decisions with respect to the adoption and use of technological solutions. Biochar has shown to be one of these products with the ability to improve productivity, particularly, in organic farming through increased water-nutrient holding capacity, organic-matter efficiency, and carbon sequestration. Additionally, biochar sorption abilities and textual features have shown to be a special solution for removing a large range of contaminants (e.g., metals and toluene) from water. However, biomass collection, transportation, and conversion costs have been identified as major challenges to produce market-responsive bioproducts. It is concluded that the recent interest in food-energy-water systems has led to research opportunity in bioproducts that can, in turn, bridge the gaps and provide ground-breaking developments for future research and growth. It is also concluded that biomass pretreatment and conversion process at collection sites can address the upstream and midstream challenges and stimulate bioproducts industry.

2.2 Keywords

Biomass; Bioproducts; Biochar; Food-Energy-Water Systems; Sustainability.

2.3 Introduction

The necessity for food, clean drinking water, and energy is the basis of the research at the nexus of Food-Energy-Water (FEW) [2,3]. As society progresses and the population steadily grows [3], there will continue to be strain on FEW systems (FEWS) [4]. The challenges facing the FEWS are that of limiting the pressure on a branch of the nexus when working to improve the other branches [2,5]. The all-encompassing qualities of FEWS solutions are what differentiate it from other renewable solutions, in which there is a resource that ails from the process [2]. For example, the production of ethanol from biomass (e.g., corn or sugarcane) reduces the necessity for crude oil-derived transportation fuels (e.g., gasoline and diesel), however, the production of ethanol places tremendous strain on land use, agricultural markets, and water use [6]. The question then arises as to what should be done to mitigate the trade-offs and what should be used for the mutual benefit of the FEWS [7]. Conducted studies reported the significant effects of bioproducts (e.g., biochar and bio-oil) and their applications on the FEWS [8], as well as the existing challenges of biomass to value-added products supply chains [9].

Biochar from biomass feedstocks has been shown to improve crop productivity, mitigate carbon emissions, contribute to the filtration of wastewater, and subsequently benefit FEWS [1,8]. The challenge of creating a sustainable biochar system is limiting the environmental footprint, catering to the needs of the market [10], and being able to produce at large enough scale to make the production cost-efficient [11]. Evaluation of biochar production is impeded by restricted access to proprietary data, inadequate real-time heterogeneous and high-volume data extraction [12]. This can be linked to the lack of standardized post-processing techniques that enable sharing information among stakeholders and identify why an operation failed or why productivity was lost through data analytics, diagnostic and prognostic assessment, and adaptive predictive models [12]. Prior studies reported that technology breakthroughs (e.g., wireless sensors and intelligent logic controllers) and data-influenced decision making are key solutions to addressing biomass to bioproducts supply chain challenges (e.g., resilience, efficiency, and productivity) at multiple spatiotemporal scales [12,13].

Recent interest in FEWS has stimulated research efforts to address current and future environmental challenges and FEW shortage crises in the United States (U.S.) and world [5]. Modernizing FEWS will enhance sustainability benefits, such as promoting FEW security, climate change solutions, and the livelihood of affected communities [14,15]. Also, there is a critical need for further databases and information to develop an adaptive decision support tool and potential products (e.g., unblended and blended biochar-based products) that do not strain any of the FEW branches. With the current research into the benefits of unblended and blended biochar-based products, it is evident that biochar could be a viable product to ease pressure on the FEWS [8].

The global biochar market is expected to reach $3.14 billion by 2025 [16], largely due to increasing consumption of organic food and increased awareness regarding the overall advantages of biochar across the FEWS [17–19], as well as carbon materials, wood polymer composites, nanomaterials, and as a reducing agent in steel production [20–23]. Delaney (2015) reported that biochar applications have significant economic and environmental impacts in the Pacific Northwest region due to the established agribusiness industry, such as crops production (e.g., potato, wheat, and barely) and food processing (e.g., milk, chess, and yogurt). The national biochar market potential is estimated at approximately $5.2 billion dollars annually within agriculture ($2.6 billion), including horticulture ($1.1 billion), environmental remediation ($800 million), potting mixes and soil conditioners ($66 million), compost ($60 million), and storm water management ($510 million) sectors [24–26].

Current studies in the renewable and sustainable energy field have shown that there is a clear interlinking between the FEW branches [27]. The focus of the research into the FEWS has turned to the synergies and trade-offs in the nexus of the three branches. The study being conducted on the FEW nexus has led to many different viewpoints on how to address the challenge of improving each branch without adding strain on the other two branches [5,14]. The connection between biochar and the FEW nexus are quite clearly drawn when analyzing the biomass-to-biochar supply chains. Biochar, sometimes referred to as black carbon, is a solid by-product of the thermochemical conversion processes (e.g., pyrolysis and gasification) of biomass feedstocks, such as forest harvest residues, invasive plant species, and animal manure [28]. Its properties are similar to traditional charcoal, produced from organic products [29]. However, biochar from biomass has the higher water-nutrient holding capacity, organic-matter efficiency, and carbon sequestration capability, which leads to addressing sustainability concerns, such as mitigating greenhouse gas (GHG) emissions, water use and reuse, energy use, and land use [1,29].

Unblended biochar products and biochar blended with other materials (e.g., nutrients) have widespread applications across FEW sectors, as a soil conditioner and additive in organic fertilizers [28], for water filtration and adsorption of contaminants in soil and water [30,31], in livestock farming and animal feeds [32,33], as a food additive and a pharmaceutical [34], as a fuel for electricity generation, heating, and cooking [1,35], among others. The uses of biochar as an additive to fertilizers show the ability to significantly benefit both food and water resources [36]. It benefits food by aiding in the growth of the plants and providing macronutrients, such as nitrogen, phosphorus, and potassium [9,37]. Biochar-based soil amendment, also known as an organic soil conditioner, lead to reducing fertigation (i.e., injection of fertilizers into the irrigation systems) and enhancing soil quality and crop health growth and yields [36,38]. Additionally, biochar application in water filtration systems, much more effective than charcoal [39], leads to entrapping unwanted contaminants in the water due to the porous nature of biochar [1]. The necessity for clean water is quintessential in the future of the population and standard of living [40].

Apart from the stated benefits, the existing biochar production process has not been implemented commercially in comparison to artificial, non-organic products with similar applications, such as conventional fertilizers or water filters [41]. A cost-competitive biochar production process is what the market needs to fully adopt this product [36]. Market-responsive biochar has application in various industries, such as soil, food, chemicals, and energy [42]. Based on prior biochar techno-economic studies, the first and second major cost-drivers are the direct production process (over 50% of total cost) and biomass feedstock collection and transportation (over 30% of total cost), respectively [43]. In the U.S. Northwest region, feedstock suppliers are from timber companies (e.g., Weyerhaeuser, Georgia-Pacific, and West Fraser supply wood residues) with forest-based products, and from dairy companies (e.g., Magic Valley Dairies in Idaho) with livestock products. Delaney (2015) reported that biochar market value was approximately $400,000 annually in this region, and the biochar prices ranged from $90 to $600 per cubic yard.

Among thermochemical production processes, pyrolysis technology is expected to witness rapid growth due to higher yield processes and high-quality products in terms of carbon content and stability [16]. Pyrolysis process is one of the most efficient ways of producing high-quality biochar and bio-oil from biomass; particularly, slow pyrolysis is reported as a cost-effective conversion process for biochar production due to high operation yield and end product quality [44]. The competing gasification technology has witnessed increased demand due to the growing need for electricity in distributed energy systems [45]. However, gasification is expected to lose its share over the forecast period, as it does not produce biochar that is stable enough to be used in agriculture for soil amendment and enhancement purposes [45].

2.4 Review Methodology

As the focus on the intersection of FEWS is relatively new, a literature review of prior studies will assist in the compilation of persuasive data and information to form a better understanding of the existing linkages and to maximizing effective management of FEWS. The methodology applied in the presented study consists of both narrative and systematic review techniques to explore the state-of-the-science and the possible solutions and products that have the capability to improve FEWS, as well as to identify prospective directions for enhancing sustainability benefits across FEWS. The narrative review was conducted by comparing existing FEWS methodologies, along with exploring the potential impacts of biochar-derived products to FEWS. The systematic review was conducted using both quantitative and qualitative methods on studies published from January 1, 2008 to January 1, 2019.

2.4.1 Narrative Review Method

The narrative literature review method (1) identifies the key concepts and advancements of research in FEWS, exploring the purpose of current FEW studies, defining the challenges facing FEWS as reported in existing articles, and discussing the possible solutions to overcome these challenges, and (2) identifies the evolution of research on the biochar and its application in various sectors (e.g., energy and agriculture) with a focus on sustainability aspects, i.e., economic, environmental, and social. The existing linkages in the effective management of FEWS are identified through key concepts and major contributions discussed in the current literature. Several studies discuss that the advancement of FEWS will be critical in the future of sustainable living as each branch of FEW nexus is co-dependent and necessary to sustain current standards of living.

2.4.2 Systematic Review Method (presented in the Supplementary Materials section)

Systematic literature reviews are key to efficiently keep scholars up-to-date on current research and development [46]. A systematic review (SR) utilizes a series of strategies, evaluations, and analyses to classifying previous studies based on their key attributes [47,48]. One of SR benefits is the reduction of author bias in the analysis of literature compared to a narrative review, which avoids picking information and examples from the narrative review to support the author’s point of view [47]. The SR conducted herein includes qualitative and quantitative methods to provide a classification for available studies from leading journals and scholars. The quantitative method analyzes recently published studies, citation data, and keywords. The qualitative method comprehensively characterizes current literature to classify the research methodologies of the most-cited publications. Traditionally, qualitative literature reviews are classified into two main categories (i.e., analytical and empirical) and several subcategories, which have been identified in recent studies [47].

2.5 Narrative Literature Review

2.5.1 Key Concepts in Food-Energy-Water Systems

The FEWS acronym and definition is presented in different ways across the literature. Some reports rearrange the acronym to be WEF, which easily gets confusing, for example when presented at the World Economic Forum (WEF) in 2011 [49]. This forum presents the nexus as Water-Energy-Food-Climate in other studies, and Agriculture and Land are also interchanged with Food. When analyzing the literature of FEW research, it is first important to examine the nexus thinking [50]. The nexus definition could vary greatly based on the supply, demand, and resources of the area of interest; for example, natural water resources can be used in the generation of hydroelectric energy or irrigation of the land to produce different crops, such as potato or wheat [50]. The utilization of these resources is dependent on the short-, middle-, and long-term goals of the decision makers. A fundamental understanding of FEW nexus is useful in addressing the complex, interdisciplinary nature of existing challenges in this field and stimulate interactions to meet often-conflicting objectives [51].

The connection between three branches is the key to FEW nexus (Figure 2.1). The understanding of the interlinkages in FEWS is critical in decision making processes as it relates to managing stressors on each branch [7]. The primary goals of FEW focused research are maximizing mutually beneficial outcomes, as well as reducing system-level costs [43], environmental impacts, and risks through improved process-/system-level efficiency and productivity. The analysis of the interlinkages provides a blueprint on how to approach environmental needs and maintain competitiveness in the marketplace [52]. Additionally, the analysis of FEWS is much like a life cycle assessment, in which the facilitation of complex decision making in terms of socio-environmental responsibility and techno-economic aspects is assessed with an emphasis on the connection of all three branches [8].

Earlier FEWS efforts focused mostly on the acknowledgment of FEW nexus and the need for new strategies and decision support systems that show potentials to address existing limitations and challenges [53]. FEW nexus thinking was conceived by the World Economic Forum in 2011, which led to an unprecedented discussion on the future of water security and a call to action on water

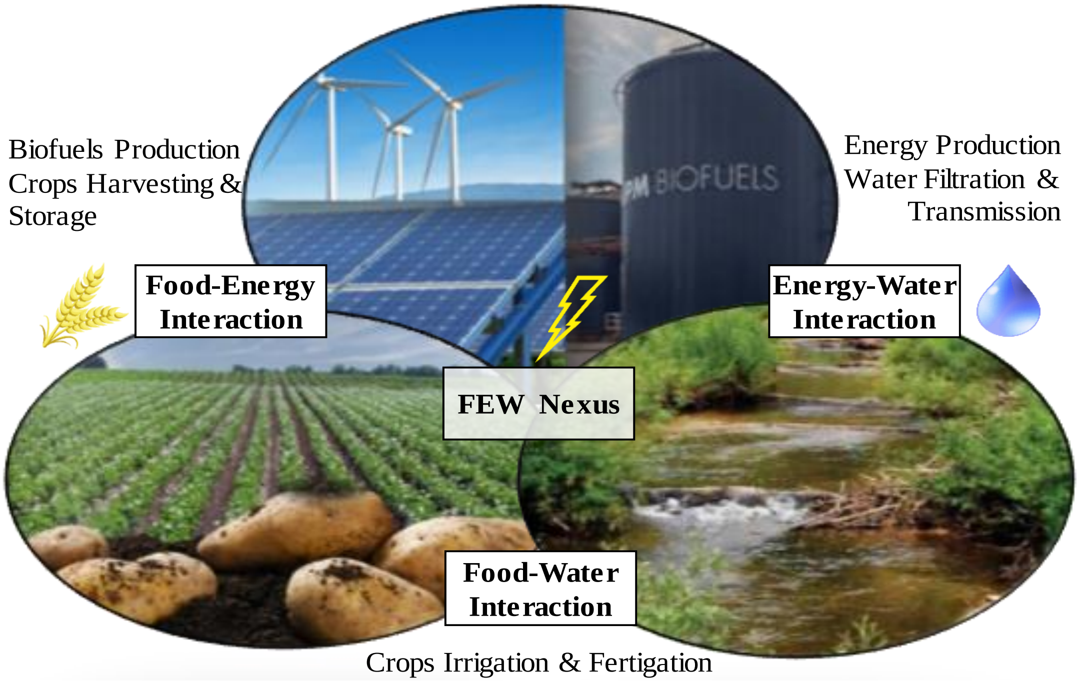

Figure 2.1 FEW nexus and key attributes (biorefinery image courtesy of UPM Lappeenranta, Finland)

awareness [14,49]. Population growth was established as the main concern facing the nexus, as well as the role climate change plays in contributing to the difficulties facing FEW nexus.

Recent studies centered on integrating the existing methods to develop a holistic approach and address FEW issues as a whole [54]. Al-Saidi and Elagib (2017) reported that there is currently no uniform scientific approach or policy to overcome FEWS barriers. They reviewed the integration of the smaller connections (i.e., food-water, food-energy, and water-energy systems) to guide decision makers (e.g., researchers, managers, and policy makers) to meet the global needs instead of reviewing FEWS as a whole.

Food-Water Systems. The growth of the human population is expected to increase the food demand globally by 60% by 2050 [6], which is coupled with the loss of available farmlands (due to urbanization) and the shortage of available water resources (due to projected climate change and water contamination). Without the addition of organic and non-organic fertilizers, the current agricultural production cannot sustain the needs of humanity [36]. Food and crop production levels are dependent on water availability [56]. The agricultural sector accounts for approximately 71% of global water withdrawals and consumes approximately 6.6% of the renewable water resources available, generated through hydrological cycles that flow into lakes, rivers, and streams [4,57].

A couple of major concerns in food-water systems that have to be monitored and managed to minimize health risk and degradation of water resources are:

- the use of wastewater for irrigation purposes in the areas without freshwater resources [57,58],
- erosion of land resources and runoff from the inefficient irrigation and fertigation of agricultural lands [59],
- eutrophication and water pollutants due to the oversupply of nutrients (e.g., nitrates and phosphates), synthetic fertilizers, and pesticides [60], and
- salt level of soils and salinization of water resources that, in turn, inhibits water uptake by plants [58].

Thus, the evaluation of surface and groundwater used in irrigation/fertigation is critical to managing global water consumptions and food supply. Traditional irrigation practices are no longer effective and viable to address challenges arising from water scarcity and consumption, as well as contamination. In addition, new water district restrictions, policies, and jurisdictions across several U.S. states (e.g., Idaho, California, and Texas) play an important role in the nation's agricultural vulnerability and crop productivity as 80% of global agriculture is rain-fed [56,61]. These restrictions increase the production risks in rain-fed cropping systems when the precipitation is unpredictable, especially in semi-arid zones [62].

Irrigation technologies (e.g., drip and sprinkler systems) and management strategies stabilize water supplies for crop production and agriculture-driven economy through promoting irrigation efficiency and ‘crop per drop’ measurements, using adaptive conservation operations [63,64]. Deficit irrigation (DI) is one of the promising irrigation management strategies that utilizes collected data about water stored in the soil, evaporate losses, crop water use dynamics, and precipitation throughout the growing season [63,65]. DI determines the effects of the mentioned parameters on crop productivity and quality. On-farm irrigation technologies poorly evaluate crop water demand to match the supplies and incorporate conservation measures into practice in real time [61]. Ultimately, monitoring of soil moisture content provides useful insights into agriculture infrastructures (e.g., water distribution and management) for determining sustainable, optimal irrigation strategies to meet national priorities and food-water security.

Food-Energy Systems. Crops and food production has a profound effect on the energy branch of FEWS as currently agriculture accounts for nearly 30% of global energy consumption and accounts for 20% of GHG emissions [6]. The majority of the energy needed in the food sector comes from the processing, distribution, preparation, and cooking [27]. In the U.S., the food industry is the fifth largest energy consumer in the manufacturing sector [66]. The food sector relies heavily on fossil fuels and volatility in the market has adverse effects on food prices; this dependence leaves the food sector very vulnerable to fluctuation and makes sustainable development more difficult [67].

Over the past 50 years, the need to advance food-energy systems to make them more reliable, efficient, and productive has been fueled by the rapidly growing population (expected to reach nine billion by 2050) and the expectation of doubling the global food demands in the next 30 years across the world [68,69]. Precision agriculture and other advanced production practices play a key role in food-energy security. The utilization of cyber-physical initiatives for big data analytics allows for better irrigation/fertigation, as well as forecasting crop yield under a wide variety of conditions [70].

Alternative and renewable energy sources arise in the industrial sector to overcome major challenges (e.g., energy security and environmental emissions) regarding high energy consumption and energy footprint [71–73]. One of the main attributes of food-energy nexus is bioenergy production from agricultural leftovers and residues (e.g., corn stover, wheat straw, and diseased crops) by using uncultivated lands [74]. Bioenergy production from food resources (also known as first-generation biofuels) puts pressure on food industry and increases food demand and price, which is one of socio-economic concerns of food-energy nexus [6,75]. Additional to the stated shortcomings, energy production from water resources via thermal power and hydropower generation places a burden on fisheries and freshwater resources [27].

Water-Energy Systems. Water and energy are critical resources in economic growth and have a unique interdependence on each other [76,77]. The water-energy nexus is quantified by either kilowatt-hour consumed per cubic meter of water supplied, or alternatively, by the cubic meters of water used per kilowatt hour produced [78]. The links that are drawn to the usage of these respective quantities are mostly broken down into production and transportation. A few examples of the production of water and electricity resources include water collection, water use for electricity generation, water use for bioenergy production, and electricity use for wastewater treatment and water desalination, purification and transmission/distribution [79]. Transportation of water resources includes pumping or other forms used for groundwater extraction, surface water transfers, retail distribution, and wastewater collection [79]. The energy-water nexus can also be broken down into multiple scales, for example, end-users and individuals (small scale) who consume large amounts of energy in the heating of water, and large amounts of water in the cooling of their households; or water and energy supplies for an entire country (large scale) for various purposes, such as food processing and crops production, as well as waste and wastewater treatment [78].

Most electricity production requires water in different phases, steam for electricity generation in nuclear and thermoelectric, or liquid for hydroelectric [77,80]. Energy production consumes (without the ability to reuse) approximately 66 billion cubic meters of fresh water each year and requires 580 billion cubic meters of water across energy production methods globally [27]. In the U.S., energy accounted for 27% of water consumption in 2010 [80] and rose to 37% by 2014 [81]. Each energy production technology has unique water consumption needs. Thermoelectric power plant cooling is responsible for around 4% of all U.S. water consumption with nuclear energy being the highest consumer [80]. Thermoelectric water consumption will likely increase due to the introduction of closed-loop steam turbines and increased nuclear power generation [80]. Biofuel produced from corn ethanol is one of the most water-intensive energy sources due to the amount of water needed to irrigate corn fields, particularly in the low-precipitation areas [82]. Water usage in fossil fuel energy production is dependent on the fossil fuel source, with coal and oil being more water-dependent than shale gas and natural gas, which requires the least amount of water [80]. There is a shift occurring in the U.S. that will change energy generation sources, utilizing more closed-loop systems to both decrease CO_2 emissions and impacts on aquatic species. However, such a shift will increase water consumption levels [83].

Food-energy-water systems (FEWS). There is increasing recognition that FEWS are tightly intertwined and interdependent, such that activities within one of the three sectors (e.g., food, energy, or water) will affect the other sector(s), which is the main reason behind the 'nexus' concept [84]. Since global challenges are interconnected, nexus approaches (if well implemented) can detect trade-offs and interactions among various sectors, mitigate process-level impacts, and promote sustainable development strategies. Table 2.1 represents a number of FEW studies published between 2011 and 2018.

2.5.2 Biochar-Based Applications across FEWS

Biochar-based products (unlike charcoal) have many socio-environmental sustainability benefits. When applied to soil, biochar reduces the amount of harmful gases (e.g., NO, N2O, NH3, and CH_4) released into the air [85–88]. In addition, if produced from wood residues, the natural carbon stored in the plant matter is retained in the biochar, which is proven to degrade at a much slower rate than standard organic waste (e.g., forest harvest residues) [88,89]. Biochar-based soil conditioner is able to improve both physical and biological soil properties, including the soil moisture and nutrient retention, along with the various benefits to plant growth including disease suppression [90]. Some of the known biochar benefits to soil are: (a) soil toxicity reduction due to immobilization and/or transformation of heavy and toxic metals, (b) soil pH and structure improvements, (c) soil tensile strength reduction, and (d) the fertilizer use efficiency enhancement, which overcomes the aforementioned FEWS barriers [1,9,91].

Table 2.1. Previously conducted food-energy-water studies (2011-2018)

Study	Research Overview	Year
Bazilian et al.	An overview of the linkages across FEW nexus was provided to develop a framework and address policy making at a national level.	2011
Siddiqi and Anadon	A country-level quantitative analysis of FEW nexus was conducted to suggest possible considerations for food and water policy in the Middle East and North Africa regions.	2011
Jägerskog et al.	An overview was reported to determine how regional FEW nexus centered in collaboration could benefit the economic and environmental aspects in the Central Asian and Aral Sea Basin.	2012
Villarroel Walker et al.	A pros and cons analysis of adopting FEW perspectives was conducted for addressing the needs of urban areas based on case studies performed in Atlanta, GA, USA and London, UK.	2012
Ringler et al.	A review and analysis of FEW Land nexus were provided, in which the resource use efficiency is the main focus. This review lays out the connections between FEW branches and gives examples of FEW Land improvement methods.	2013
Lawford et al.	A summary of major factors influencing the security of FEW nexus in the Lake Winnipeg and Southern Asia region was presented. This study focued on the importance of water resources and water security across FEW nexus and nexus decisions.	2013
Rasul	A literature review of FEW nexus research being conducted in South Asia region was provided. This study focused on the synergies and trade-offs, as well as the regional FEW challenges.	2014
Stein et al.	This study included a quantitative method of social networks, linked to FEW nexus in Tana and Beles subbasins.	2014
Villarroel Walker et al.	A quantitative analysis of FEW nexus was conducted in urban areas, utilizing a multi-sectoral system analysis to quantify resource use, synergies and antagonisms, and monetary value of FEW nexus in the London, UK region.	2014
Biggs et al.	A critical review of FEW nexus thinking was presented, which the livelihood is taken into consideration for FEW nexus decision making. This study reviewed current literature on sustainable livelihoods and how they can be applied to improve FEWS.	2015
Conway et al.	A review study with empirical data was provided to examine FEW nexus in the southern Africa region, which highlighted the climate change implications of nexus decision making.	2015
Daher and Mohtar	A FEW nexus modeling tool was proposed to identify sustainable national resource allocation approaches and evaluate case studies in Qatar, Middle East.	2015
Jeswani et al.	This study explored the environmental sustainability issues in FEW nexus, using life cycle assessment for breakfast cereals.	2015
Kraucunas et al.	This study proposed a platform to stimulate interactions among natural and human systems at a regional scale. The conducted experiments focused on the eastern U.S.	2015
Mukuve and Fenner	This study explored the stresses over FEW physical resources in Uganda’s food system. It is concluded that	2015

	the results help food security policy and management, particularly in Uganda.	
Ozturk	This study examined FEW nexus for long-term sustainability in Brazil, the Russian Federation, India, China, and South Africa.	2015
Endo et al.	This study collected the existing method to examine FEW nexus and classified them as quantitative or qualitative approaches. It is also discussed case studies in Japan and Philippines.	2015
Middleton et al.	This study defined FEW nexus as a concept and narrative and applied the concept to South Asia through an environmental justice lens.	2015
Villamayor-Tomas et al.	The development of a FEW nexus framework was presented by combining the insights fo the Institutional Analysis and Development framework and value chain analysis.	2015
Keskinen et al.	This study focused on the definition of FEW nexus, employing this definition, and using a study of the Tonle Sap system to fill a research gap in the understanding of the nexus.	2015
Garcia and You	A literature review of FEW nexus was reported, highlighting the FEW challenges and identifying process engineering research opportunities.	2016
Rasul	A conceptual analysis of FEW nexus with emphasis on climate change was presented. This study analyzed FEW nexus in South Asia region and provided FEW decision making suggestions.	2016
De Laurentiis et al.	This study reviewed food security challenges and proposed three pathways to address consequences. The concluded FEW approach is prerequisite for using the proposed pathways.	2016
Cairns and Krzywoszynska	This study discussed the importance of FEW nexus research and development. It is concluded social sciences have major roles to play and may provide opportunities.	2016
Y. E. Yang et al.	A scenario analysis under FEW nexus thinking was presented to identify the sustainability challenges and conflicts in Brahmaputra River. Their proposed method is expected to diagnose the water resources deficiencies due to various reason, e.g., climate change.	2016
de Strasser et al.	This study proposed a nexus approach for assessing a transboundary basin, impacts across sectors, and policy measures at national level to reduce intersectoral tensions.	2016
Fasel	This study focused on how FEW nexus thinking gives an innovative approach to mitigate water scarcity of the Black Sea region.	2016
Perrone and Hornberger,	An analysis of FEW nexus in Sri Lanka was provided to establish trade-off frontiers and illustrate the system-level tradeoffs of water allocation.	2016
Mortensen	A proposal was provided to employ FEW nexus policies to nutrient management in the Rio Grande region, as well as a quantitative analysis of trade-offs associated with wastewater irrigation.	2016
Wichelns	A critical review was conducted to analyze FEW nexus and reported the necessity for FEW nexus thinking and decision making.	2017
Endo et al.	A review study was presented on FEW related research to determine the state of nexus research in each Asia, Europe, Oceania, North America, South America, Middle East, and Africa regions.	2017
Howarth and	This study characterized FEW nexus to understand externalities and evaluate a bottom-up, participative	2017

Monasterolo	approach in UK, including 78 stakeholders from academia, industry, and government.	
Flammini et al.	A qualitative and quantitative analysis of the FEW nexus was conducted that defines FEWS interactions and evaluates the performance of FEW related policies.	2017
Pahl-Wostl	An analytical framework was proposed to show the potential of Sustainable Development goals in benefitting FEW nexus and analyze the governance of FEW nexus.	2017
El Gafy et al.	This study proposed a dynamic model approach to incorporate uncertainties to FEW nexus policy making and analyze the dynamic behavior.	2017
Wicaksono et al.	A literature review study focusing on the global FEW nexus was provided, including a review of nexus models and opportunities for future modeling efforts.	2017
Dhaubanjar et al.	The development of a spatially explicit framework for FEW decision making was provided, in which a comparative review of Nepalese power development is analyzed.	2017
Hussien et al.	The development of a bottom-up dynamic system model was presented to quantify FEW nexus at an end-use level.	2017
Johnson and Karlberg	An analysis of FEW nexus tools to develop a decision making framework was conducted, including the presentation of how scenario-building creates space for dialog.	2017
White et al.	A quantitative analysis of FEW nexus was performed in the East Asia region with a focus on the effect of inter-regional trade across FEWS.	2018
Albrecht et al.	A systematic review of FEW nexus assessment methods was provided to analyze current FEW assessment literatures to determine the repeatability of the studies, the attention to the interlinkages of the three branches and breaks down the focus of FEW assessment studies.	2018

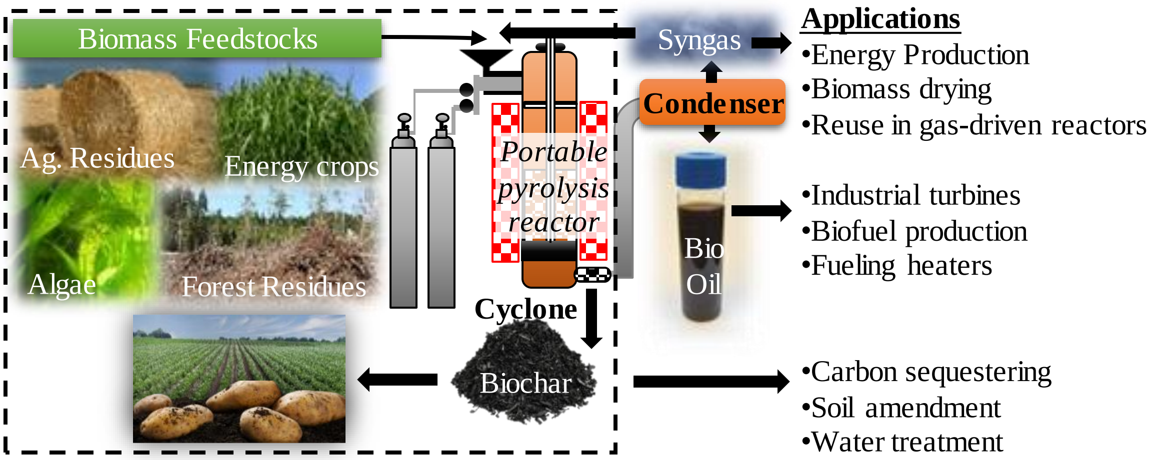

Figure 2.2. Schematic of pyrolysis process, bioproducts from biomass feedstocks, and their applications (dotted line indicates the scope of this study)

Biochar Production. The focus of this study is on the thermal decomposition of biomass feedstocks for biochar production, particularly the pyrolysis conversion pathway (Figure 2.2), due to high process efficiency and product quality [129]. Pyrolysis process yield is dependent on a few critical parameters, such as temperature, pressure, and exposure time of biomass feedstocks to the heating source [1]. The major bioproducts of biomass pyrolysis process are biochar, bio-oil, and syngas (non-condensable gas) [130]. Syngas has the potential to be recycled to pyrolysis reactors for heating purposes and for reducing biomass moisture content [131]. Until recently, the main focus of biomass pyrolysis was the optimization of the conversion process to produce pyrolysis-oil (bio-oil) and upgrade it to transportation fuels (biofuels or blended fuels). Prior studies reported that biochar production, using a slow pyrolysis process at temperatures below 300°C has high process yields [20,132]. On the other hand, biochar quality and chemical properties in respect to its applications as a soil amendment product have similarities to the charcoal [129]. The effects of charcoal use in agriculture for promoting soil health and crop yields have been reported in earlier studies in the U.S. and South America [133,134]. Jeffery et al. (2013) reported that charcoal plays an important role in the fertilization of unusable lands along the Amazon River. Taha et al. (2014) conducted a study that shows the differences in the specific surface area and total pore volume of biochar versus charcoal. Their analyses reported the specific surface area (m2/g) of two representative biochar samples to be on average 1.56 times larger, and the total pore volume (ml/g) to be 2-5 times larger, than charcoal. It was also concluded that these greater properties of biochar could lead to higher absorption of pesticides in aqueous phase [135].

When used for soil amendment, biochar effects on the food-water nexus (agricultural productivity and water security) are a direct result of the modification of soil properties, e.g., the nutrient-water holding capacity due to biochar's porous nature [136]. Biochar-based fertilizer applications for soil productivity and crop yields have been shown to increase plants nitrogen intake by 400% and the soil pH from 4-4.5 to 5-6 [137], and the plant growth by 250% [8,28]. Biochar effects are dependent on various factors, such as feedstocks used (e.g., forest/agricultural residues, advanced feedstocks, or animal manure), conversion process configurations (e.g., reactor types, temperature/pressure, or residence time/heat transfer rate), and soil conditions (e.g., soil texture, amount of micronutrients or pH) and crop types [85,138,139]. Different biochar-based soil amendment products are produced to cater to the needs of specific crops and soil conditions. Some of properties that can be controlled are the concentration of specific elements, and the cation exchange capacity of soil [8].

Applications to FEWS. Biochar-based soil conditioners change the consistency, packing, density, and porosity of soil, and have direct effects on water and air penetration that can benefit the root zone of plants [37,131]. Since biochar is inherently more porous than soil, the influence of biochar to water-nutrient holding capacity is measurable, along with the workability, permeability, and swelling-shrinking dynamics [37,140]. The changes to the soil physical nature and biochemical properties are also seen in the increase of soil-specific surface area, which improves the structure and aeration of soil [37,141]. Biochar also improves the amount of soil cation and anion exchange capacity, which has a direct impact on increasing soil pH, nitrogen, and phosphorous levels, as well as to decrease the availability of heavy metals [37,142]. These properties lead to the encouragement of root development of the plants and the reduction of the available aluminum in soil [137]. A meta-analysis based on 371 independent studies found that soil amendments of biochar generally resulted in increased aboveground productivity, crop yield, plant potassium tissue concentration, soil microbial biomass, rhizobia nodulation, soil phosphorous, soil potassium, total soil nitrogen, total soil carbon, and soil pH [37].

Additionally, soil amendment of biochar-based products has been shown to increase the microbial health of the soil [143], with significant effects on soil microbial biomass, community composition, and enzymatic activities [144,145]. Particularly, biochar addition resulted in an increase in bacterial diversity, a shift in the composition of the rhizosphere microbiota, and a stimulation of microbial metabolism in the rhizosphere, which together could lead to enhanced plant performance [146,147]. Moreover, biochar has been shown to suppress soil-borne plant pathogens due to its influence on the soil-rhizosphere-pathogen-host system [148,149]. Furthermore, biochar may affect microbial decomposers and thereby the turnover and availability of soil organic matter, e.g., carbon, nitrogen, phosphorus [37]. Additionally, biochar-microbe interactions contribute to soil improvement, including carbon sequestration, and pollution remediation [150].

Biochar-treated soil has a higher water holding capacity, which decreases nutrient leaching and soil erosion and reduces the effects of drought and environmental stresses on crops [85,151]. Soil moisture content is one of the important factors to consider in linkages among all three FEW sections because soil with higher water retention requires less water and energy to deliver the necessary resources to crops, subsequently relieving irrigation levels [64]. The high water content is also one of the key factors to increase the crops yield obtained by biochar amended fields [91]. Biochar adds a physicochemically active aspect of soil that is capable of removing heavy metals and toxic compounds from soil [91]. Some of the metals that can be absorbed include aluminum, manganese, arsenic, nickel, copper, and lead [152]. Specifically, biochar leachate was shown to facilitate microbially-mediated dissimilatory metal reduction, likely due to electron shuttling capacity of biochar-associated semiquinone functional groups and adsorption of reduced metals on biochar [153].

Carbon Sequestration and GHG Emissions Mitigation. Carbon sequestration or the process of long-term storing carbon has become essential to prevent GHG emissions into the atmosphere [133,154]. In order to be properly stored, carbon must be transformed from an active state to an inert passive state [155]. When biochar is used as a soil amendment, the carbon sequestration takes place within biochar for several decades [28,39]. Storage of carbon in soil through biochar application can greatly reduce atmospheric CO_2 as the uptake of CO_2 by plants is significantly greater than current anthropogenic CO_2 emissions [85,154,156]. Therefore, compared to the natural decomposition of organic materials, biochar amendment serves as a significant carbon sink.

The use of fertilizers is necessary to secure the global food supply; however, the production process of fertilizers is highly energy-intensive and results in releasing significant GHG emissions [157]. Replacing current non-organic fertilizers with biochar-derived soil conditioners has been identified to not only improve soil conditions but also stabilize organic carbon and reduce GHG emissions [158]. Soil contains low amounts of unstable carbon, and when biochar is added to soil, it improves the stability of organic carbon in soil [37,154]. Additionally, biochar-treated soil adds resistance of global carbon to chemical and biological degradation by increasing terrestrial carbon stock or soil carbon content. In biochar production process, the carbon contained in biomass is either captured in biochar or other co-products of the pyrolysis process, e.g., bio-oil. Latest studies reported that 20% to 35% of the carbon stored in biomass feedstock is captured in biochar [85].

Biomass pyrolysis process has the potential to be a net-zero or even a net negative carbon emission process because the carbon released during plant bioproducts combustion is part of the nature from biogenic substances and nearly equal to carbon absorbed by plants in farms or by trees in forests [159–161]. Carbon is naturally found in biochar produced from carbon-based feedstocks and organic waste streams, which is a natural derivative of the photosynthesis process. In other words, soil and plants absorb carbon dioxide from the atmosphere through the photosynthesis process, which later unused feedstocks can be utilized to produce biochar, and return and trap the carbon in soil through the use of biochar-derived soil conditioners. Biochar releases carbon at a much slower pace than the organic carbon cycle, therefore, a net negative or carbon neutrality occurs [85,154,155]

Animal manure-based biochar production has the potential to reduce up to 10% release of CH_4, a GHG with a significantly higher warming potential than CO_2, to the atmosphere in relation to livestock [85]. N2O is the main contributor to climate change as it absorbs 300 times more thermal tropospheric radiation [86]. N2O can be emitted through the process of soil nitrification and denitrification. When applied to soil, biochar is also effective in the trapping and immobilization of nitrogen from inorganic sources and decreases the volatilization of ammonia, which is due to the high carbon to nitrogen ratio of biochar [86]. Manure-based biochar can not only add micronutrients and carbon to soil but also control the release of odor and amine gases from of the animal manure [162–164].

Management and Utilization of Organic Wastes. The runoff from agricultural leftovers and animal wastes can become harmful and pollute ground and surface water due to the overloading of biohazards (e.g., microbial pathogens) and nutrients (e.g., nitrogen and phosphorus) [165]. Fresh animal manure has been used as a fertilizer because it can add nutrients and organic matter to soil [166]. Prior studies reported that chicken manure is more beneficial due to high nutrient value in comparison to cattle manure [167,168]. However, there are various environmental, public health, and biosafety concerns linking to the use of untreated animal wastes and manure [169–171]. For example, microflora associated with animal manure, such as bacteria Escherichia coli O157:H7, Listeria, Mycobacterium, Salmonella, and Campylobacter, and protozoal Cryptosporidia and Giardia, could pose a public health risk [172–174]. Thus, adding manure of both livestock and poultry to soil is risky because it can (a) burns the plant roots, (b) inhibit seed germination, and (c) transfer bacteria and disease from animal manure to humans [170].

Biochar production from these organic wastes will alleviate the stress on the environment, as well as provide environmentally beneficial bioproducts [175,176]. The utilization of wastes (especially near the collection fields) for bioenergy and biochar production could not only provide an economic opportunity but also reduce the digestion and decomposition of the organic matter that contributes a significant amount of GHG emissions [35]. The carbon contained in the wastes is unstable, meaning that it will be returned to the atmosphere quickly. Biochar has the ability to lock the carbon in the soil for long-term storage or be utilized in a combustion process as a low-emission energy source with either syngas or co-fired in coal plants [177,178]. Biochar benefits over untreated biomass include the increased biosafety, energy density, and carbon stability [179]. Biochar is also beneficial in the reduction of cost and environmental footprint of the bioenergy production process by burning both biochar and syngas for heat and electricity generation [177]. Moreover, biochar co-firing with coal reduces the emissions of coal-fired power plants, although biochar energy density is low, which requires more biochar to be combusted to obtain the same amount of energy as coal (Table 2.2) [178].

Table 2.2. Attributes comparison of woody biomass, bioproducts, charcoal, and coal [180, 181]

	Density kg/m^3	**MC w.b.%***	**Energy Density MJ/kg**
Green whole tree chips	350	45	10.7
Solid wood, low density (Douglas-fir)	400	12	17.1
Solid wood, high density (Oak)	865	12	17.1
Bio-oil	1200	25-30	18.0
Biochar (pine wood)	350-500	5	28
Charcoal (oak)	700	5-7	29
Coal (anthracite)	800-929	5-15	33

* wet base

Water Purification Purposes. Availability of clean water resources is essential to promote the sustainability of all ecosystems, as no living organism can survive without access to water. For humans and terrestrial plants, clean water is critical, but only around 3% of the Earth’s water is freshwater; and out of 3%, only 0.6% is available for human use [180]. When focusing on the purification and decontamination of water for the consumption by humans, there are many factors to take into account [181]. Particularly, the sources of drinking water contamination include, but are not limited to, pathogenic organisms, toxic inorganics, radionuclides, and synthetic/organic materials. Even groundwater that is normally more pristine than surface water may contain harmful chemicals, such as arsenic and high levels of fluoride [182]. Especially in poverty-stricken areas, there is a need for a cost-effective water filtration process. It has been found that biochar made from crop residues has the ability to be utilized in cost-competitive water treatment systems [180,181].

Biochar can provide a cost-effective addition to filtration systems due to its ability to be created from unused organics and wastes [183]. Unlike other filtration methods that are expensive and only target certain organic materials or heavy metals, feedstocks-based biochar is able to remove both metals and organic materials [183]. Other than filtration by boiling water, each different filtration approach requires the use of outside materials and chemicals [184].

Biochar filtration approach is similar to the traditional charcoal approach and is used as an effective contaminant removal system due to biochar ability to absorb heavy metals and other chemical contaminants [183]. Pyrolysis process is able to activate the naturally occurring celluloses, hemicelluloses, sugars, and proteins in the organic waste to absorb unwanted chemicals. The porous carbon-structure of biochar has a large surface area with an affinity for toxic chemicals and heavy metals [1]. The removal of heavy metals depends on the pore size, porosity, and cation exchange capacity of biochar, which correlates directly to the molecular sieving capability and selectivity of biochar [85,183].

Wastewater treatment, especially for the food processing and manufacturing industry, has gained particular attention [41,185]. In order to avoid penalties, companies must first treat their wastewater to contain no more than 1000 mg/L of biodegradable organic compounds [41]. This process currently is expensive and generates significant GHG emissions [41,181]. The sorption of aqueous contaminants including heavy metals by biochar produced from animal manure and crop residues has been found to be quite successful, allowing compliance with stringent discharge limits at low economic costs and GHG emissions [186]. A benefit of biochar-based filters is the absorption of lead in drinking water, which is toxic to humans and causes long-term health problems [187]. Cao et al. (2009) conducted an experiment where lead sorption was tested by mixing biochar with a sodium nitrite solution containing lead. They reported after half an hour the sorption reaction reached equilibrium and the lead levels in the solution decreased to near the limit of the detector at 0.05mg/L from the original concentrations of up to 1 mm. Biochar is also able to treat water contaminated by agricultural runoff from croplands receiving phosphorus-rich fertilizer. Excessive aqueous phosphate is harmful to both humans and the ecosystem in short- and long-term aspects and is responsible for increased eutrophication in aquatic environments [180].

2.6 Discussion

With the recent wave of interest in the FEW research, there are opportunities to identify potential pathways, products, and systems for future FEW research, as well as enhance the resilience and sustainability of the integrated forest-fuel-food (F3) industries across the U.S. that will benefit the current state-of-the-art in FEWS. The earlier studies focused on each of the three FEW branches for addressing the tensions and to respond to the growing global needs. Later studies centered on life cycle assessment and integrated either two of the three FEW branches, which are well-suited for global scale studies to respond to the FEW crises. Recent studies established field-based models to optimize nutrient-energy-water systems. A suggested form of integrated F3 processes and products for FEW complexity mitigations would be the development of biofuels and biochar from organic wastes and agricultural residues. Bioproducts creation would reduce the dependence of agriculture production on the energy sector and provide a product that can be applied to improve soil quality and crop yields, mitigating the necessity for excessive irrigation/fertigation by increasing moisture content and nutrients [189].

Biochar has yet to realize its full potential across FEWS, and it is staged to become a key player in the organic food industry. Since biochar production is not an established industry in the U.S., there is a need to expand market demand for the product by educating farmers about its benefits compared to traditional crop applications and non-organic fertilizers. Commercializing biochar addresses market priorities and end-user needs, particularly in agribusiness industry. Additionally, sustainable biochar serves as a valuable carbon sink by holding carbon in soil and displacing fossil fuels used in energy production. Sufficient cost reduction will be necessary before biochar can become a viable option to replace current synthetic products, mainly as a soil amendment for organic farming.

Biochar is primarily utilized in agriculture to improve overall crop productivity, necessary for supporting the livestock sector in the form of animal feed. This is generally true in North America where meat is viewed as an essential product for the human diet. Depending on the properties, biochar has widespread applications across various sectors. Property variables include the heating value, energy content, carbon content, water-nutrient holding capacity, and organic-matter efficiency. Additionally, manure-based biochar is an emerging product, and the industry is in its nascent phase, but growing gradually with increased awareness and improved production processes.

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2.7 Conclusions

Understanding the ramifications of nutrient-energy-water systems (e.g., complex compounds, mechanisms, multifunctional performance, and commercial viability) and elucidation of the effects of various operational parameters and variables are essential to provide a base of knowledge to enhance FEWS sustainability benefits. The need for further investigation is increasing not only in the creation of conceptual platforms but also in empirical work for specific applications that will increase industrial growth. A narrative and systematic literature review has been conducted to investigate the state-of-the-art within FEW disciplines and explore the socio-economic resilience and ecological integrity of regional FEWS by coupling recent improvements. This study examines the linkages among bioproducts (particularly biochar) and FEWS to identify potential solutions that will bridge existing research gaps.

With the current focus of renewable and sustainable processes and systems research, there is an essential need for a connection to be drawn between the challenges facing the FEWS and biochar-derived products. Therefore, an in-depth review of biochar-related prospects is presented and the significant impacts of biochar-based products on improving FEWS and mitigating carbon footprints are explored. The viability and implications of biochar-derived products to FEWS and associated factors (e.g., soil amendment and crop growth, water treatment, energy generation, and reduction of GHG emissions) have been discussed within the narrative review. However, questions remain on the long-term viability of biochar-amended soils, as well as the possible competition for land space if crops are being grown for biochar production. Over the last ten years, the interdisciplinary FEW research has been a fast-growing field of study due to the dearth of literature for effective strategies to improve FEWS efficiency and productivity. The systematic review (provided in the Supplementary Material) used WEB OF SCIENCE^{TM} to generate two databases, including 146 and 164 articles in each database and 57 articles shared by both databases, and analyzed the various factors based on the number of publications, citations, and keywords. From both narrative and systematic reviews, it is concluded that there is an essential need for solutions-oriented projects at the FEW security nexus at both domestic and global level.

2.7.1 Potential Paths for Future Research.

Moving beyond current practices and techniques to promote FEWS and further breakthroughs offers the opportunity to advance existing FEW infrastructures, streamline the information, and support sustainable FEWS. Advanced FEWS play a key role in addressing national priorities, however, based on the disparate nature of operations and inherent complexity associated with FEW entities, it is not surprising that little work has been done to integrate all three branches. The following potential paths are defined for further investigation to advance existing FEWS at various spatiotemporal scales:

- Development of bioproducts classification tools by determining the market opportunities and end-users.
- Exploration of the biochar market and sustainability impacts associated with biochar-derived products.
- Establishment of standard metrics, indicators, approaches, and computational tools for FEW life cycle analyses.
- Development of techno-economic and socio-environmental studies for solutions with potential to improve FEWS.

Chapter 3: Commercializing biochar production through a novel conversion pathway and data-driven decision making

3.1 Abstract

Pyrolysis-based char (biochar) from organic wastes and biomass feedstocks is beneficial for organic and sustainable soil amendment and several other food-energy-water related applications. Biomass collection and dewatering, as well as production costs represent the cross-cutting sustainability challenges in biomass-to-biochar supply chains. This study proposes a cost-effective biochar production process near the feedlot or drylot areas to address major challenges in the biochar industry infrastructure. The developed pretreatment and conversion processes include a rotary dryer, using bio-oil and syngas (other combustible products of pyrolysis process) for dewatering biomass, and a portable refinery unit locating at or in close proximity to collection sites for conversion operations, as well as a data-driven decision making platform to effectively control and optimize the production processes. The decision making platform employs new mechanical inventions with growing cyber-based advances for economic and environmental analyses (e.g., process yields and energy consumption). The results indicate that the proposed approach herein is capable of reducing the handling, transportation, and storage costs by producing and transferring higher energy density products instead of transferring low-energy density biomass.

3.2 Introduction

Biochar has been introduced as a means to address the food-energy-water system (FEWS) challenges, however, the existing approaches have not been integrated to convert biomass feedstocks into cost-competitive biochar. Biomass collection and dewatering, as well as high production cost are the key challenges across the biomass-to-biochar supply chains [47,196]. Therefore, we construct a portable conversion process, including a catalytic fast pyrolysis (CFP) reactor for bio-oil production and a fixed bed slow pyrolysis (FBSP) reactor for high-quality biochar production. Our small-scale conversion process is able to convert biomass to bioproducts (e.g., biochar, bio-oil, and syngas) near the collection sites to reduce economic and environmental impacts of upstream segment operations, such as biomass transportation. The motivation behind the proposed conversion process in this study lies in optimizing biochar quality and process yields to promote sustainability and commercialization through developing an advanced conversion process to address inefficient resource (e.g., biomass and energy) usage across pretreatment and conversion processes.

Biochar is the solid byproduct obtained through the carbonization or thermal decomposition of biomass feedstocks [1,129]. This thermal decomposition can be accomplished through various conversion processes, such as pyrolysis, gasification, and hydrothermal carbonization [1]. Biochar yield of each process is dependent on various parameters, such as reactor temperature and pressure, as well as flow rate and exposure time of biomass to the heating source [1]. Prior studies reported that slow pyrolysis is one of the promising approaches for biochar production due to high quality and production yields [20,132], but with may not be the best overall process for percent yield [197]. Pyrolysis production process causes biochar to be enriched with organic carbon forms called fused aromatic structures [198]. Additionally, biochar is sought after for being enriched in phosphorus, calcium, magnesium, and nitrogen making it a promising candidate for soil enhancement [199].

Biochar-based products act as a soil conditioner that can improve soil physical and biological properties, such as moisture and soil-nutrient retention, along with other benefits to plant growth [90]. Biochar-based soil conditioners, unlike other similar products (e.g., non-organic fertilizers), have several sustainability benefits, such as reduced emissions in the production, as well as carbon sequestration, an attribute that can cut carbon pollution and mitigate environmental emissions when applied to soil [199]. The primary market target for biochar is its application to soil due to (a) soil toxicity reduction due to absorption of heavy and toxic metals, (b) soil pH amelioration and structure improvements, (c) soil tensile strength reduction, (d) nutrient retention and cation exchange capacity enhancement, and (e) the water holding capacity, crop nutrient bioavailability, and microbial activity enhancement [1,9,91]. Each thermal decomposition process results in a unique biochar product in terms of the physical and chemical structure, thus, the conversion process configuration (e.g., temperature, residence time, and pressure) plays an important role in determining the end use of the biochar.

Pyrolysis technology is one of the most efficient and cost-effective approaches for biochar production. Pyrolysis is a thermochemical decomposition at 250-1200°C (500-2200°F) temperature in the absence of oxygen, which can be grouped into two main categories (i.e., slow and fast pyrolysis) and differs in residence time, temperature, and heating rate [194,199,200]. Fast pyrolysis is characterized by the short residence time (1-5 seconds), where slow pyrolysis is characterized by longer residence times with studies reporting residence times between 10-120+ minutes [1,201]. Biochar produced via pyrolysis technology is characterized by its high carbon mass percentage and moderate pH [9]. Due to these properties biochar from pyrolysis has been well studied in its application to soils [19]. Pyrolysis reactors can be broken down into two main categories: fixed bed (heat is transferred to the biomass as a stationary mass) and moving bed (biomass is mechanically moved through or stirred in a heating source) [189]. Slow pyrolysis process within a fixed bed reactor has shown to produce favorable biochar yields [194,202]. An FBSP reaction is normally accomplished at atmospheric pressure, through external heating of the oxygen-limited containment bed at temperatures ranging from 300-600°C (600-1200°F) [202]. Yields from slow pyrolysis reactors have been measured at approximately 35% by mass of by-products, and can range anywhere from 30-60% of feed mass[194,203]. Biomass moisture content is one of the key parameters for achieving high biochar quality and process yields, particularly it can lead to lower yield percentages in the pyrolysis of non-dried vs. dried biomass [201].

Gasification technology is similar to pyrolysis, but is a process that occurs at higher temperatures approximately 700-1100°C (1300-2000°F). The major products of biomass gasification are synthetic gas (syngas) around 65%, tar around 5-10% and biochar around 15% [204]. The purpose of the gasification process is to create syngas thus leading to lower biochar production rates. Biochar obtained from gasification at high temperature is characterized by having a smaller mass percentage of carbon, however, the carbon is in a more stable state in comparison to pyrolysis-derived biochar [198,200]. In addition, gasification-based biochar has the highest pH in comparison to other cost-effective thermochemical processes (Table 3.1), which is beneficial for low soil pH [205].

Hydrothermal carbonization (HTC) is the process of stimulating the biomass coalification through mainly dehydration and decarboxylation [206]. HTC-derived biochar (also referred to as hydrochar) is accomplished by suspending the biomass in water for several hours at 180-200°C and saturated (self-generated) pressure [207]. Unlike gasification and pyrolysis, HTC can be applied directly to wet biomass, such as animal manure and algae with over 80% moisture content [197]. Therefore, HTC is a cost-effective conversion process due to the low energy requirement for pretreatment step, particularly biomass dewatering [197,207,208]. Hydrochar compared to thermally produced biochar has been shown to provide higher adsorption rates of organic materials in aqueous solutions, however, hydrochar adsorption of heavy metals was lower than thermally produced biochar [197]. Also, hydrochar has lower pH and ash content in comparison to biochar, which are major factors in soil amendment [90,200,208].

Table 3.1. Comparison of biochar production technologies

Technology	Temp. (°C)	Residence Time	Yields	Advantages	Disadvantages	Source
Fast Pyrolysis	400-1100	1-5s	10-25%	• High biochar pH • Low capital cost • Well developed • High bio-oil yields	• Low biochar yields • Low biochar carbon content • Difficult solid separation	[194,209]
Slow Pyrolysis	250-400	10min-days	~35%	• High biochar yields • High biochar carbon content	• High energy consumption and operational cost • High biochar volatile matter	[194,210]
Gasification	800-1200	10-20s	5-15%	• High syngas yields • High biochar carbon content • High biochar pH	• High plugging issues due to tar production • Formation of aerosol • Low biochar yields	[210–212]
Hydrothermal Carbonization	180-220	1-12h	35-65%	• Easy solid separation • No dewatering requirement • High biochar carbon content	• High reactor pressure requirement and high operational costs • High biochar moisture content and drying requirement • Low biochar bulk density	[206,207,210]

With growing populations and reduction of useable farmlands, the available farms must be able to accommodate the growing necessity for agricultural products. Biochar has been suggested as an organic source that has full potential in the agricultural sector, and is staged to become a key player in the organic fertilizer [213]. The benefits of biochar to agricultural lands are dependent on the biochar quality (e.g., chemical and physical properties) [90]. The International Biochar Initiative (IBI) has developed a process to determine the biochar quality based on various parameters, such as the organic carbon mass percentage, pH, moisture holding capacity, and particle size [214]. Biochar by definition given by the European Biochar Certificate (EBC) must contain at least 50% organic carbon, otherwise EBC classifies it as pyrogenic carbonaceous material, IBI defines biochar in a three-tier class system based on organic carbon levels starting at 10-30%, 30-60%, and above 60% [214–216].

Biochar characterization has been studied and reported in prior studies [215], however, establishing standard procedures and metrics for quality analysis, as well as a defined quality has not been developed yet. Depending on the quality, biochar has widespread applications across various sectors. Quality variables include heating value, energy content, carbon content, water-nutrient holding capacity, and organic-matter efficiency.

The primary focus of this study is on the pyrolysis process due to its low capital cost, high-quality biochar achieved, and high-process yield. Pyrolysis can be designed to be biomass agnostic and is amenable to distributed processing, e.g., portable refinery [47]. Additionally, pyrolysis is one of the most promising pathways among existing, nascent thermochemical technologies for cheap, local, non-food, lignocellulose feedstocks [9]. Therefore, a continuous, flow-through conversion pathway was developed and empirically verified (detailed in Section 2), utilizing pyrolysis reactors, along with inline-sensors, programmable automation controller (PAC), and several cyber-physical based technologies to produce high-quality biochar with high process yields. The biochar quality parameters (e.g., water-holding capacity, carbon content, and particle size) are assessed based on the characterization procedures developed by IBI and EBC (discussed in Section 3) due to their well-defined assessment procedures and metrics [214].

3.3 Biochar Production and Characterization

3.3.1 Biochar Production

In this study, we designed and built in-house a modular entrained flow CFP reactor for bioenergy (e.g., biochar and bio-oil) production. The developed portable CFP conversion setup is unique due to its modularity, which allows us to easily transport the equipment for off-site operations and upgrade the components in a timely and profitable manner to test multiple designs. Since slow pyrolysis process can produce high-quality biochar in terms of carbon content of the solid product (around 95% in mass) due to long residence time (minutes to days) [210], we developed FBSP reactor in conjunction with CFP setup to improve biochar quality.

The developed CFP setup includes a feed system, CFP reactor, cyclone, and condenser, as well as sensors, valves, actuators, and controllers (Figure 3.1). The feed unit is a continuous, flow-through system at the top of the reactor with approximately 60 grams biomass capacity per run, which works with an auger screw and motor to feed the biomass into the reactor at the various rates. The auger screw supplies biomass directly into the flowing nitrogen gas, which transports the biomass to the main reactor. The cyclone separator includes an offset inlet to encourage circular flow, and a solid product containment unit capable of holding approximately 50 grams biochar. The condenser includes a copper coil inside a stainless steel containment unit. The heating unit comprises pre-heater cartridge to increase the temperature of nitrogen gas, as well as internal and external heating systems for CFP reactor that can control the internal reactor temperature between 375-450°C with continuous flow. The produced biochar, utilizing CFP reactor needs further upgrading to improve the end-product quality. Thus, FBSP reactor unit was added to the solid product containment unit at the bottom of the cyclone to produce high-quality biochar through extra heating, approximately 20-60 minutes at

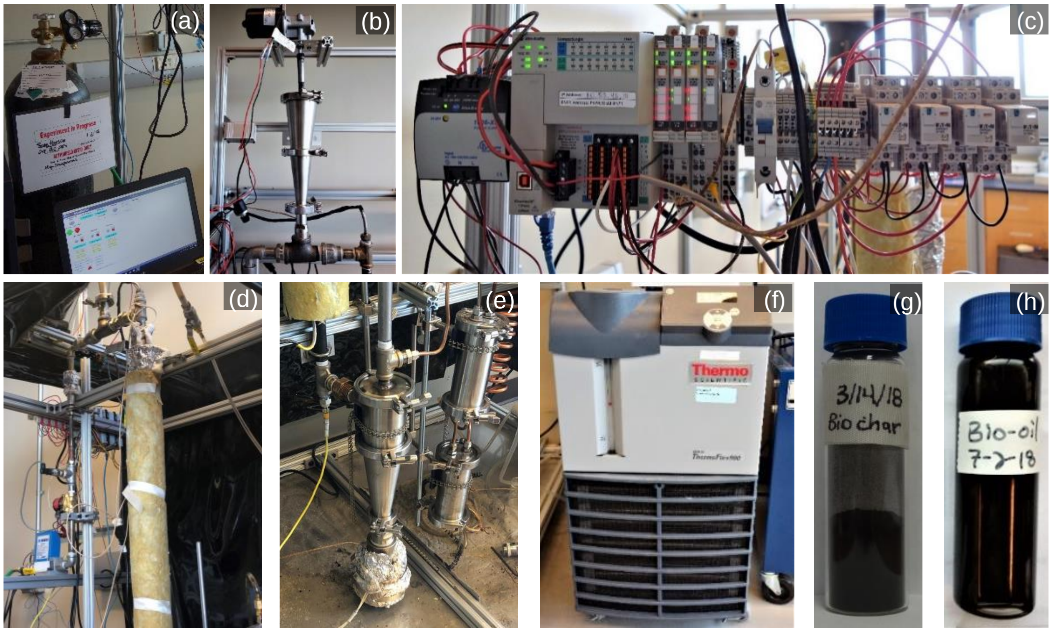

Figure 3.1. Small-scale CFP apparatus, including (a) laptop with VTScada and Rockwell Logix 5000 software package, nitrogen gas supply and regulator; (b) biomass auto feed system; (c) programmable automation controller interface secured via DIN rail; (d) CFP reactor, gas flow controller, solenoid valve, and pressure gauge; (e) cyclone vortex separator (left) and custom built condensers (right); (f) Glycol chiller; (g) biochar sample; (h) untreated bio-oil sample

around 325°C external temperature.

The developed setup employs a PAC, actuator valves, in-line sensors to real-time monitoring and control the process. PAC aids in process automation via monitoring inputs (e.g., gas, biomass, and energy) and controlling outputs (e.g., feeding rate, reactor pressure/temperature, and gas flow rate). In this study, we used RSLogix 5000 for programming the PAC, using a ladder logic-based program with structured text, a function block diagram, and sequential function charts. The developed ladder logic program helps to integrate the multiple separate aspects of our system, such as feed and flow rates, as well as required temperature and pressure. The flow control utilizes a solenoid valve and a flow rate controller, as well as gas flow set point designated by the user in the human-machine interface (HMI) and is scaled in Studio 5000 to a 0-20mA output. Controlling the solenoid valve for gas flow rate has two different approaches, i.e., pulse and manual. The pulse option has a user set timer that will count down to zero when the user initiates the opening of the solenoid, and the manual option opens and closes only by user commands.

The feed motor can control the feed rate by both a user set rate (similar to flow rate) that is controlled with a scaled value entered by the user, and an on/off switch located in the interface HMI. An analog output 4-20 mA signal is converted to 0-10V output necessary for the feed motor. An extra stipulation is coded into the running of the feed motor to prevent plugging in the reactor. The feed motor can only run if and when it is turned on in the HMI and the solenoid valve is open. This prevents biomass from entering the system before or without airflow to push it through to the cyclone. The biomass used in this study was pine wood chips obtained from a local wood shop. For CFP process, the pine wood biomass feedstock was sifted, using a 2mm screen. Biomass size and moisture content are two primary factors for producing high-quality bioproducts, increasing process yields, and

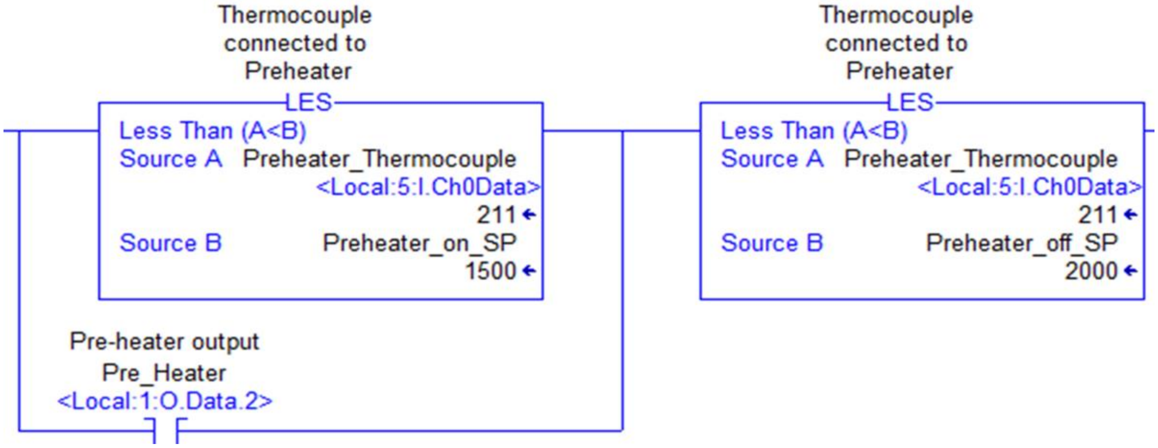

Figure 3.2. Heater set-point ladder logic diagram developed in Studio 5000

reducing production costs [15].

Reactor temperatures are controlled with inputs from thermocouples placed or contained in the heating units. Each heating unit is controlled by an on/off switch located in the HMI. When a heater is turned on, if the temperature is lower than the set-point, the integrated PAC will output the required 120V to the heating unit. Once the temperature of the heating system reaches the top limit, the output stops until the temperature reaches the bottom limit thus beginning a cycle (Figure 3.2). PAC is able to keep the temperature in the desired range while both the system is on and the heating unit switch is on. Additionally, the pre-heating unit located before the feed system can work when the system is on, the temperature is below the set points, and the solenoid valve is open to provide the required gas flow for transferring biomass to the CFP reactor.

The process monitoring and control, as well as data collection are accomplished with the use of VTScada open source software, which creates an interactive HMI. The developed HMI in our setup helps the user to effectively control the multiple parameters (e.g., temperature, gas flow, and feeding process) through a reliable, easy-to-use interface. The interface displays (1) the current and set points of each individual entities that can be updated in Studio 5000, (2) the feed motor speed can be controlled on a 0-100% output scale or 4-20mA output card, and (3) on/off switches of the entire process, e.g., heaters, feed motor, and valves. The solenoid valve controls the gas (i.e., nitrogen) flow through the reactor that can be either manually opened/closed or set to be open for a period of time (pulse). During the pyrolysis process, the organic matter of the biomass feedstock is mostly released in the syngas and bio-oil, leading to nutrient enrichment of biochar [215].

3.3.2 Biochar Characterization

Biochar quality analysis was conducted using the key parameters and standards developed by prior researchers and biochar companies (e.g., Gabilan lab, IBI, EBC, and Huffman Hazen lab) to explore the interaction between biochar and soil. Carbon storage value, fertilizer value, limiting value, particle-size, and the use in potting mixes and soilless agriculture are key factors to analyze the benefits of biochar to soil [217,218]. The carbon storage value is determined by the stability of biochar and another variable BC+100, which is defined as the amount of biochar that is expected to remain stable after 100 years [217,218]. Biochar volatility can be attributed to the molar ratios of hydrogen to organic carbon and oxygen to carbon. These ratios are obtained through an elemental analyzer. BC+100 percentages are analyzed by incubating biochar in the soil for 3-5 years with the addition of a microbial inoculation and nutrient solution to promote decomposition [218]. Due to the time limit and materials constraints, this study was unable to evaluate the carbon storage value of the produced biochar in this project.

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The total carbon analysis of each biochar sample can be accomplished with elemental analysis through combustion, employing thermogravimetric analysis (TGA) at above 950°C. The calculated number can be deemed the total organic carbon (C_{org}) if there are no carbonates present. If carbonates are deemed to be present than the removal of inorganic carbon can be accomplished with acid or muffling at 500°C [215]. The obtained results indicate that the recalcitrant carbon percentage of each sample is given as 80% of the total carbon, and defined as an estimate of the carbon that can be sequestered. Therefore, the total carbon can be calculated, using Equation 1.

$$\text{Total Carbon \%} = \text{Recalcitrant Carbon \%} * \frac{100\%}{80\%} \tag{1}$$

Elemental analysis was conducted to calculate the mass ratio of other main elements (e.g., H, O, S, and N). Inductively coupled plasma atomic emission spectroscopy (ICP-OES) is another approach to calculate the mass ratio of the elements if the elemental analyzer is not capable of measuring all of them, e.g., Sulphur [215]. Nitrogen determination also can be accomplished, using the Kjeldahl Method [219]. Oxygen analysis can be conducted using the mentioned approaches (e.g., elemental analysis) or indirectly using other methods, such as the conventional Deutsches Institut (DIN) and American Society for Testing and Materials (ASTM) methods.

Combustion at 550°C was performed to determine the total ash content of biochar and the remaining fraction of solid material being the ash. The ash content is then broken down into the soluble acid percentage, which contains the nutrient, carbonates, and oxides and acid non-soluble percentage, which contains dirt, stones, and silica. The analysis of trace, heavy metals (e.g., Cd, Cr, Cu, Ni, Pb, and Zn) in biochar is challenging due to the recalcitrance of the carbonaceous matrix to degradation and acid dissolution, which is out of the scope of this study.

A preliminary water-holding capacity test was conducted by first suspending one gram of biochar Sample 1 (B1) without FBSP and 1.01 gram of biochar Sample 2 (B2) with FBSP process in 15.25mL and 15.40mL water, respectively for five minutes, and letting biochar absorbed the water for an hour. The excess water was drained, then to remove any non-absorbed water the wet biochar was then filtered using filtering containers under light suction, and weighed post filtration. We allowed biochar to dry overnight in closed containers and placed them in an oven at 110°C for 150 minutes to dry and extract any retained water. The dry biochar was then weighed and the mass-to-mass ratio was calculated using Equation 2 where ρ_{water} is the density of water, it is important to note that biochar water-holding capacity is a measurement of potential, not the moisture already contained in the char, which is a different factor entirely.

$$\text{Water} - \text{holding capacity} \left(\mathrm{mL}/_{\mathrm{g}}\right) = \frac{\left(\text{mass}_{\text{wet}} - \text{mass}_{\text{dry}}\right)/\rho_{water}}{\text{mass}_{\text{dry}}} \tag{2}$$

The IBI standard for testing biochar particle size reported that the particle sieving is the best method for testing [214]. The IBI classification tool breaks down the particle size as such: above 50mm, 50mm-25mm, 25mm-16mm, 16mm-8mm, 8mm-4mm, 4mm-2mm, 2mm-1mm, 1mm-0.5mm, and below 0.5mm. We determined the likelihood of biochar particles being greater than 2mm was unlikely, due to the reduction of biomass feedstock particle size to less than 2mm. A Gilson Sieving shaker was used to test the particle size of the biochar. For biochar size particle analysis in this study, the sieve sizes were as follows: above 1.4mm, 1.4-1.00mm, 1.00mm-850µm, 850-600µm, 600-425µm, 425-250µm, 250-106µm, and below 106µm. These sizes were chosen based on the preliminary sieving on the biomass sample before the pyrolysis process. 13.61 grams of B1 sample and 12.63 grams of B2 sample were sieved under similar conditions. The Gilson Sieving shaker was run for 14 minutes to allow proper time for sieving to occur. Each tray was weighed before and after the sieving and the mass balance was calculated. The mass was recorded and the percentage of mass was calculated and is presented in the Results and Discussion section for each particle size.

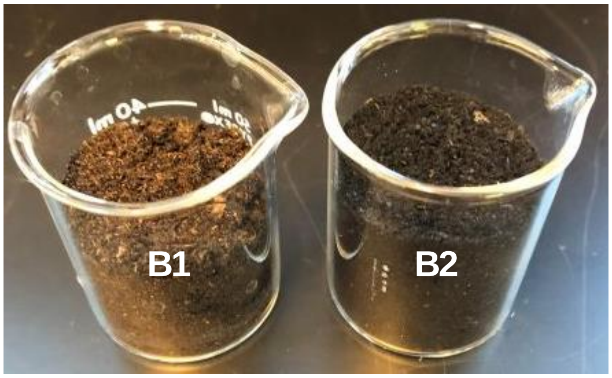

Figure 3.3. Biochar B1 (after CFP process) and B2 (after CFP and FBSP processes) samples

3.4 Results and Discussion

This section presents the results of preprocessed biomass and biochar physicochemical properties obtained from various characterization approaches. The differentiation in the samples comes from the addition of FBSP reactor and the results in the difference between the physical appearances of the samples can be seen in Figure 3.3. The particle size distribution testing indicates that most of the mass of B1 and B2 (91.2% and 93.5% respectively) was found in the pan as the smallest particle size sieved was 1mm (Table 3.2). The developed in-house particle sieving process shows that 71% and 67% mass of the respective biochar was contained in the below 0.250mm range, which is considered as fine biochar [220]. The majority of biochar being in this range is most likely due to the smaller particle size of biomass, which is sifted before. Biochar particle size is important in both water-holding capacity and penetration into soils. Medium biochar particle size (between 250mm and 850mm) was found to retain the most water in a study of biochar added to sand [220]. The finer biochar particles have shown to migrate further down into soils and contribute to higher micrometer-particle and nanoparticle transport [221]. However, the particle size of biochar is not static in that the particles can break down over time and impact microbial degradation rates [222].

Table 3.3 reports the results of samples B1 and B2, which show as-received and dry weight. The results of each test are differentiated as the moisture contained in biochar adds to the overall mass, as well as some of biochar properties. Some of the tests require biochar to be suspended in water, and therefore the dry weight measurements are not analyzed and listed in the results.

Table 3.2. Particle size distribution testing

Sieving pan size	**B1 (g)**	**% mass B1 (12.64g)**	**B2 (g)**	**% mass B2 (13.57g)**
2.0mm-4.0mm	-	0.70	-	0.80
1.0mm-2.0mm	-	8.10	-	5.70
>1.4mm	0.14	1.11	0.06	0.44
1.0mm -1.4mm	0.09	0.71	0.05	0.37
850µm-1.0mm	0.08	0.63	0.07	0.52
600µm-850µm	0.40	3.16	0.62	4.57
425µm-600µm	0.80	6.33	1.27	9.36
250µm-425µm	2.14	16.93	2.40	17.69
106µm-250µm	5.25	41.53	4.95	36.48
<106µm	3.74	29.59	4.15	30.58

Table 3.3. Characterization results of preprocessed biomass and two types of biochar

	B1		B2		Biomass
pH	4.3		4.5		-
Electrical conductivity (mmhos/cm)	0.5		0.2		-
Moisture (%w/w)	5.6		3.5		-
Water holding (mls water/100g dry char)	76.5		74.2		-
Density (lb/cu)	10.4		8.7		-
Mass composition (%w/w)	**As-Rec.**	**Dry**	**As-Rec.**	**Dry**	**-**
• Volatile fraction	93.0	98.6	95.1	98.5	-
• Ash	1.4	1.4	1.4	1.2-1.5	0.54
• C	29.8	31.6	58.4	59.0-60.5	50.42
• H				5.33	5.86
• N				0.45	0.36
• O (diff.*)				33.94	42.80
• S				0.02	0.02

*Oxygen by difference is calculated as (100 - C - H - N - S - ash) % and may be in error due to oxidation of inorganic components during ashing, double subtraction of components such as sulfur remaining in the ash, or volatilization of other species (such as halogens) not measured or subtracted.

The pH results for B1 and B2 are 4.3 and 4.5, respectively that are significantly lower than the expected value of biochar pH from fast pyrolysis processes [223]. Biochar pH produced in this study is similar to the result of slow pyrolysis-based biochar produced at 300-400°C, reported by [202]. Another explanation of low pH given by Gabilan lab was that the duration of time to let biochar sit could contribute to oxidation, as well as the wood vinegar buildup.

The electrical conductivity of B1 and B2 was found to be 0.055 S/m (0.55 mmhos/cm) and 0.022 S/m (0.22 mmhos/cm), respectively; which are slightly lower than earlier studies, reported wood-based biochar electrical conductivity [224,225]. Biochar electrical conductivity is the key factor in transferring salt content into the soil and is derived from the measure of salt content in soil and depends on the salt content, composition, and affinity to biochar [215].

The water-holding capacity of B1 and B2 are 0.5 and 0.2 mls water/100g dry char, respectively that are significantly lower than results reported by [226]. This could be attributed to differences in biomass feedstocks, production process configurations, and characterization methods (e.g., testing parameters and initial biochar drying). To calculate the water-holding capacity, the overnight evaporation method (i.e., drying biochar, rehydrating/soaking, filtering, and letting rest overnight) has been applied because it can reduce the amount of ambient moisture and partially dry biochar. The similarity of the obtained results of various methods is that the water-holding capacity of

B1 is greater than B2, which are expected as B2 is heated for a longer period of time. This longer heating duration of B2 leads to drying and the removal of access oil.

The volatile fraction results of B1 and B2 are slightly higher than prior reported results in the literature, employing slow pyrolysis at lower temperatures by [202,227]. Biochar volatile fraction contains most of the main nutrients and reactants, including most of the major chemicals, except biochar ash [215]. Ash content results of B1 and B2 are lower than prior studies, reporting similar pyrolysis-based biochar from wood. The lower ash content could be a direct result of the lower residence time of the conversion process. Additionally, the low pH and high volatile fraction are also indicators of low ash content [215].

The recalcitrant carbon levels measured for B1 are 29.8% mass as received and 31.6% of dry mass, and for B2 are 58.4% mass as received and 60.5% of dry mass. The results indicate that the total carbon are 37.25% mass as received and 39.5% of dry mass for B1, and 73% mass as received and 75.6% of dry mass for B2. The total carbon levels of B1 being less than 50% mass place as low end Class 2 biochar in the category of pyrogenic carbonaceous material [214,216]. The total carbon levels of B2 are nearly double in comparison to B1. The B2 carbon levels are consistent with the results of earlier reported studies, using slow pyrolysis technology [215,224,228].

The bulk density of B1 and B2 are 166.6 kg/m^3 (10.4 lb/cu ft) and 139.4 kg/m^3 (8.7 lb/cu ft), respectively. The bulk density of biochar is feedstock dependent, and biochar produced from feedstock with low bulk density will, in turn, have a lower bulk density [229]. Biochar with the low bulk density of is more desirable as it increases desirable physical properties, such as porosity [229].

The elemental analyses performed in this study show that the total carbon of B2 is higher than B1 and over the 50% w/w required by the EBC. In comparison to the earlier conducted study by Bachmann et al. (2016), using woody-based biochar, the ash levels of produced biochar in this study are much lower (1.5% vs. 11%) and the total carbon levels are also lower in our biochar (60% vs. 81%) [215]. Also, the oxygen level of our biochar is much higher (33% vs. 5.8%), however, the results of chemical elements (e.g., H, N, and S) analysis are similar to prior reported results. Based on the data collected using the IBI biochar classification tool, it was determined that the produced biochar after CFP and FBSP processes in this study could be classified as a Class 1 fertilizer [230].

3.5 Conclusions

Biochar production from biomass feedstocks can be accomplished in different ways and is beneficial for organic and sustainable soil amendment and several other food-energy-water related applications. Based on the study performed herein, it was determined that biochar production through

CFP process is not sufficient in terms of process yield and biochar quality. Therefore, a mixed fast and slow pyrolysis conversion pathway is proposed and empirically verified to address the sustainability and commercialization challenges through improving productivity and efficiency. Biochar produced using a continuous, entrained flow CFP reactor has the total carbon content of 39.5% of dry mass, which is considered as low-quality biochar based on IBI and EBC standards. However, the mixed conversion pathway is able to produce high-quality biochar with the total carbon content of 76% of dry mass. Biochar produced in both cases (i.e., B1 and B2) was slightly more acidic than the reported studies for other wood-based biochar produced, employing fast pyrolysis reactors, however, the results of mixed processes (CFP and FBSP) are similar to other conducted studies. According to the IBI classification approach and obtained results from physiochemical properties analysis, biochar produced in this study characterized as a Class 1 fertilizer. Further research paths include (a) exploration of empirical studies and various conversion processes to promote physicochemical and agronomic properties of biochar and (b) exploration of real-time biochar characterization to evaluate the conversion parameters and optimize the biochar quality for various application purposes.

Chapter 4: Life cycle assessment of pyrolysis-derived biochar from organic wastes and advanced feedstocks

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4.1 Abstract

Recent interest in reducing stress on the food-energy-water (FEW) nexus requires the use of renewable, organic products that can subsequently address environmental sustainability concerns, such as mitigating greenhouse gas emissions. Pyrolysis-derived biochar from organic wastes (e.g., nutrient-rich agricultural wastes and leftovers, forest harvest residues, and cattle manure) and advanced feedstocks (e.g., algae) is capable of addressing ever-increasing global FEW concerns. Biochar water-nutrient holding capacity and carbon sequestration are key attributes for improving organic farming and irrigation management. The major challenge to commercialize biochar production from organic wastes is the conversion process. Pyrolysis process is a cost-effective and successful approach in comparison to other conversion technologies (e.g., gasification) due to low energy requirement and capital cost, as well as high process efficiency and biochar quality. To determine the environmental impacts of the biochar production process, an analysis of the material, energy, and emission flows of a small-scale pyrolysis process is conducted for a real case study, using life cycle assessment method with the assistance of available life cycle inventory databases within OpenLCA software. The results demonstrate that this study is able to enhance sustainability aspects across FEW systems by (a) employing a portable refinery to address upstream challenges (i.e., collection, transportation, and preprocessing) of waste-to-biochar life cycle, (b) recycling domestic forest and agricultural residues (e.g., pine wood), (c) producing organic biochar-derived soil conditioners that can improve organic cropping and FEW systems. Ultimately, we conclude by discussing techno-economic and socio-environmental implications of biochar production from organic wastes and advanced feedstocks.

4.2 Nomenclature

Wattage of heater (W)
Cooling rate
Heating rate
Wattage of CFP external heater (W)

ext

Cooling rate of CFP external heater

ext	
	Heating rate of CFP external heater
ext	
	Wattage of bed reactor heater (W)
bed	
	Cooling rate of bed reactor heater
bed	
	Heating rate of bed reactor heater
bed	
$\dot{Q}_{loss}$	Heat loss over time (MJ/S)

4.3 Introduction

Growing concern within society over the use of FEW resources due to the population growth has stimulated research efforts to find FEW beneficial products that can address current FEW needs without compromising the future generation's ability to meet their needs [111]. Sustainable and organic bioproducts (e.g., biochar) can address not only FEW needs but also mitigate greenhouse gas (GHG) emissions and the environmental impacts factors, which is one of the national priorities and requires special attention [231]. Recently, a focus has been shifted to the generation of renewable energy sources (e.g., bioenergy) from carbon neutral or low-emission fuel sources [232]. Biochar, a carbon-rich and solid by-product of the pyrolysis process has been found to have many different applications from the improvement of soil health, structure, and water-nutrient holding capacity to the generation of energy when co-fired in coal-powered plants [1,179]. In addition to these FEW benefits, biochar production is a sustainable process that can improve resource reuse and waste management by utilizing domestic biomass feedstocks (over one billion dry tons available annually [233]), producing value-added products, and developing a solid method for waste removal [200]. Pyrolysis is one of the promising technologies for biochar production due to several attributes, such as feedstock agnostic and amenable to portable processing with relatively low energy consumption [39].

Pyrolysis process is the thermal decomposition of organic materials in an oxygen-deprived environment, which can produce three different products, e.g., bio-oil, biochar, and syngas [201,224]. Conversion process configuration (e.g., residence time, temperature, and pressure) and feedstock type play a major role in the yield and quality of the final products [228]. Formally the bulk of research has been in the production practices and uses of bio-oil due to high energy density in comparison with biochar. However, a shift to the production and application of biochar has occurred due to the growing awareness on organic farming and waste management [138]. Prior studies investigated various sustainability aspects of biochar production from various biomass feedstocks, e.g., forest harvest and agricultural residues [234,235]. Using other pyrolysis products (e.g., bio-oil and syngas) as a heat and energy source can enhance sustainability benefits in the midstream segment (i.e., pre-/post-conversion processes) of biomass-to-biochar supply chains [236,237].

The sustainability and life-cycle assessment of biomass pyrolysis has been key in the understanding of the benefits of biochar as a soil amendment product. Peters et al. (2015) reported that the pyrolysis of biomass has several carbon mitigation benefits, such as reducing global warming potential (GWP) by using biomass-based biochar to soils or used as an energy source [238]. Utilizing organic biomass and the co-firing of biochar was compared to alternative energy sources, which the results show that biochar co-firing benefitted both the abiotic depletion potential and GWP of the energy sources [238].

Table 4.1. Estimated syngas composition [188,211,223,224]

Molecule	**Volume Fraction**	**Estimated Emission (w/w)**
CO	0.312	0.101
CO_2	0.197	0.064
H_2	0.132	0.043
CH_4	0.078	0.025
O_2	0.006	0.002
C_2H_4	0.027	0.009

Similarly in a study conducted by Roberts et al. (2009), the energy, GHG, and economic flows of the biochar production process was analyzed [234]. They reported the energy consumed vs. generated, and the GHG emitted vs. reduced in the processing of several different biomass feedstocks. From the earlier studies, we see the importance of the utilization of the by-products to improve the sustainability of biochar. It was determined that the analysis of our syngas would be a key factor in determining the sustainability of our process, as well as show the potential for future research in the utilization of this gas.

Recent studies reported the average volume fraction of molecules contained in woody biomass (e.g., pine wood) and estimated syngas composition produced using pyrolysis technology (Table 4.1) [204,227,239,240]. Dufour et al. (2012) investigated synthesis gas (syngas) production from spruce wood chips, using fast pyrolysis in a tubular reactor at high temperature (~700°C), as well as the effect of reactor temperature on final products distribution [204]. Wang et al. (2005) explored pyrolysis of different woody biomass feedstocks in a fluidized bed reactor at 450-550°C and reported the data collected about the produced syngas from the pine wood [239]. Aguado et al. (2000) investigated fast pyrolysis of sawdust in a conical spouted bed reactor at various temperatures and reported the process yields and product composition from pine sawdust with a particle size of 0.8 to 2.0 mm [227]. Frau et al. (2015) reported the characterization of several kinds of coal, and biomass feedstocks (e.g., stone pine wood chips), using pyrolysis and gasification for hydrogen production, as well as product analyses and process optimization [240]. The estimated emission reflects the volume fraction of each molecule in syngas with the assumed 32% syngas production during the pyrolysis process.

This study focuses on sustainability assessment of biomass-based biochar production, using a unique, small-scale conversion pathway. A real case study is conducted to collect the experimental data for the input and output analysis, such as material, energy, and emission flows. Next section provides details about the constructed biochar production process and developed decision models for LCA.

4.4 Methodology

4.4.1 Biochar Production Process

Pyrolysis conversion process has been used in this study due to high process yield and

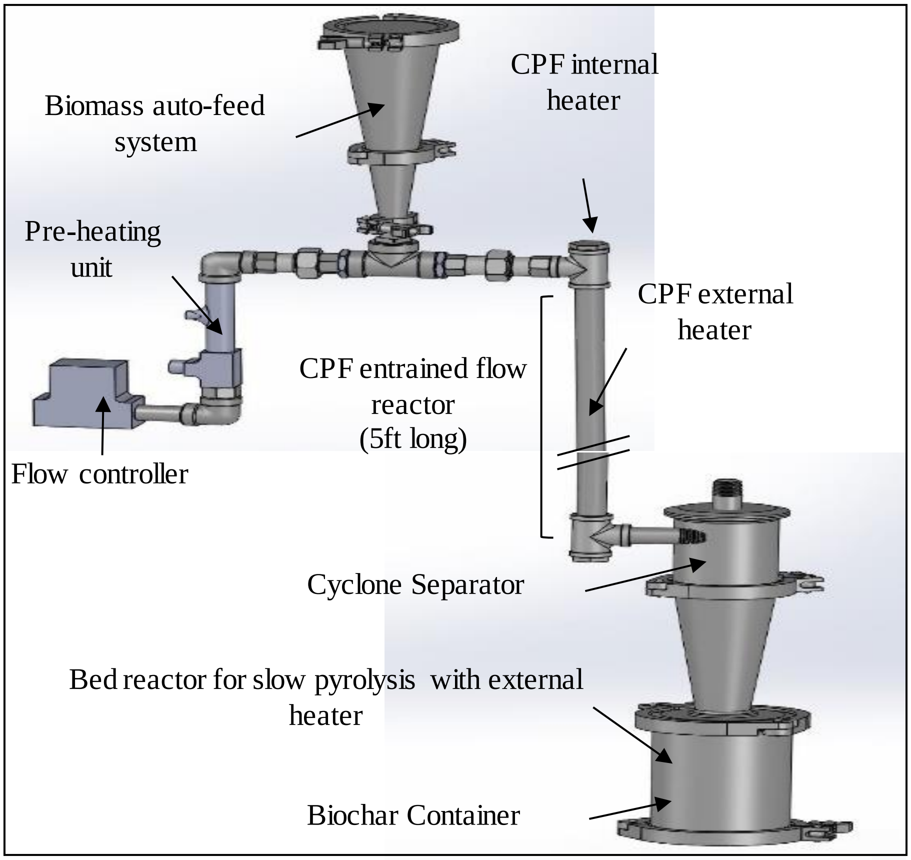

Figure 4.1. Schematic of biochar production process.

product quality. The constructed apparatus for biomass pyrolysis includes an auto-feed system with approximately 60 grams of biomass capacity that continuously transfers biomass from the feed hopper to the reactor with various feeding speeds. The conversion process is accomplished with the controlled flow of nitrogen gas that entrains and passes the biomass feedstock to the reactor units at a rate of around 20 liters per minute at 15-20 psi pressure and preheating with a temperature around 400°C.

The customized conversion pathway developed in this project contains two different reactors, i.e., an entrained flow reactor (approximately five feet) with temperatures around 400-450°C for around two seconds for catalytic fast pyrolysis (CFP) and a bed reactor with temperatures around 300-350°C for 30-60 minutes for a slow pyrolysis (SP) process (Figure 4.1). The energy flow of the system can be seen mostly in the heating units, which are the pre-heater before the feed hopper, internal and external heating for CFP reactor, as well as external heating for the bed reactor. Biochar collection is accomplished with the use of a cyclone separator with approximately 60 grams capacity. On the other hand, bio-oil collection is performed with the use of a two-stage condenser and a chiller that can reduce the temperature of produced gas from around 400°C to 5°C, and convert the gas to liquid.

4.4.2 Sustainability Assessment

In addition to conversion process analysis, an LCA is conducted to measure environmental impacts over the biomass-to-biochar production life cycle. The conducted LCA method in this study includes four steps: (1) a definition of the goal and scope, (2) life cycle inventory (LCI) to quantify the inputs and outputs of this system, (3) life cycle impact assessment (LCIA) to quantify the environmental impact metrics based on the data sourced in the LCI, and (4) interpretation of generated knowledge based on the results obtained in the LCIA.

Goal and Scope. The goal is to identify the limiting factors for mitigating environmental pressures (e.g. GHG emissions) and improving energy efficiency across waste-to-biochar operations. The LCA study applies the gate-to-gate system boundary to assess the small-scale pyrolysis conversion process. The scope includes the midstream segment of biomass-to-biochar supply chains, particularly conversion processes. The functional unit in this study is one gram of biochar produced under various scenarios. The LCA is performed in OpenLCA (an open-source, free software for LCA and sustainability assessment), using the collected data from several small-scale experiments and open-source LCI databases.

Table 4.2. LCIA data based on the CML baseline from OpenLCA.

Impact category	Reference unit	Result
Acidification potential - average Europe	kg SO_2 eq.	68.5
Climate change - GWP100	kg CO_2 eq.	1,044.6
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	3.9
Depletion of abiotic resources - fossil fuels	MJ	67,774.5
Eutrophication - generic	kg PO_4 eq.	12.8
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	9.1
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	1,934.0
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	1.27E+6
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0.0
Photochemical oxidation - high Nox	kg ethylene eq.	-14.3
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	1043.8

LCI. In order to determine the certain gasses emission to air, a short literature review was conducted and limited to pyrolysis technology and pine wood as biomass source. With the data collected for the electricity inputs and gas emission outputs, biomass pyrolysis process was created based on both the experimental and collected data. The collected data was obtained from the European Life Cycle Database (ELCD), i.e., Pine wood, production mix, at sawmill, timber, 40% water content. The key parameters selected for this study are: (a) biomass (average mass contained in feed system), (b) runs (number of refilling and emptying of the feed hopper), (c) gas (calculated amount of nitrogen used per run), and (d) electricity (Watt-hours used). The determination of bio-oil and biochar outputs are based on the biomass and the yield percentage.

The electricity usage of the system was based on both the experimental and the reported data on Idaho Falls power and Bonneville Power administration's websites. Based on the data from Idaho Falls power, approximately a one-third of the electricity used is produced by their hydroelectric plants, and the rest is sourced from Bonneville power administration [241]. Based on the Bonneville power administration data, and available data in OpenLCA, the two-thirds of the electricity supply is assumed to be sourced from 53.5% Hydroelectric, 15.1% Coal, 3.0% Nuclear power, and the rest was assumed to be general U.S. grid mix [242].

The data collected from the execution of the biochar production process and resulting outputs were entered into OpenLCA, and the resulting LCIA was created from the production of one ton biochar.

LCIA. The process developed herein was converted into a product system, which biochar is the primary product of interest. The LCIA was performed, using the defined product system and process for the production of one metric ton of biochar and Institute of Environmental Sciences (CML) baseline from the OpenLCA, LCIA database (Table 4.2).

Interpretation. The data collected in the OpenLCA study shows the quantitative analysis of the impact factors involved with the production of one ton biomass. The key components of the developed LCA in this study in terms of environmental impacts include global warming potential (GWP) for 100 years (kg eq.), the human toxicity (kg 1,4-dichlorobenzene eq.), eutrophication potential (kg PO_4 eq.), and the depletion of abiotic resources (kg antimony eq.) [243]. In this study, the depletion of resources is also given as depletion of fossil fuel resources. An analysis of each factor and their effect on the environment is given. The contributing sources of each environmental impact are given as well. This quantitative data will be useful in both the understanding of the environmental impacts of system inputs, as well as determining where future optimization efforts should be focused.

4.5 Case Study

Biomass sample used in this study is composed of mostly Pine sawdust. The pretreatment process includes dewatering, size reduction, and separation, using a rotary dryer, grinder, and sieving with a 2mm mesh size sieve, respectively. The experimental data is collected using various equipment (e.g., in-line sensors and controllers) and developed human-machine interface (HMI). Mass-to-mass analysis of biochar production is essential in the calculation of sequestered carbon and environmental impacts. The use of woody biomass as an input to the process has inherent environmental impacts, such as eutrophication and depletion of abiotic resources. At full operation, our conversion setup consumes 20 liters per minute of N_2 gas, which is 200 liters per batch. Each batch contains

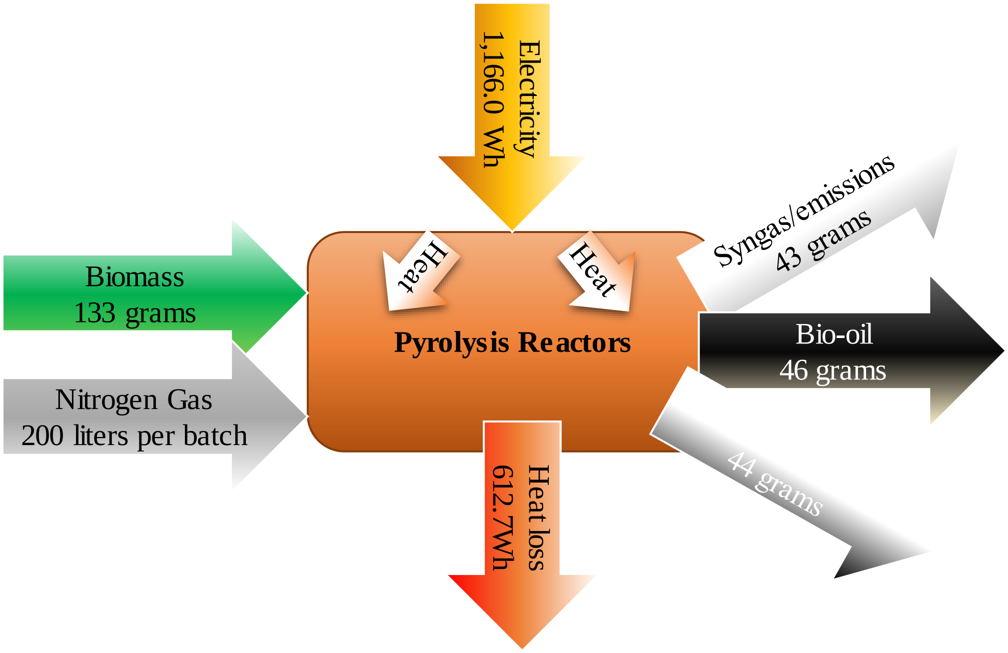

Figure 4.2. Block diagram of inputs and outputs of biochar production process from biomass feedstocks.

Table 4.3. Product characterization and process analysis.

Sample	Ash (w/w)	C (w/w)	H (w/w)	N (w/w)	O (diff)* (w/w)	S (w/w)
Biomass	0.54	50.42	5.86	0.36	42.80	0.02
Bio-oil	0.08	20.07	2.00	0.11	12.33	0.00
Biochar	0.41	19.51	1.76	0.15	11.22	0.01
Syngas	0.05	10.84	2.09	0.10	19.25	0.01
% mass gas/loss	8.71%	21.49%	35.74%	26.96%	44.98%	49.64%

* Oxygen by difference is calculated as (100 - C - H - N - S - ash)% and may be in error due to oxidation of inorganic components during ashing, double subtraction of components, such as sulfur remaining in the ash, or volatilization of other species (e.g., halogens) not measured or subtracted.

approximately 60 grams of biomass, and two to three batches are completed before fully biochar collection. The average biomass processed is 130 grams, resulted in producing approximately 40 grams biochar, 45 grams bio-oil, and the rest is either lost in the system or off-gassed in syngas. Based on the process analysis and major product characterization, the estimated amount of key elements (e.g., C, H, N, O, S, and Ash) either not collected or off-gasses are listed in Table 4.3 as a weight product vs. weight feedstock ratio.

To determine the sustainability benefits and environmental impacts of the developed conversion process, the amount of energy used is compared to the return in products. The energy needed to produce one gram biochar is key in determining the cost and environmental impacts of biochar production from biomass feedstocks. Table 4.4 presents the average results from pyrolysis experiments, including three five-minute runs and an additional 30 minutes of heating performed via the bed reactor for increasing biochar quality. A total of 133 grams of biomass were processed, which produced around 44 grams of biochar (33 wt. %). The total energy used in the conversion process was 1,166Wh, and therefore a total of 8.7Wh are consumed per gram biomass processed, and 3.76E-2 grams biochar are produced per Watt-hour consumed (Figure 4.2).

To complete the environmental impact analysis, the following assumptions were made based on the collected data and reported information from the conducted experiments and prior studies:

- The pretreatment processes (e.g., dewatering, size reduction, and separation) are not considered in the LCA.
- All loss (e.g., syngas and tar) is considered as emission to air, and the amount is the percent mass unaccounted after biochar and bio-oil collection.
- The data collected (e.g., released syngas) in prior studies was chosen based on similarity to our conversion pathway. The reported data was averaged to approximate the syngas production of our system.

- The estimated emission is calculated with the assumption of the syngas produced accounts for all mass not accounted for bio-oil and biochar production, which is approximately 32% of the mass input.
- The environmental impact of each electricity source was found in the OpenLCA, Product Environmental Footprints free database. Based on the data from Idaho Falls, ID Power website, approximately one-third of the electricity used is produced by hydroelectric plants and the rest is sourced from Bonneville Power Administration [241].

It was found from the experiments that the temperature drops at a decreasing rate. Therefore, we can determine that heat loss is temperature dependent. To perform a small analysis of the heat loss, the following simplifications and assumptions are made about the heat loss in the system:

- Heat loss correlates directly to the ΔT of the CFP external heating unit and SP reactor heating unit as they are the main heaters that are exposed to the outside.
- Heat of the system directly correlates to energy consumption.
- Heat loss is calculated when the system reaches the high-temperature set point and the heater shuts off, which heat loss is the highest. (Figure 4.3c, 4.3e)
- Energy required to heat up 1°C is calculated within the first 30 seconds of heating units, which heat loss is the lowest (Figure 4.3b, 4.3d).

The time that it takes the temperature to drop below the low set point is recorded. With this data, the time and energy potential needed to return the system to the high-temperature set point are used to determine the heat loss, using Equation 1.

$$\dot{Q}_{loss} = \frac{E * C}{H} \qquad \textbf{1)}$$

Plugging in the values for E_{ext}, C_{ext}, and H_{ext}, the calculated heat loss of external CFP heating

Table 4.4. Pyrolysis process input-output analysis.

Base Case	Unit	Result
Biomass	Gram	132.6
Pre-heater for gas heating	Temp. (°C)	250.0
	Temp. (°C)	465.0
Fast pyrolysis reactor configuration	Gas Flow (Lpm)	20.0
	Pressure (psi)	15.0
Energy consumption	Electricity (Wh)	1,166.0
Bed reactor for biochar	Temp. (°C)	325.0
Bio-oil	Gram	45.9
Biochar	Gram	43.8
Syngas/Tar/Loss	Gram	42.8

unit is approximately 312 MJ/s (watts). Our calculation of energy loss is approximately 296.4 Wh for a two-batch operation with an average run time of 57 minutes and average energy consumption of 1,175 Wh. On the other hand, the heat loss of the bed reactor is similar to external CFP heater due to the identical configuration and operation procedures. Plugging in the values of E_{bed}, C_{bed}, and H_{bed}, the calculated heat loss is approximately 302 MJ/s (watts). The bed heater is activated once the CFP reactor heats up to full temperature and is run for an additional 30 minutes at 300-350°C after conversion processes. The bed heater is run for an average total of 64 minutes. Consequently, the total energy loss of bed reactor is 322Wh, and the total estimated energy loss of both external CFP and bed reactors are 618.7 Wh.

4.6 Results and Discussion

With the assistant of OpenLCA databases and experimental data, we developed the LCA study for biochar production, using the pyrolysis technology to explore sustainability strategies across biomass-to-biochar life cycle. Certain assumptions are made and listed in Case Study section to compare the results with other studies. The total energy used (when all the heating units are operating) is approximately 1,412 Watts, and can be broken down as follows: 12 Watts for controllers (e.g., temperature, flow, and pressure monitoring), 20 Watts for solenoid controllers, 370 Watts for the pre-heater, 540 Watts for the CFP external heater, 120 Watts for internal CFP heater, and 470 Watts for bed reactor heater. The material flows out of our system based on experimental data are 34 and 32 grams of bio-oil and biochar per 100 grams biomass, respectively. The rest is combined in syngas production and loss. We can determine that loss is greater than zero due to build up contaminants and tar in the conversion apparatus that requires cleaning. The breakdown of the individual components is given by the analysis of the biochar process, developed in OpenLCA (Table 4.5). Results are calculated in OpenLCA based on the available data and the inputs and outputs of the biochar production process.

The results indicate that the produced GHG emission per metric ton of biochar is predicted to be 1,044 kg CO_2 eq. The bulk of GHG emission within the production process comes from the direct emission of syngas to the air with the secondary source being the electricity generation for running the process. Woody biomass resources deduct from the total GWP at nearly -3,000 kg CO_2 eq. per metric ton of biochar produced. Prior LCA studies of other biomass-to-biochar systems reported the GWP of negative values for biochar production and consumption [234]. The discrepancy is due to the lack of post-processing data, such as the carbon storage potential of biochar [238].

The human toxicity impact of biochar production is 1,934 kg 1,4-dichlorobenzene eq. per metric ton of biochar due to toxic effects on humans or animals based on the developed standards within OpenLCA (LCIA method) for the daily intake of 1,4-dichlorobenzene [244]. The main contributor to the human toxicity in this study is the grid mix of the electricity and the compressed nitrogen used in the production process. In addition, the depletion of adiabatic resources is 3.8 kg antimony (Sb) eq., which nitrogen production and consumption is the main factor of environmental impacts on human health, biodiversity, and material welfare due to the natural resources depletion [245]. The eutrophication potential is estimated as 12.8 kg PO_4 eq., which mainly comes from the leaching of nitrates during the production of nitrogen gas and generation of grid mix electricity, and the pine wood production.

The energy used to increase the temperature by about 1°C in our pyrolysis reactors is measured, using a power data logger to record the energy consumption. The amount of heat lost to the environment Q_{loss} is calculated with the flow off. This was done because the gas flow cools the reactor internally, and the heat transferred to the gas flow is considered in the pyrolysis of the biomass. The required time to reach the CFP internal temperature set point (~450°C) is approximately 26 minutes from our average starting temperature of 21°C (Figure 4.3a). For power consumption and

Table 4.5. LCIA impact contributors.

Impact Factor*	**Reference unit**	**Wood Pyrolysis**	**Electricity (delivered)**	**Nitrogen gas**	**Pine wood**
AP	kg SO_2 eq.	0.00	30.24	37.95	0.30
GWP100	kg CO_2 eq.	2,668.95	1,389.88	0.00	-3,014.27
Dep E, U	kg antimony eq.	0.00	0.02	3.85	0.00
Dep. FF	MJ	0.00	66,815.01	0.00	959.49
Eut.	kg PO_4 eq.	0.00	2.75	9.99	0.06
HTP	kg 1,4-dichlorobenzene eq.	0.00	1,040.56	891.39	1.92

*Impact categories: Acidification Potential - average Europe (AP); Climate change - GWP100 (GWP100); Depletion of abiotic resources - elements, ultimate reserves (Dep E, U); Depletion of abiotic resources - fossil fuels (Dep. FF); Eutrophication – generic (Eut.); Human toxicity - HTP inf (HTP) time-saving purposes, it was determined the best option for heat up was to first heat up the CFP reactor externally (Figure 4.3b), then use the internal CFP heater, which prepares the conversion setup at a faster rate. When the heating units stop working, the temperature begins to decrease at a rate of approximately -1.3°C per second (Figure 4.3c). After fast pyrolysis, the SP reactor is used for over 60 minutes to improve the quality of the collected biochar (Figure 4.3d). The average SP cooldown is predicated as -0.45°C per second (Figure 4.3e).

In the analysis of our developed conversion reactors, the energy used has the possibility to be remedied with the implementation of better insulation to reduce heat loss, or the combustion of syngas and bio-oil to produce energy and heat for the production process. For example, syngas can be used for biomass dewatering, using a dryer, or reuse it within pyrolysis reactors [236]. However, recycling the syngas into the conversion process requires extra energy for collection and pumping back into the system. Additionally, the bio-oil produced can be co-fired and used as an energy source [237].

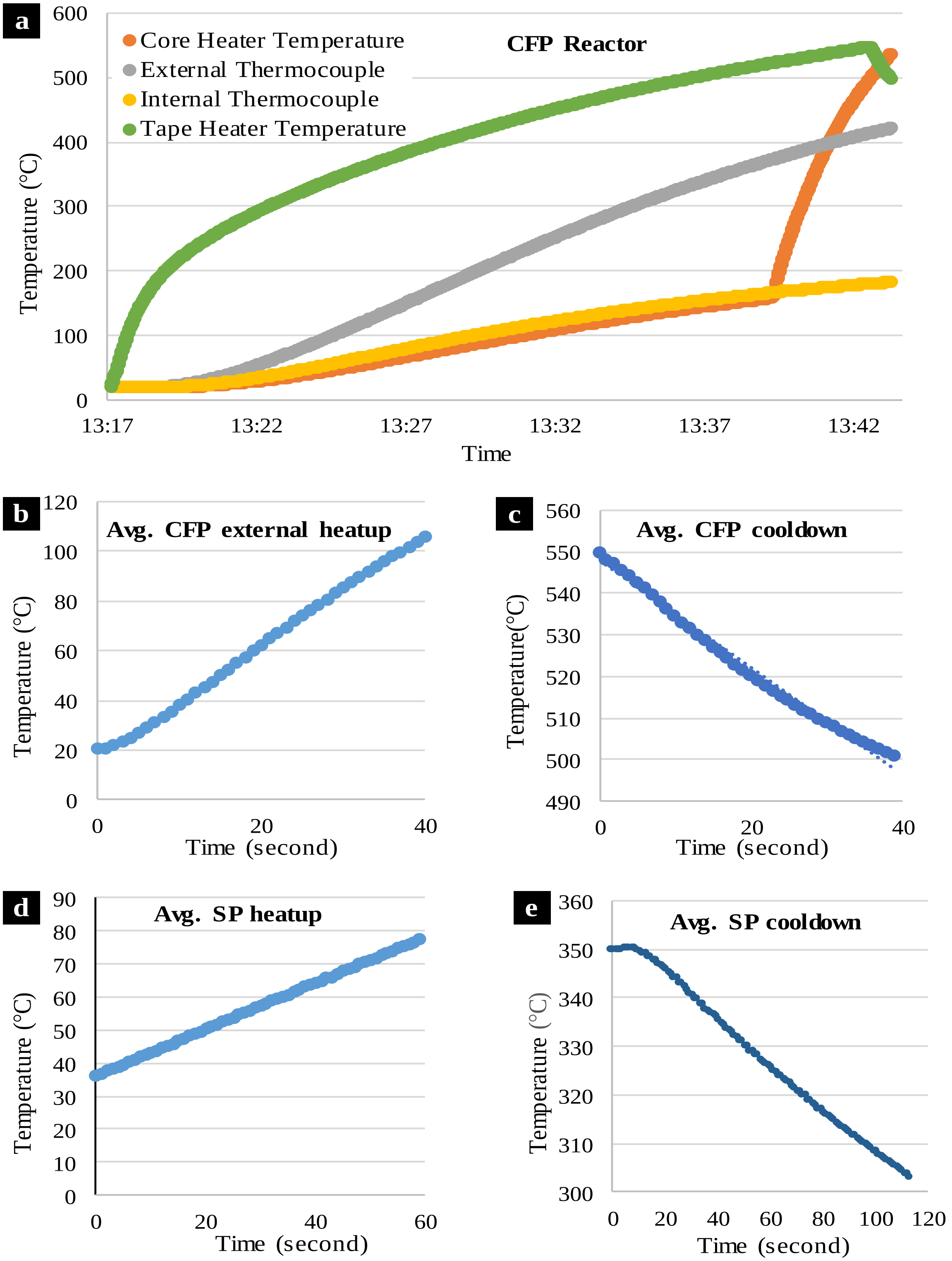

Figure 4.3. Required time and reactor temperatures for biochar production: (a) time and temperature correlation in CFP reactor, (b) average initial CFP external heating rate, (c) average initial CFP cooling rate, (d) average initial SP heating rate, and (e) average initial SP cooling rate.

With the current reactor configuration and the assumptions made in the calculation of the heat loss of the system, approximately 52% of energy used is lost to the environment. The assumptions made lead to a higher result than expected as the temperature drop over time is contributed to heat loss to the environment not heat transferred into the system. Since the temperature increases during heat up and does not initially drop off with the termination of the outside heating source, therefore, the heat transfer into the system is greater than zero. However, the heat transfer was deemed negligible in the calculation of heat loss. With the current heat loss calculation, there is room for optimization of the conversion process and faster heats up the reactor to heating set points.

4.7 Conclusions

Growing concerns in global climate change and negative impacts on the FEW resources have led to investigate potential sustainable products and solutions through the LCA method. Recent studies dealing with reusing organic wastes (e.g., forest and agricultural residues) to produce value-added products have shown to be a promising approach to enhance FEW sustainability. This study focuses on the environmental impact assessment of biochar production from woody biomass, using a unique, small-scale conversion process. The develop conversion pathway includes catalytic fast pyrolysis reactor and a SP bed reactor to produce high-quality biochar from various biomass feedstocks. We combined the data from experiments and prior studies, as well as OpenLCA available databases to explore the environmental impacts across the biomass-to-biochar life cycle, particularly midstream segment, including pre-/post-conversion processes. The LCA results show that the GHG emissions of small scale entrained flow reactor were sourced in the form of syngas, and without proper collection and recycling, syngas is emitted directly into the air.

The mass-to-mass and energy consumption analysis of the small-scale conversion process indicate that biomass, inert nitrogen gas, and electricity are the only inputs into the system. The outputs are biochar, bio-oil, and syngas, as well as heat loss and associated emissions. The LCA results indicate that part of the energy input is expelled in loss to the environment, which provides opportunities to improve the conversion process via better insulation to prevent energy and heat loss. The heat loss calculation is necessary to determine future direction and assess the potential for biochar commercialization. Additionally, bio-oil and syngas utilization for biochar production can reduce energy requirement, and subsequently mitigate environmental impacts and production costs. The potential paths for future research include (a) life cycle assessment to elucidate the application impact of pyrolysis derived biochar on the FEW nexus and (b) biochar effects on the soil-plant systems, organic farming, and waste management.

Chapter 5: Conclusions

5.1 Summary

In Chapter 2, it is shown that over the last ten years, the interdisciplinary FEW research has been a fast-growing field of study due to the shortage of literature for effective strategies to improve FEWS efficiency and productivity. With the current focus of sustainable development goals, there is a need for a connection to be drawn between the challenges facing FEWS and biochar-derived products. The viability and implications of biochar-derived products to sustainable development goals, FEWS nexus challenges, and associated factors have been discussed in this chapter. However, remaining questions include the cost of biochar production, the long-term viability of biochar-amended soils, and the possible competition for land space if crops are being grown for biochar production.

In Chapter 3, it is shown that biochar production from biomass feedstocks can be accomplished in different ways and is beneficial for organic and sustainable soil amendment and several other FEW related applications. It is also determined that in the review of biochar quality testing methods, there is a lack of standard biochar characterization approach within the literature to compare biochar quality results. The IBI and EBC have determined a characterization method to determine the soil applications of biochar, but not the water treatment and energy potential of biochar. The application of the literature review is shown in the advancement of our real world pyrolysis system. The effect of the changes made to this system on biochar yield and quality in the application of biochar to soil is analyzed using the guidelines and standards set developed by IBI and EBC. From this analysis, it is found that biochar produced using a continuous, entrained flow CFP reactor has the total carbon content of 39.5% of dry mass, which is considered as low-quality biochar based on IBI and EBC standards. However, the mixed conversion pathway is able to produce high-quality biochar with the total carbon content of 76% of dry mass.

In Chapter 4, it is discussed that the growing concerns in global climate change and negative impacts on the FEW resources have led to investigative potential in sustainable products and solutions through the LCA method. Recent studies dealing with the thermochemical conversion of organic wastes to produce value-added products have shown to be a promising approach to enhance FEW sustainability. This study focuses on the environmental impact assessment of biochar production from Pine Wood biomass, using a unique, small-scale conversion process. We combined the data from our experiments and data collected from similar studies, and imported this into OpenLCA's available databases to explore the environmental impacts across the biomass-to-biochar life cycle. The LCA results show that the GHG emissions of small-scale entrained flow reactor are sourced in the form of syngas, and without proper collection and recycling, syngas is emitted directly into the air.

5.2 Conclusions

In Chapter 2, from both narrative and systematic reviews, understanding the ramifications of FEWS is essential to provide a base of knowledge to enhance FEWS sustainability benefits. It is concluded that there is an essential need for FEW nexus frameworks and models to improve FEW security nexus, and sustainable development goals at the domestic and global level. The need for further investigation is increasing not only in the creation of conceptual platforms but in empirical work for specific applications that increase industrial growth. This literature review has been conducted to investigate the state-of-the-art within the FEW disciplines and explore the socio-economic resilience and ecological integrity of regional FEWS by coupling recent improvements.

In Chapter 3, exploration of the proposed portable, mixed fast and slow pyrolysis conversion pathway indicate that this approach is able to address sustainability (e.g., cost and environmental) challenges across biochar production from biomass feedstocks. The decision making platform developed in this study employs new mechanical inventions with growing cyber-based advances for economic and environmental analyses (e.g., process yields and energy consumption). The collected data and obtained results from biochar characterization and LCA aid to enhance sustainability benefits across FEWS. It is also concluded that biochar produced, using the proposed mixed reactors has a higher carbon content, which is one of the major parameters for improving FEWS, particularly organic farming.

In Chapter 4, the gate-to-gate LCA study of the small-scale, mixed pyrolysis process shows that the main environmental impact factors are that of the electricity used to generate heat, and the emission of gasses. The GHG emissions of small-scale entrained flow reactor are sourced in the form of syngas, and without proper collection and recycling, syngas is emitted directly into the air. Of the electricity used in this system, it is shown that a majority was consumed in the heated of the reactors and calculated that approximately 50% of this electricity input is lost to the environment.

5.3 Contributions

The following contributions have been provided to research community:

- Development of a nominal small-scale reactor.
- Collection and evaluation of biochar in the FEW literature.
- Development of a biochar characterization pathway.
- Development of a life cycle assessment of biochar production.

- Development of a Studio 5000 manual.

5.4 Opportunities for Future Research

Future research into the sustainable development of products for the improvement of the FEW nexus should be focused on advancing existing FEW frameworks, streamlining FEW nexus information, and supporting sustainable development. The first step to advancing FEW frameworks will be the establishment of standard metrics, indicators, approaches, and computational tools for FEW life cycle analyses. These standards and computational tools will bring congruity in the presented data that will allow proper comparative analysis to be performed.

The second step will be the development of bioproducts classification tool by determining the market opportunities and end-users. With the proper classification tools, the benefits of products can be applied directly to the FEW needs of a certain region. This classification tool will help further the research and exploration of the biochar market and sustainability impacts associated with biochar-derived products.

Lastly the research and development of techno-economic and socio-environmental studies for solutions with the potential to improve FEWS. With the congruity of FEW data analysis of FEW improvement, solutions will be easier to evaluate and compare to the standards set for FEWS. These standards can then be employed to analyze the productivity potential of biochar-based products.

5.5 Recommendations

In order to improve the future of biochar production and analysis using the small-scale modular reactor, there are a few options. It is recommended that the analysis of the system be performed and modeled to analyze resonance time and thermodynamics. Furthermore, the identification of a quicker test of the quality and characterization of the biochar could allow a determination of optimal pyrolysis conditions. Lastly, the optimization of environmental impacts of the system through improving insulation to reduce heat loss, and utilization of syngas to reduce emission and pre-processing costs.

While the pyrolysis conditions of this system are known, the use of a computer model may be able to determine the optimal pyrolysis conditions. A quantitative model will help understand the possible benefits of changing reactor length and width. Although the modeling will help to determine possible results; the actual results may vary, and therefore it is recommended that the UI team use Thermogravimetric analysis TGA to analyze the chemical components of biochar (e.g., carbon, nitrogen, and hydrogen). This test of quality will cut the large cost of sending the biochar to a lab for quality analysis.

The physical components of the small-scale reactor that need attention are first and foremost the loss of syngas through emission. The current system has no way to contain and utilize the syngas produced, thus under-utilizing the potential of syngas for heating and drying purposes. The system as well could benefit from a slightly larger cyclone and biochar container. At the current rate, the system requires cleaning after just three runs. This requires the system to be turned off and cooled, then reheated after cleaning. In addition, enlargement of the current cyclone may reduce the amount of plugging and encourage better separation.

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Appendix A - Systematic Literature Review

A.1) Analysis of Publication Data

Advanced searches were conducted, using the following keyword sets in WEB OF SCIENCE™ (Thomson Reuters – ISI Web of Knowledge) to collect archival journals and peer-reviewed conference publications based on abstracts, titles, and keywords published (i.e., TS field tag) between *January 1, 2008* and *January 1, 2019*. The keyword sets were used to develop two databases, including publications relating biochar applications with the food-energy-water systems (FEWS).

- **Keyword Set 1.** TS = ((Food OR Agriculture OR Land OR Soil) AND (Energy OR Carbon) AND Water AND (Sustainable OR Sustainability OR Renewable) AND Biochar).
- **Keyword Set 2.** TS = ((Food OR Agriculture OR Soil) AND (Energy OR Water OR Carbon) AND Pyrolysis AND Biochar AND (Sustainable OR Sustainability)).

The period January 1, 2008 to January 1, 2019 was chosen for this systematic review (SR) based on the low number of studies concerning FEWS published outside of the past ten years. Prior to 2008, there are only six and three articles published in Keyword Set 1 and Set 2, respectively. These records were dismissed from this review as prior to the World Economic Forum 2011, the nexus thinking was limited [14]. Directly searching for FEWS and biochar resulted in a database of only 17 publications that all published in 2009 or later. The query of Keyword Set 1 run through the WEB OF SCIENCE™ produced a database of 157 publications and Keyword Set 2 query produced a database of 181 publications. A comparison was conducted to find 60 papers in common between the two

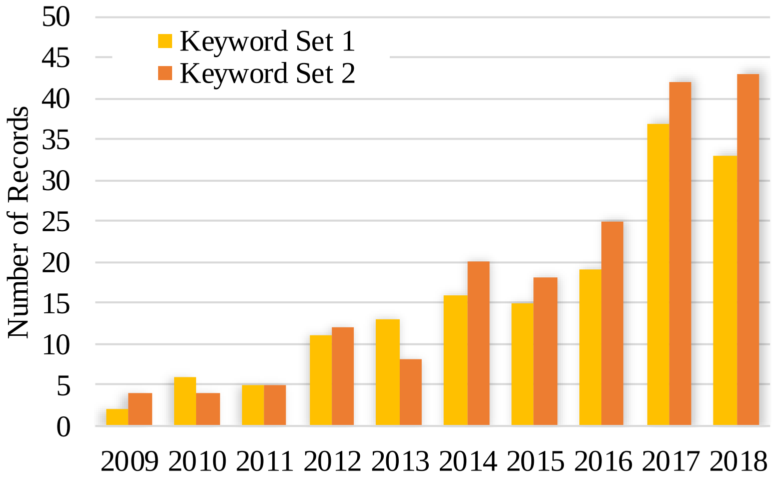


Figure A.1. Number of records produced in each keyword set per year (Jan. 2008 to Dec. 2018) datasets. The results of SR for the selected keyword sets show that the research in this field is accelerating with the most rapid publication growth being seen in the last three years (Figure A.1).

Table A.1. Top ten countries based on number of records (Jan. 2008 to Jan. 2019)

Keyword Set 1			Keyword Set 2		
Countries/Regions	**Records**	**% of 157**	**Countries/Regions**	**Records**	**% of 181**
USA	50	31.85	USA	51	28.18
China	30	19.11	China	32	17.68
Germany	18	11.47	Australia	18	9.95
Italy	15	9.55	Italy	14	7.74
Australia	14	8.92	Germany	13	7.18
South Korea	10	6.37	Spain	12	6.63
India	10	6.37	Greece	11	6.08
Scotland	9	5.73	Scotland	10	5.53
England	7	4.46	England	9	4.97
Greece	6	3.82	India	9	4.97

Table A.1 presents the top ten countries in this field based on the number of publications. In both cases, the U.S. and China were the most and second most productive, respectively, where Germany and Italy rounded out the top four of Keyword Set 1, and Australia and Italy in Keyword Set 2. The data recorded was based on the publication origin not the author's country of origin.

Table A.2 presents the top ten journals based on the number of publications in this field, recorded between *Jan. 2008* and *Jan. 2019*. The Science of the Total Environment journal published the most papers pertaining to the first keyword set and the sixth-most for the second keyword set. The Journal of Cleaner Production published the most papers in Keyword Set 2, but only published two papers in the first keyword set. Journal of Environmental Management contained the second most in both keyword sets; and Agriculture Ecosystems Environment and Renewable and Sustainable Energy Reviews the third most in Keyword Set 1 and Set 2, respectively

Table A.2. Top ten journals based on number of records (Jan. 2008 to Jan. 2019)

Keyword Set 1			**Keyword Set 2**		
Source Titles	Records	% of 157	Source Titles	Records	% of 181
Science of the Total Environment	8	5.10	Journal of Cleaner Production	9	4.97
Journal of Environmental Management	7	4.46	Journal of Environmental Management	8	4.42
Agriculture Ecosystems Environment	4	2.55	Renewable & Sustainable Energy Reviews	7	3.87
Environmental Science and Pollution Research	4	2.55	Environmental Science and Pollution Research	5	2.76
Geoderma	4	2.55	Global Change Biology Bioenergy	5	2.76
Journal of Environmental Quality	4	2.55	Bioresource Technology	4	2.21
Applied Energy	3	1.91	Environmental Science and Technology	4	2.21
Applied Soil Ecology	3	1.91	Journal of Analytical and Applied Pyrolysis	4	2.21
Bioresource Technology	3	1.91	Journal of Environmental Quality	4	2.21
Chemosphere	3	1.91	Science of the Total Environment	4	2.21

Table A.3. Ten most productive organizations based on records (Jan. 2008 to Jan. 2019)

Keyword Set 1			Keyword Set 2		
Organizations	**Records**	**% of 157**	**Organizations**	**Records**	**% of 181**
USDA	12	7.64	USDA	13	7.18
Kangwon National University	7	4.46	Aristotle University of Thessaloniki	7	3.87
Chinese Academy of Sciences	6	3.82	University of Edinburgh	6	3.32
State University System of Florida	6	3.82	Hong Kong Polytechnic University	5	2.76
University of Edinburgh	6	3.82	Jawaharlal Nehru University	5	2.76
Marquette University	5	3.19	Kangwon National University	5	2.76
University of Bologna	5	3.19	Leibniz-Institut für Agrartechnik und Bioökonomie	5	2.76
Jawaharlal Nehru University	4	2.55	NSW Department of Primary Industries	5	2.76
Martin Luther University Halle Wittenberg	4	2.55	State University System of Florida	5	2.76
Mississippi State University	4	2.55	U.S. DOE	5	2.76

Table A.3 presents the top ten organizations that they have done research in the field of biochar and FEWS. In both records, the U.S. Department of Agriculture (USDA) was the most productive with 12 and 13 publications in each keyword set, respectively. They were followed in Keyword Set 1 by Kangwon National University with seven publications and the Chinese Academy of Sciences, the State University System of Florida, and University of Edinburgh with six publications. In Keyword Set 2, Aristotle University of Thessaloniki with seven publications was the second most productive followed by University of Edinburgh at 6, and seven other organizations that published five papers, including the U.S. Department of Energy (DOE), and the State University System of Florida.

Table A.4 lists the top ten most productive scholars based on their number of publications in each keyword set. For this analysis, both lead and co-authors were analyzed. In both keyword sets, Yong-Sik Ok was the most productive scholar in biochar and FEW research with seven and eight publications, respectively. In Keyword Set 1, Dinesh Mohan was involved with the second most publications, and eleven scholars were involved with three publications. For Keyword Set 2, A. Zabaniotou was the second most productive scholar with six publications, and L. Van Zwieten with the third most at six publications.

Table A.5 reports the most common research areas in each data set. The top four research areas are Environmental Sciences and Ecology with 63 and 81 publications for both sets, followed by Agriculture with 54 and 51 publications, Engineering with 37 and 57 publications, and Energy Fuels with 26 and 43 publications in Set 1 and Set 2, respectively. The top nine research areas for each keyword set are the same areas, the difference being the order and number of publications in each research area.

Table 5.4 Top ten most productive scholars based on number of records (Jan. 2008 to Jan. 2019)

Keyword Set 1			Keyword Set 2		
Authors	**Records**	**% of 157**	**Authors**	**Records**	**% of 181**
Ok, YS	7	4.46	Ok, YS	8	4.42
Mohan, D	4	2.55	Zabaniotou, A	7	3.87
Bird, M	3	1.91	Van Zwieten, L	6	3.32
Cantrell, K	3	1.91	Tsang, D	5	2.76
Glaser, B	3	1.91	Cornelissen, G	4	2.21
Joseph, S	3	1.91	Mohan, D	4	2.21
Kumar, S	3	1.91	Monteleone, M	4	2.21
Lee, S	3	1.91	Verheijen, F	4	2.21
Lui, Z	3	1.91	Al-Wabel, M	3	1.66
McNamara, PJ	3	1.91	Bastos, A	3	1.66

Table 5.5. Top ten research areas based on number of records (Jan. 2008 to Jan. 2019)

Keyword Set 1			Keyword Set 2		
Research Areas	**Records**	**% of 157**	**Research Areas**	**Records**	**% of 181**
Environmental Sciences Ecology	63	40.13	Environmental Sciences Ecology	81	44.75
Agriculture	54	34.40	Engineering	57	31.49
Engineering	37	23.57	Agriculture	51	28.18
Energy Fuels	26	16.56	Energy Fuels	43	23.76
Science Technology other Topics	16	10.19	Science Technology other Topics	31	17.13
Biotechnology Applied Microbiology	14	8.92	Biotechnology Applied Microbiology	18	9.95
Water Resources	13	8.28	Chemistry	17	9.39
Chemistry	8	5.10	Plant Sciences	9	4.97
Plant Sciences	7	4.46	Water Resources	8	4.42
Food Science Technology	5	3.19	Geology	3	1.66

A.2) Analysis of Citation Data

The combined keyword sets contain 278 papers, and they have been cited by 5,642 articles from *January 01, 2008* to *January 1, 2019*. The sum of the total times the papers have been cited each year is shown in Figure A.2, in total the combined sets have been cited a sum of 8,760 times. The number of publications and citations per year has increased greatly in the last three years as seen in Figures A.1 and A.2 with 54% of the records and 64% of the citations occurring from *January 2016* to *January 2019*.

Table A.6 presents the top ten most cited journals in the combined datasets. The top three cited journals are led by Nature Communications with 680 citations, followed by Bioresource Technology with 598 citations, and Environmental Pollution with 558 citations.

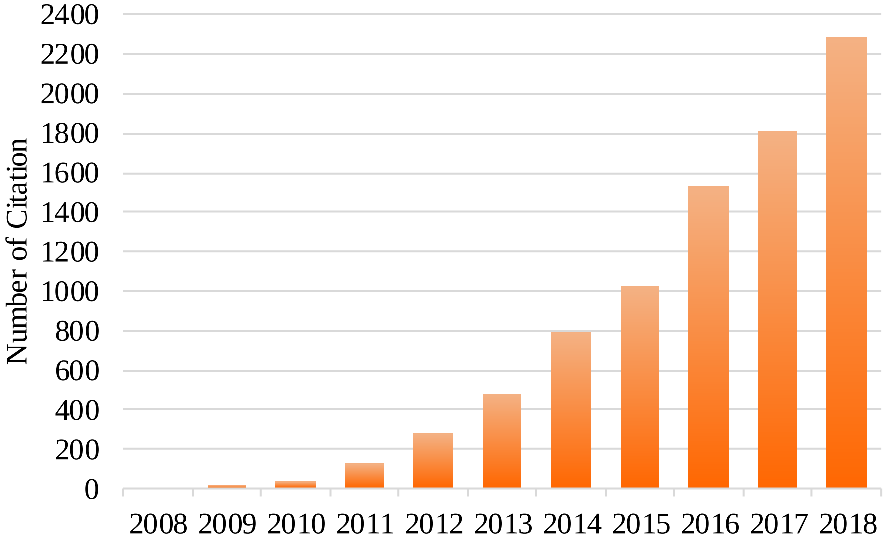


Figure A.2. Number of citations per year (Jan. 2008 to Jan. 2019)

Table A.6.. Top ten most cited journals (Jan. 2008 to Jan. 2019)

Source Title	Cumulative Citations
Nature Communications	680
Bioresource Technology	598
Environmental Pollution	558
Plant and Soil	536
Renewable and Sustainable Energy Reviews	466
Geoderma	424
Soil Biology and Biochemistry	410
Journal of Environmental Quality	390
Biofuels Bioproducts and Biorefining-Biofpr	306
Journal of Plant Nutrition and Soil Science	302
Journal of Environmental Management	249

Table A.7. Top ten cited articles and authors across the field (Jan. 2008 to Jan. 2019)

Author	Article Title	Source Title	Citations	Year
Woolf et al.	Sustainable biochar to mitigate global climate change	Nature Communications	650	2010
Mohan et al.	Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review	Bioresource Technology	563	2014
Beesley et al.	A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils	Environmental Pollution	558	2011
Van Zwieten et al.	Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	Plant and Soil	536	2010
Laird et al.	Impact of biochar amendments on the quality of a typical Midwestern agricultural soil	Geoderma	411	2010
Steinbeiss et al.	Effect of biochar amendment on soil carbon balance and soil microbial activity	Soil Biology and Biochemistry	398	2009
Laird et al.	Review of the pyrolysis platform for coproducing bio-oil and biochar	Biofuels Bioproducts and Biorefining-Biofpr	278	2009
Kookana et al.	Biochar application to soil: agronomic and environmental benefits and unintended consequences	Advances in Agronomy	210	2011
Regmi et al.	Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process	Journal of Environmental Management	169	2012
Méndez et al.	Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil	Chemosphere	166	2012

The majority of the citations for the top ten most cited journals are attributed to the top cited publications in the combined datasets. Table A.7 lists the top cited articles in the combined datasets. Over 95% of the total cumulative citations of the top cited journals are from the top cited article published by that journal. The three most cited articles are by Dominic Woolf in Nature Communications with 650 citations [190], Dinesh Mohan in Bioresource Technology Journal with 563 citations has the highest citations per year of the top cited papers [191], and Luke Beesly with 558 citations in Environmental Pollution [91]. Also, not far behind is L. Van Zwieten with 536 citations published in Plant and Soil [137].

A.3) Analysis of Keywords

Figure A.3 depicts the bibliometric map illustrating the frequency of keywords found in top 50 most cited publications the combined datasets. VOSviewer software was used to create a density map that clustered keywords based on their relevance. The map clusters the keywords based on their frequency of use together in the publications, with the fingers of the map showing the separation of certain keywords that are less frequently used together. The map also uses color to illustrate the number of occurrences of each keyword, for this illustration a rainbow color density was used with

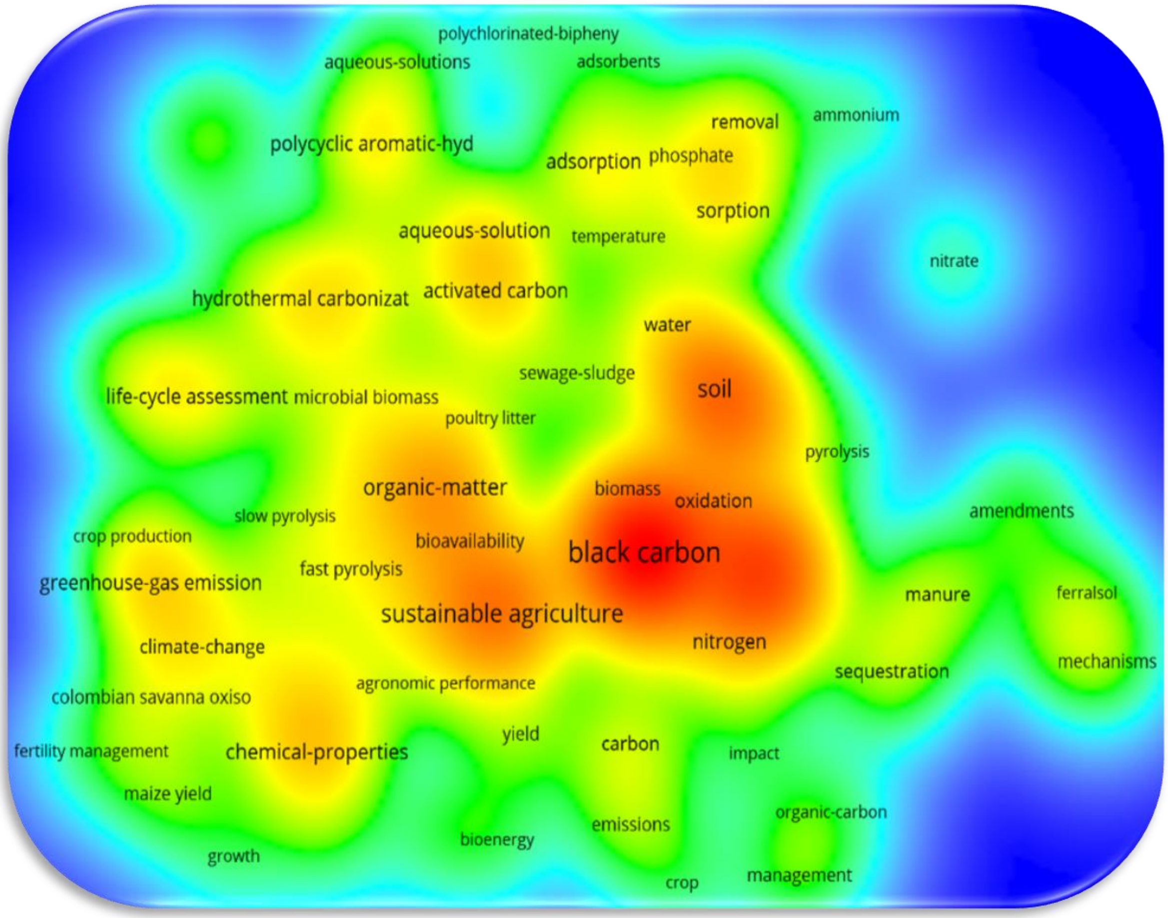


Figure A.3. Bibliometric map of keyword found in top ten most cited publications (VOSviewer result) warmer colors (red and orange), correlating to higher usage and transitions to cooler colors (green and blue) corresponding to lower usage. For the top 50 used articles in the datasets, black carbon, sustainable agriculture, soil, organic-matter, activated carbon, chemical properties, greenhouse gas emission, life-cycle assessment, and biomass were some of the most frequently used keywords. The less frequently used keywords are related to supplementary research in the biochar and FEW fields [36]. The study of the keyword occurrence was limited to the top 50 cited articles due to software limitations. Keyword length was also limited to 25 characters to clean up the visualization. Most of the keywords are related to agriculture and GHG emissions, possibly showing the increased emphasis in applications of biochar in these areas.

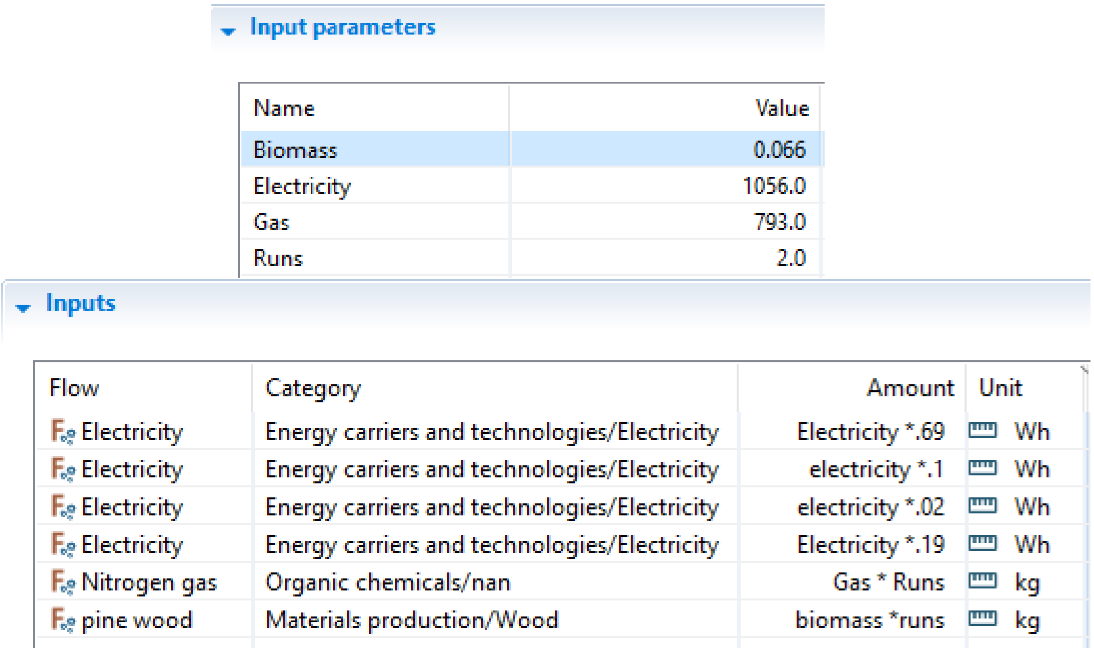
Appendix B - Life Cycle Assessment Tables and Additional Information

This Appendix serves as a source of additional information on the Life cycle assessment of the biochar production process. Included in the appendix is the expansion of the LCA goal and scope, life cycle inventory (LCI), and the life cycle impact assessment. The interpretation of the LCA data is given in chapter 4 results and discussion.

B.1) Goal and Scope:

For this particular study the gate to gate analysis of the biomass pyrolysis process is analyzed. The goal of the LCA of biochar production is to identify the limiting factors and give optimization advice for the small scale reactor in question. The scope of this study is a gate-to-gate analysis to identify the sustainability of the process alone, and a discussion of possible future studies will be given. The LCA study will be based on the results of the pyrolysis data collected and will be performed in openLCA software. The values of interest in this study will be the energy efficiency as well as the GHG emission and climate change factors attributed to the energy use and syngas emission of the process.

B.2) Life Cycle Inventory:



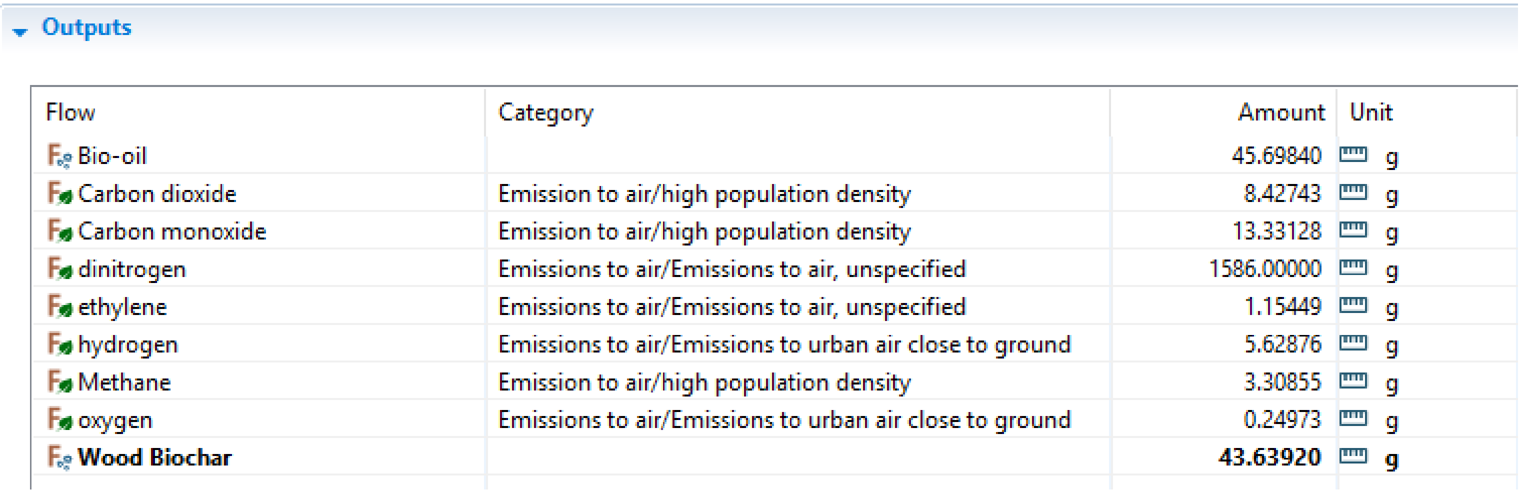
Input parameters

Name	Value
Biomass	0.066
Electricity	1056.0
Gas	793.0
Runs	2.0

Inputs

Flow	Category	Amount	Unit
Electricity	Energy carriers and technologies/Electricity	Electricity *.69	Wh
Electricity	Energy carriers and technologies/Electricity	electricity *.1	Wh
Electricity	Energy carriers and technologies/Electricity	electricity *.02	Wh
Electricity	Energy carriers and technologies/Electricity	Electricity *.19	Wh
Nitrogen gas	Organic chemicals/nan	Gas * Runs	kg
pine wood	Materials production/Wood	biomass *runs	kg

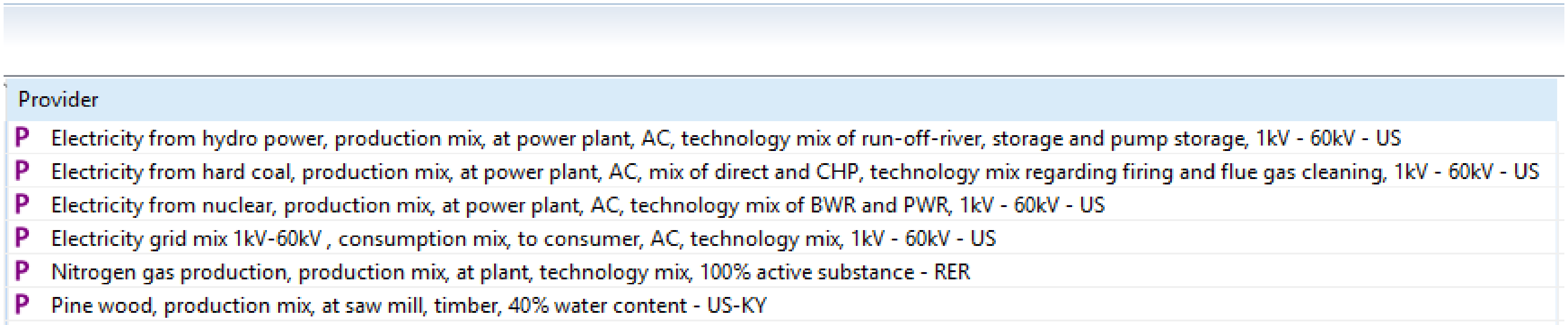
Figure B.1 LCI input parameters and inputs



Outputs

Flow	Category	Amount	Unit
Bio-oil		45.69840	g
Carbon dioxide	Emission to air/high population density	8.42743	g
Carbon monoxide	Emission to air/high population density	13.33128	g
dinitrogen	Emissions to air/Emissions to air, unspecified	1586.00000	g
ethylene	Emissions to air/Emissions to air, unspecified	1.15449	g
hydrogen	Emissions to air/Emissions to urban air close to ground	5.62876	g
Methane	Emission to air/high population density	3.30855	g
oxygen	Emissions to air/Emissions to urban air close to ground	0.24973	g
Wood Biochar		**43.63920**	**g**

Figure B.2 Outputs of biochar production process



Provider
P Electricity from hydro power, production mix, at power plant, AC, technology mix of run-off-river, storage and pump storage, 1kV - 60kV - US
P Electricity from hard coal, production mix, at power plant, AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV - US
P Electricity from nuclear, production mix, at power plant, AC, technology mix of BWR and PWR, 1kV - 60kV - US
P Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV - US
P Nitrogen gas production, production mix, at plant, technology mix, 100% active substance - RER
P Pine wood, production mix, at saw mill, timber, 40% water content - US-KY

Figure B.3 Provider source of input parameters (openLCA database)

The life cycle inventory inputs and outputs defined in chapter 4 are displayed. The input parameters were established based on the average amount of each parameter used in the process and are left without units. The inputs (Figure B.1) are established based on the parameters and flows determined in the production process. The electricity inputs were established based on the data established in chapter 4 and the provider for each input can be seen in figure B.5 and are sourced from OpenLCA databases. The providers correspond to each input. The outputs(figure B.3) were calculated in chapter 4 and represent the calculated outputs developed in chapter 4 Tables 4.1 and 4.3.

B.3) Life Cycle Impact Assessment

The life cycle impact assessment can be seen in chapter 4 Table 4.2 and the contributing factors can be seen in Table 4.5.

Appendix C - Instruction Manual for PLC

Controller: Allen Bradley 1769-L16ER-BB1B

Link to Manual:

http://literature.rockwellautomation.com/idc/groups/literature/documents/um/1769-um021_-en-p.pdf

For information on initial setup of the controller see manual.

C.1) Connection to controller

Ethernet IP of controller 10.88.95.10

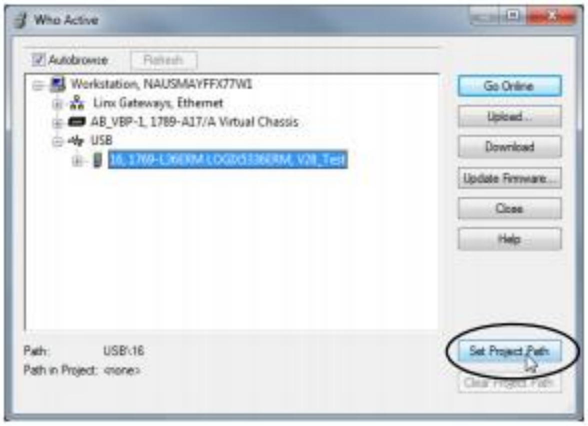
Using Ethernet into the ports located on the bottom of the controller:

If connecting with laptop, there are no extra steps required for connection to be made.

If using different computer with RS software

1. Start Studio software
2. Set project path
   (a) Click RSWho

   (b) Navigate to AB_ETHIP-1, Ethernet and select 1769 L16ER-BB1B controller



Path: USB\16
Path in Project: <none>

   (c) Click Set Project Path

(d) If using Program already downloaded to controller click upload, if loading new program, click go online

C.2) Studio 5000 Ladder Logic

Creating a basic program and downloading to the controller:

https://www.youtube.com/watch?v=Knp322EX7Ao

Our Main Routine with components:

1. Bool: Normally open: When toggled system turns on
2. Bool: Normally closed: When toggled system can turn on
3. Bool: Normally open: Toggled when system is running to keep system on
4. Bool: Outputs when system is on
5. Sends main routine to subroutines

C.3) Adding a subroutine to Studio 5000:

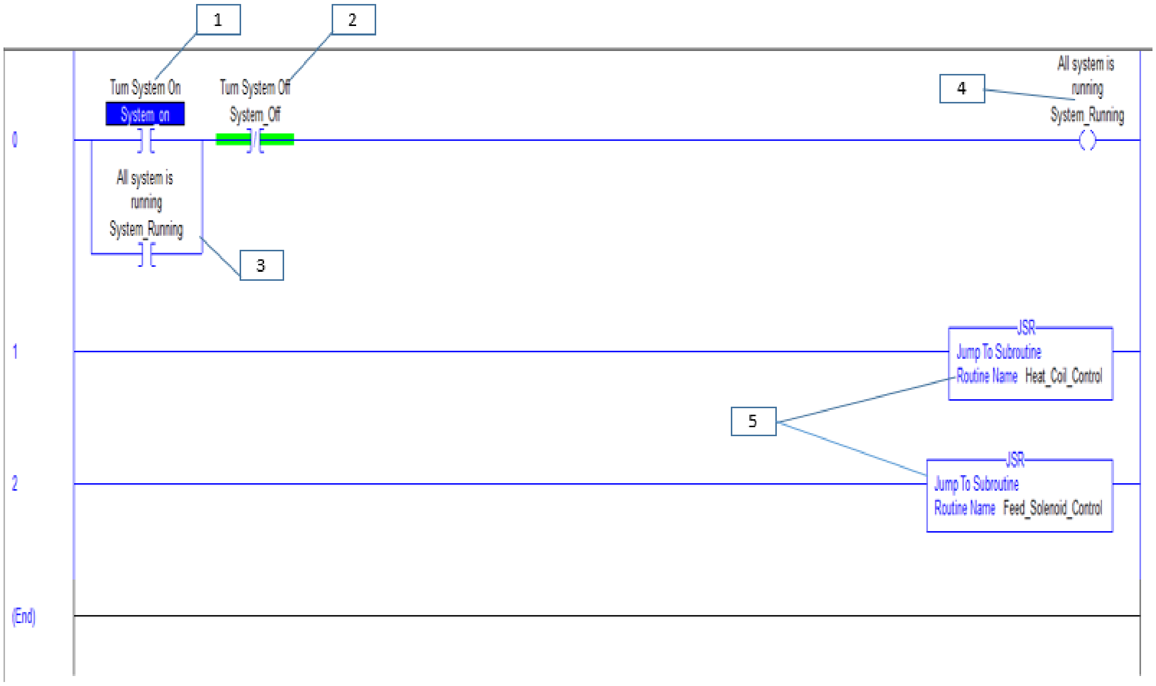


Figure C.1 Studio 5000 main routine example

The subroutines in Studio 5000 is where the majority of the control ladder logic is located. In our case, when looking at Figure C.1 the subroutines are referenced in the main routine in lines 1 and 2 with a JSR command which sends the main routine to a subroutine. To create a subroutine:

1. right click on main program tab in the control organizer toolbar
2. go to the Add tab

3. select “New routine”
4. Name Subroutine

C.4) Adding control tags in Studio 5000

The controller tags addition of Controller tags can be accomplished in a few different methods. The first method used can be accomplished as follows:

1. Right Click on the controller tags tab of the control organizer toolbar
2. Click “Add New Tag” (A new tag properties box will open)
3. Name the Tag appropriately and add a description
4. Designate Tag type Base, Alias, Produced, Consumed
5. Designate Data type

The second method used was the “on the fly” method and can be accomplished as follows:

1. (In the development of a routine) Add the desired control element
2. Click on the “?” dialog box that appears on the element added
3. Type the desired name of the new tag (press enter)
4. Right click the name of the new tag and click the New tag tab
5. Designate Tag type and data type

For this project, the tag types used were Base and Alias. The base tag was used to define set points, as well as communicate the status of a device. The Base tag with the Bool data type returns either a 0 or 1 and was used in the tags such as system_on. For this tag if the system is turned on a 1 returned. As seen above in the main routine this toggles the normally open control element in the main routine. The Base tag with the DINT data type allows an integer value to be assigned and was used in tags such as the set point of the core heater. The Alias tag reads from a base tag in which they refer to. The two main Alias tags used in this system have the INT or REAL data types and return Integers or Real numbers, respectively. The Alias tags used such as the Core Heater thermocouple tag refers to the Local 3 Channel 0 data slot which is the input position of our Core heater thermocouple.

For more data on controller tags and how to create tags visit:
http://www.plcdev.com/an_introduction_to_rslogix5000_tags

C.5) Adding a scaled value

A scaled value may be necessary in the development of the controller. For example, the signal we receive from the pressure transducer is a 4-20mA analog signal that represents a value from 0 to 30 psi. To create this scaled value follow these steps:

1. In a functional block diagram subroutine open the process elements tab.
2. Add an input reference, scale (SCL), and output reference.
3. Click on the “?” above the input reference to define the input reference tag (This is the tag that represents the data to be scaled).
4. Click on the “?” above the output reference to define the output reference tag (This is the tag that represents the scaled data).
5. Click on the three dots in the right corner of the SCL element to open the scale properties.
6. Fill out the values for InRAWMax and InRAWMin (20000 and 4000 for the pressure transducer).
7. Fill out the values for InEUMax and InEUMin (30 and 0 for the pressure transducer)

C.6) Our Controller

This section describes the basic aspects of the program developed for the control of the IDeaL pyrolysis unit, located at Center for Advanced Energy Studies. Figure 5.7 above shows the main routine and the main elements are described. The main routine is primarily used for the initialization of the system (System_Running tag), then refers to the developed subroutines. The system running tag will be referred to in the first element of most subroutines.

For this project, there are four subroutines: Feed_motor (Figure C.2), Heat_coil_control (Figure C.3), Solenoid Control (Figure C.4), and Scale (Figure C.4).

Feed system: The Feed_motor subroutine is used to control the output of the controller to the feed motor. Figure C.2 shows how we output to the motor

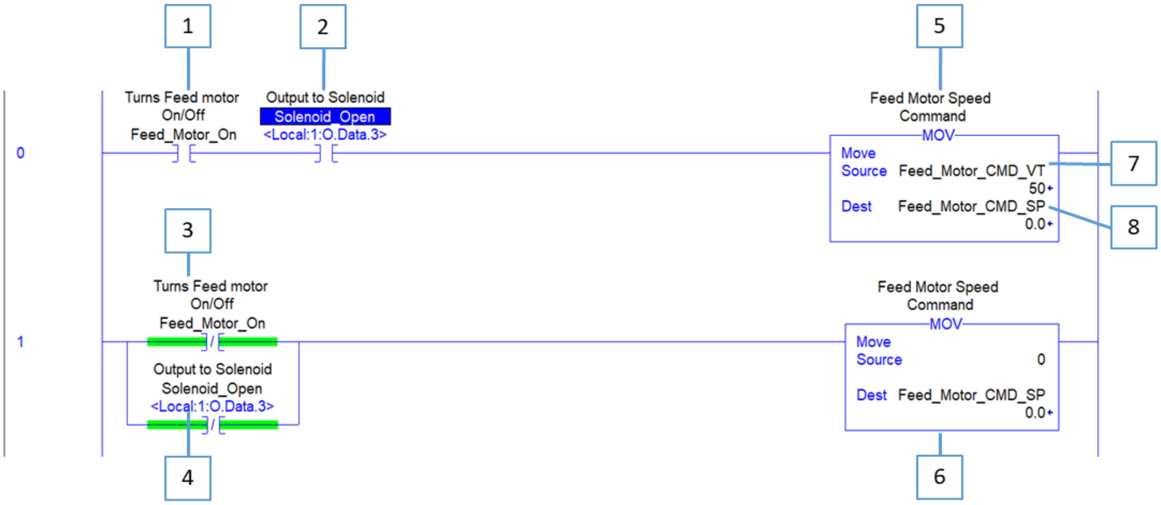


Figure C.2. Feed System Logic

1. Bool: Turns feed motor on when toggled.
2. Alias: Allows heater to be turned on when solenoid valve is toggled open.

3. Bool: Turns feed motor off when “Feed_motor_on” tag is not toggled.
4. Alias: Turns feed motor off when Solenoid valve is not toggle open.
5. Outputs user set value to motor set point.
6. Outputs 0 to feed motor set point when feed motor should be off.
7. Retrieves set point set by user in HMI.
8. Sends Command set point value to scale.

Notes: The first line sends a set point value to the scale subroutine before sending an output to the feed motor. Bubble 7 represents the data received the HMI as a percentage of the power to be outputted to the motor 0-10V. The second line sends a value of 0 thus turning off the motor if either the feed motor is turned off or the solenoid valve is closed (gas flow stops).

Heat control: Located in the Heat coil subroutine is ladder logic behind our heater control.

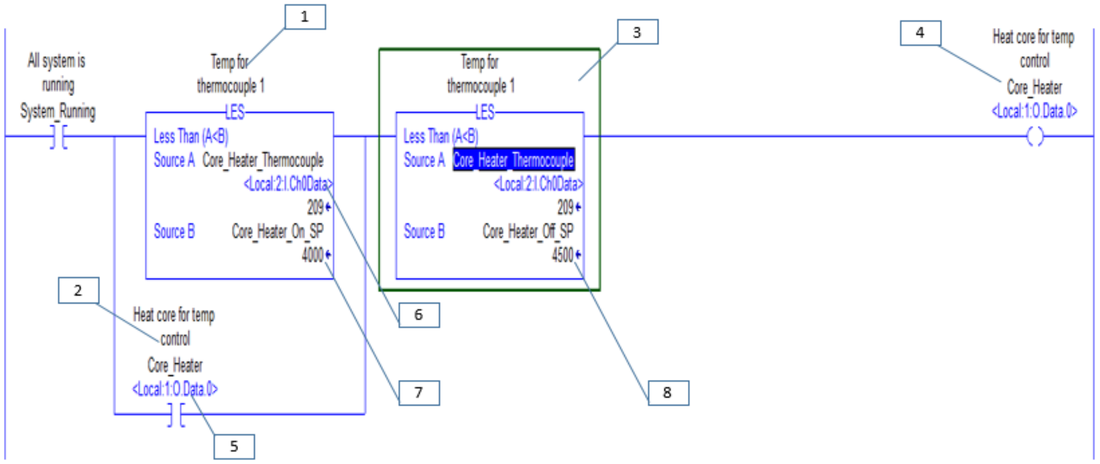


Figure C.3. Heater logic

Figure C.3 shows how we run our Core heaters power supply:

1. Turns heater on if lower than set temp: true value occurs.
2. Turns heater on when system turns on.
3. Turns heater off when we reach our top set point: false value occurs.
4. Outputs to heater located on Output channel 0.
5. Outputs to heater located on Output channel 0.
6. Reads temperature from thermocouple located in channel 0 on module card.
7. The low end set point of our heater when drops below heater turns on.

8. High end set point, heater turns off when reached.

Notes: For this line to run the system must first be turned on as represented by the initial examine on element. The branch allows for the system to heat up when the core heater is toggled and the temperature is lower than the "On" set point. The second LES element returns a false value when the temperature is higher than the "off" set point, and turns the heater off.

Solenoid control: The solenoid valve logic control is located in the Solenoid_Control subroutine. Figure C.4 shows how we control the solenoid valve.

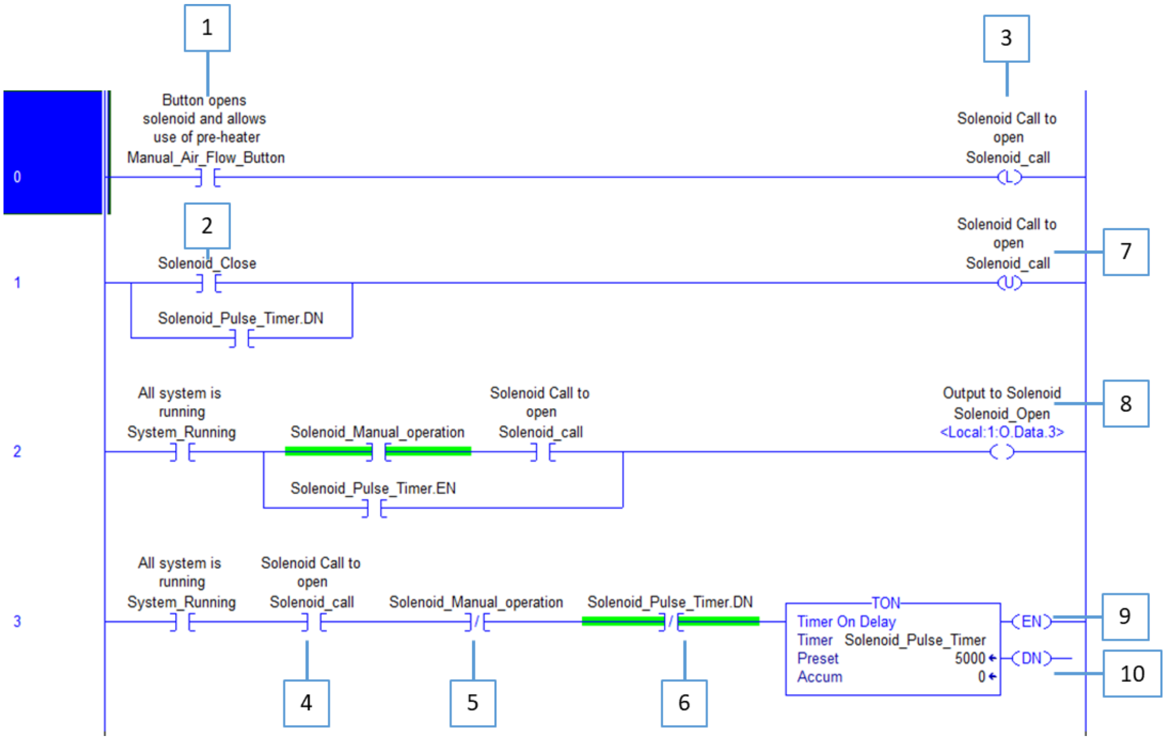


Figure C.4. Solenoid valve logic

1. When toggled allows the solenoid valve to open.
2. When toggled closes solenoid valve.
3. Latch element: When latched the solenoid call tag is toggled.
4. Toggled when solenoid call is toggled.
5. Toggled when the Manual operation is selected for solenoid control.
6. When the timer reaches zero this closes the solenoid.
7. Unlatches Solenoid call and closes solenoid valve.
8. Opens solenoid valve.

9. Engages timer for pulsed control and toggles Solenoid_Pulse_Timer.EN tag
10. This is the timer which has a user set time duration for the solenoid valve to open.

Notes: The Solenoid valve can be controlled two ways (manual and pulse) and is set by the user in the HMI. The manual control option opens the valve when the air flow button is toggled and keeps the valve open until the user toggles the solenoid close button. The pulse option allows the user to set a time duration for the valve to be open and counts down from the time the user toggles the valve to open and closes the valve when the timer reaches zero.

Scale: The final subroutine of the system is the scale. In the scaling analog values are scaled to represent pressure, flow rate, voltage, and motor speed (Figure C.5).

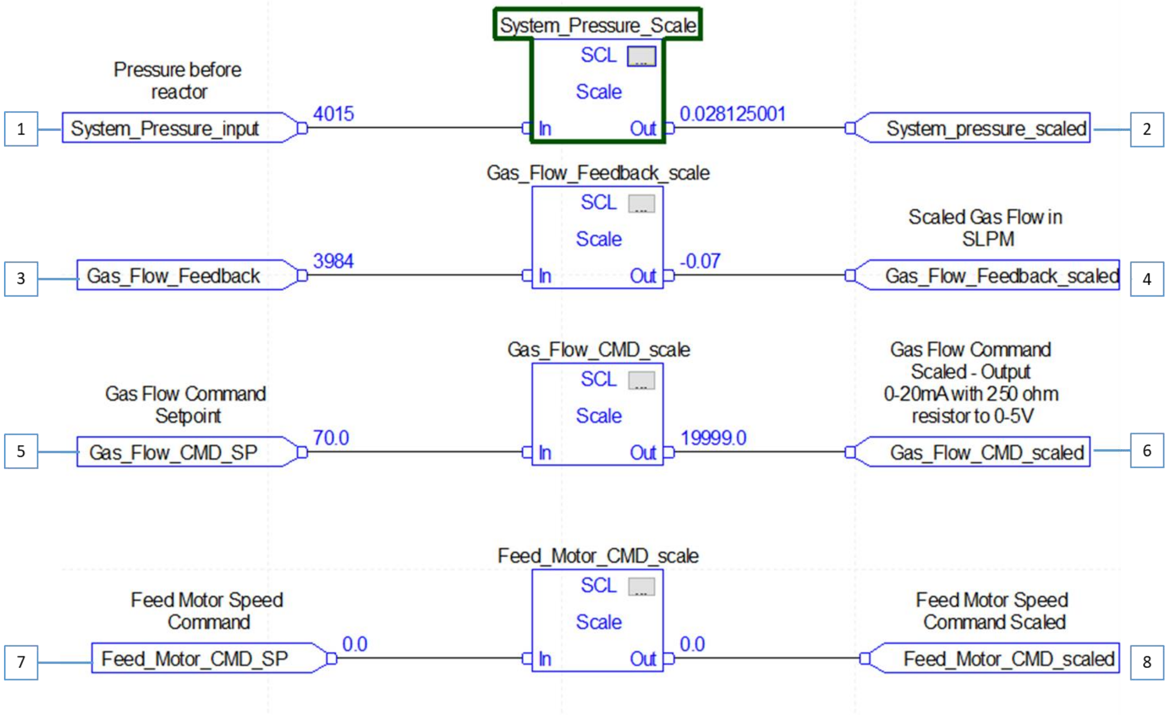


Figure C.5. Scaled values (functional block subroutine)

1. Reads pressure analog value.
2. Displays pressure scaled value in psi.
3. Reads flow analog value.
4. Displays flow rate scaled in LPM.
5. Reads flow set point in LPM.
6. Displays scaled analog value of set point converted to volts.

7. Reads motor control set point as percent of 100.
8. Displays scaled value of set point as amperage to be outputted to motor.

Appendix D - Instruction Manual for VTScada Lite

This manual will serve as a guide to developing a Human-Machine-Interface (HMI) for the logic control developed in studio 5000 or other similar software. This manual will be comprised of the basics of setting up an HMI in VTScada, along with a description of the VTScada HMI developed for the control of the IDeaL pyrolysis unit.

D.1) Starting a new application:

1. For first time VTScada users see: https://www.trihedral.com/scada-software-video-tutorials
2. For use with Allen Bradley controller see: https://www.trihedral.com/vtscada-cip-driver-tutorial
3. Download the AB CIP Driver demo snapshot from: https://www.trihedral.com/free-scada-software

Important notes:

TCP/IP Name/Address for our controller 10.88.35.10 and TCP/IP Port Number 44818

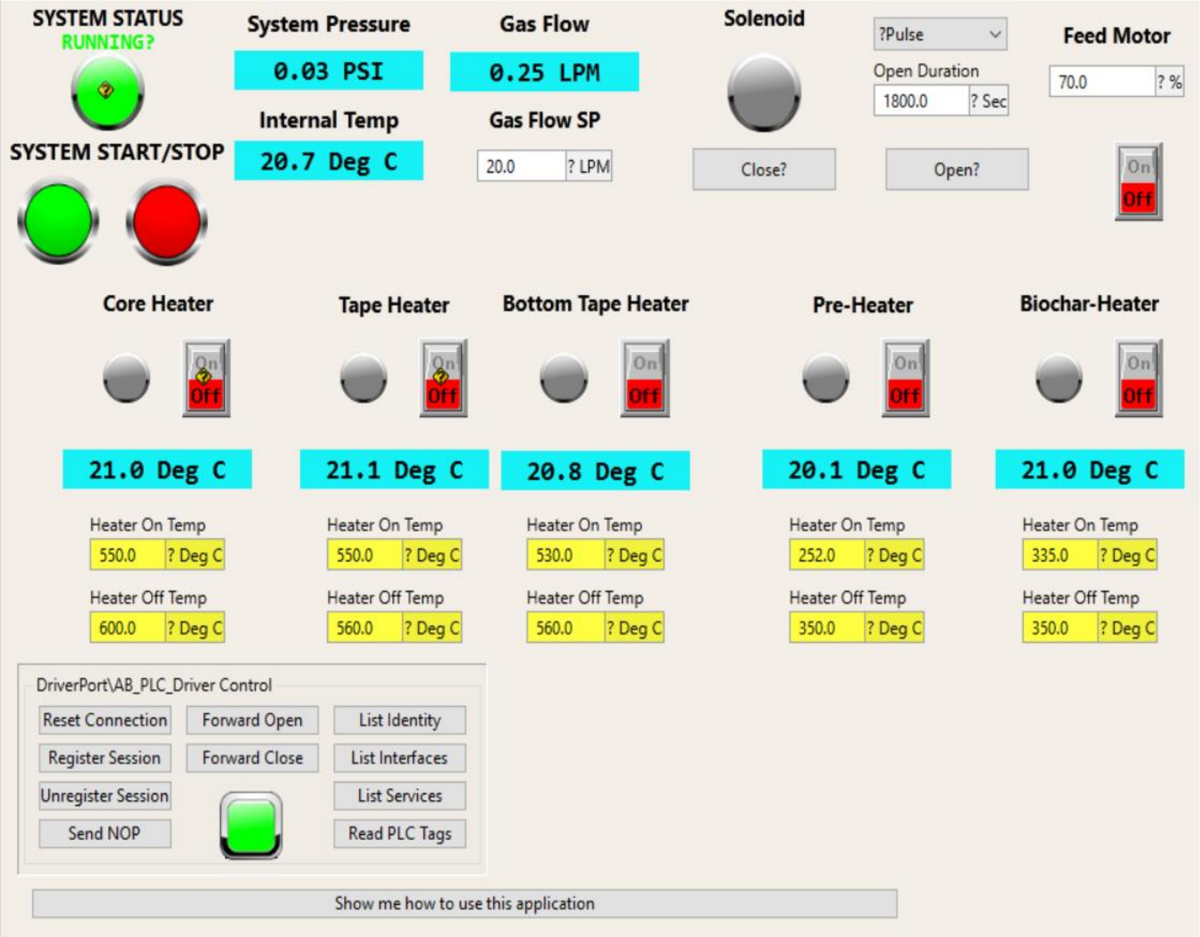
D.2) Creating I/O tags.

1. To start creating the controller I/O tags open the tag list in the top right corner.
2. Click on Driver port to open drop down.
3. right click on driver and select new child.
4. select the tag type.
5. name the tag appropriately and add description of tag (Note: We will be connecting this tag to a controller tag in studio 5000, it is good practice to name the tags similarly).
6. open I/O tab
7. click tab button next to the Address dialog box.
8. add tag address from studio 5000 and click ok.

Note: When adding tags, if you are creating a tag in VTScada that serves a similar purpose as another tag (e.g. top external thermocouple and bottom external thermocouple) you can copy/paste a tag, rename it, and designate its appropriate address.

D.3) Our system:

The following section will describe the HMI developed in VTScada to run the pyrolysis system. This section will be broken down into two sections. 1) The HMI and the operational aspects integrated into the display, and 2) A description of the tags and widgets.



System Pressure 0.03 PSI

Gas Flow 0.25 LPM

Internal Temp 20.7 Deg C

Gas Flow SP 20.0 ? LPM

Open Duration 1800.0 ? Sec

Feed Motor 70.0 ? %

	Core Heater	Tape Heater	Bottom Tape Heater	Pre-Heater	Biochar-Heater
	21.0 Deg C	21.1 Deg C	20.8 Deg C	20.1 Deg C	21.0 Deg C
Heater On Temp	550.0 ? Deg C	550.0 ? Deg C	530.0 ? Deg C	252.0 ? Deg C	335.0 ? Deg C
Heater Off Temp	600.0 ? Deg C	560.0 ? Deg C	560.0 ? Deg C	350.0 ? Deg C	350.0 ? Deg C

Figure D.1 VTScada Human machine interface

D.4) The HMI:

This is the current HMI (April 2018) set up in the overview tab of VTScada. Each widget is labeled with its proper function and can be adjusted in the idea studio tab. The following will describe the main functions of the main blocks of the HMI.

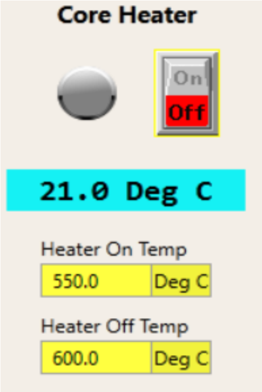
D.5) Connection to the PAC

In the development of the HMI using the steps above the Driver control panel in the bottom right is established. The Green button is connected to the PAC, which when the HMI is connected to the PAC displays green and when it is not displays red. Pressing the Reset Connection button will reestablish connection should the connection fail.

D.6) Turning the System on/off:

In the top right corner are two green buttons and red button. The top green button is normally Grey but when the system is running displays green. This button is a display and does not serve a function. The lower green button is a push button that will write a 1 in the system_running tag in the PAC thus turning the system on. The red will write a 0 in the system_running tag and turn the system off. The user will note that a command prompt tab opens asking is the user wants to control the action of turning the system on, but will not prompt the user to turn the system off. This was added for security. (note: the pre-heater will not run without the solenoid valve in the open position)

D.7) Controlling Temperature:

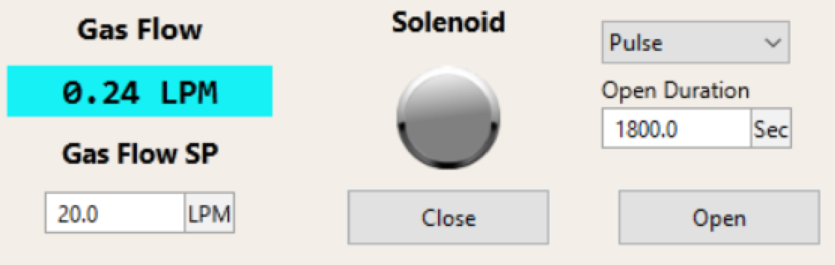


21.0 Deg C

Heater On Temp: 550.0 Deg C

Heater Off Temp: 600.0 Deg C

Each of the five different heating units of the system has a block of controls in the HMI located in the middle of the dispaly. Each block has the name of the heater displayed and consists of a display button, a selector switch, a temperature display, Heater on set point, and heater off set point. The user can interact with the selector switch, turning the heater on/off similar to a light switch. As well both the On and off set points can be changed by the user to an integer value of °C. The grey button displays when the heater is on and will display green, and the temperature reading is displayed in the blue bar.



0.24 LPM

Gas Flow SP: 20.0 LPM

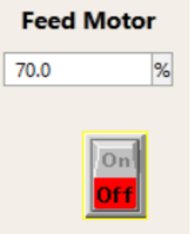
Pulse

Open Duration: 1800.0 Sec

D.8) Controlling Gas flow:

Gas flow of the system is controlled in two ways, first the control of a solenoid valve and second with the use of a flow controller. The solenoid valve is opened and closed using the labeled buttons, and can be controlled manually or on a timer (pulse). The user is able to select manual or pulsed flow by selecting from the drop down list located in the top right of the figure D.1 (The example is set in pulse mode). Below this is the duration or timer on the valve and is set by the user in seconds. Finally, when open the grey button will display green. The flow is displayed in the blue bar as liters per minute (LPM) and the desired flow set point can be set beneath this as an integer value of Liters per minute.

D.9) Feed motor control:



The motor controls are located in the top right of the HMI. The components of the feed motor control are the motor rate as a percentage, and the selector switch. The selector switch works like the heater selector switches, however to reduce plugging risk the motor will only turn on when the gas flow solenoid is open. The user us able to control the speed of the motor by entering an integer value from 0 to 100 as a representation of the percentage of total speed of the motor.

D.10) Other displays on the HMI:

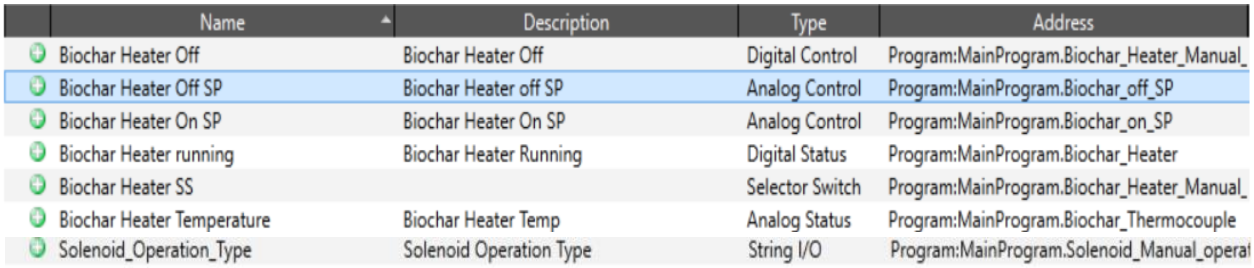
The system pressure and internal temperature of the system are also displayed on the HMI, however these values cannot be controlled and are just displayed and monitored for the user.

D.11) Widgets and Tags:

In the idea studio tab each widget or group of widgets can be right clicked on to either check the properties and tag associated with the widget, or assign a tag to a widget.

However, the best method to assign a tag to a widget is to:

1. first click on tags in the home menu of the toolbar
2. right click on the tag you would like to assign a widget
3. click draw (a menu will open showing the available widget options)
4. select the widget you like and drag into the idea studio in the desired space



Name	Description	Type	Address
Biochar Heater Off	Biochar Heater Off	Digital Control	Program:MainProgram.Biochar_Heater_Manual_
Biochar Heater Off SP	Biochar Heater off SP	Analog Control	Program:MainProgram.Biochar_off_SP
Biochar Heater On SP	Biochar Heater On SP	Analog Control	Program:MainProgram.Biochar_on_SP
Biochar Heater running	Biochar Heater Running	Digital Status	Program:MainProgram.Biochar_Heater
Biochar Heater SS		Selector Switch	Program:MainProgram.Biochar_Heater_Manual_
Biochar Heater Temperature	Biochar Heater Temp	Analog Status	Program:MainProgram.Biochar_Thermocouple
Solenoid_Operation_Type	Solenoid Operation Type	String I/O	Program:MainProgram.Solenoid_Manual_opera

The four main tags used in VTScada for this project are Analog status, Analog control, digital status, and digital control.

The Digital status tag correlates to a Boolean value and is connected to the display buttons in the HMI such as the system status button.

The digital control tag can read/write values to the tag the correspond to in the PAC, such as the Biochar heater off tag which writes a 1 in Biochar_Heater_Manual_off tag in studio 5000.

The analog status tag reads from the PAC an analog value. These values are set to correspond to data such as temperature, pressure, and flow.

The analog control tag allows the user to write a value such as the set points of the heaters.

Other tags used include the selector switch, and the String I/O. The selector switch works similar to a digital control, but with the capability to write either a zero or one value. The string I/O allows the drop down menu, that will switch between pulse and manual control of the solenoid valve.

D.12) Generating a report:

VTScada records the data analyzed in the running of the HMI, this data can be accessed and analyzed in the reports page of VTScada. To generate a report the user needs to:

D.13) Select the report type

D.14) Select the tags to be reported by either double clicking or using the arrows

D.15) Set the reporting period (time period of the report)

D.16) Select the destination of the report by first selection the output type, and the destination of the file should a file type be selected.

D.17) For more information see: https://www.trihedral.com/scada-reporting and https://www.youtube.com/watch?v=zDB_n6g7lmk