Reducing Particulate Matter Emissions from
On-Farm Poultry Litter-Fueled Energy Systems

Project Report

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Conservation Innovation Grant

Natural Resources Conservation Service

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EXECUTIVE SUMMARY

Approximately 11% of the poultry operations in the United States are located in the five-state region of the Chesapeake Bay Watershed (Bay), representing 7,000 family farms and generating about $1.1 billion in revenues. The Bay states have identified manure management practices and programs to help meet the nutrient reduction targets of the Bay-Total Maximum Daily Load (TMDL). One approach is to move poultry litter (PL) from a region via transfer programs, where PL is hauled for land application for agronomic purposes. These fossil fuel-intensive transport programs can detract from the overall efficiency of poultry production systems due to the transport inefficiencies associated with hauling low nutrient-density PL.

Poultry-litter fueled on-farm thermal conversion processes (PL-TCP) can be used to generate renewable thermal energy for heating poultry houses. Additionally, PL-TCP can potentially enhance nutrient management alternatives by concentrating the phosphorus- and potassium-rich ash co-products to enable reaching more distant markets more efficiently. However, due to PL fuel properties, scale- and setting-appropriate emission abatement has been a challenge for on-farm PL-TCP. The goal of this project was to assess the total particulate matter (TPM) emissions abatement for two PL-TCP systems, from "OrganiLock" and "Triple Green Products" technology providers. Total particulate matter emissions were assessed using EPA source testing methods. Seventy-eight emission tests were completed using 15 different configurations across the two bioenergy systems. For the Triple Green Products system, the base case emission factor was estimated as 3.851 TPM-lb/MMBtu. For the OrganiLock system, the base case emission factor was 2.885 TPM-lb/MMBtu. These results were shared with technology providers to inform modifications to their TPM-emission abatement control systems to reduce TPM emissions by the project goal of at least 70%. Final tests were completed for the modified systems. For the Triple Green Products system, with the modified abatement technology tested in 2021, the emission factor was 0.187 TPM-lb/MMBtu, representing a 95% reduction relative to the base case. For the OrganiLock system, with the modified abatement technology tested in 2021, the emission factor was 1.887 TPM-lb/MMBtu, representing a 35% reduction relative to the base case.

Additional on-farm TCP-PL system analysis is needed to better understand the economic viability of TCP-PL systems with abatement, and to understand critical farm, and farmer, factors to inform potential broader adoption.

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DISCLAIMER

This material is based on work supported by the Natural Resources Conservation Service, U.S. Department of Agriculture, under #69-2037-18-006. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Department of Agriculture. Commercial products are named in this publication for informational purposes only. Virginia Cooperative Extension does not endorse these products and does not intend discrimination against other products which also may be suitable. Virginia Cooperative Extension programs and employment are open to all, regardless of age, color, disability, gender, gender identity, gender expression, national origin, political affiliation, race, religion, sexual orientation, genetic information, veteran status, or any other basis protected by law. An equal opportunity/affirmative action employer. Extension is a joint program of Virginia Tech, Virginia State University, the U.S. Department of Agriculture, and state and local governments. Issued in furtherance of Cooperative Extension work, Virginia Polytechnic Institute and State University, Virginia State University, and the U.S. Department of Agriculture cooperating. Edwin J. Jones, Director, Virginia Cooperative Extension, Virginia Tech, Blacksburg; M. Ray McKinnie, Administrator, 1890 Extension Program, Virginia State, Petersburg.

ACKNOWLEDGEMENTS

The project was possible because of the host technology farmers' (Mr. Doug Klingler and Mr. Earl Zimmerman) willingness to share their expertise, experiences, and on-farm bioenergy systems for use in this project. Without their hospitality, cooperation, and enthusiasm this project work would not have happened. The project required collaboration and communication with the technology providers who manufacture the bioenergy systems evaluated in this project. Technology providers OrganiLock and Triple Green Products each participated in this project in a collaborative way and contributed resources in their design and implementation of the new particulate matter emission abatement systems, and enabling their objective evaluation. Matt Aungst shared background project information regarding Total Energy Solutions design installation in 2012. Seventy of the 78 source emissions tests were conducted by Reliable Emission Measurements, Inc. who adapted to site, system, and schedule challenges to complete the emission assessment work. Dr. John Wanjura, of the Cotton Production and Processing Research Unit, Agricultural Research Service, USDA (Lubbock, TX) coordinated particle sizing analysis, and the same USDA-ARS unit loaned field testing equipment for use in the air emission assessment testing during the project period. The basis for this project work was initially conceived by Dr. Michael Buser (Oklahoma State University) in coordination with Kristen Hughes-Evans (Sustainable Chesapeake). Sustainable Chesapeake served as the primary applicant and provided project coordination and administration support.

INTRODUCTION

Approximately 11% of the poultry operations in the United States are located in the five-state region of the Chesapeake Bay Watershed (the Bay), representing 7,000 family farms and generating about $1.1 billion in revenues. Approximately, 2,655 of these poultry farms are located in Pennsylvania, including 92 poultry farms in Snyder County and 354 poultry farms in Lancaster County (USDA, 2017).

The Bay states have identified manure management practices and programs to help meet the nutrient reduction targets of the Bay-Total Maximum Daily Load (TMDL). One approach is to move poultry litter from a region via transfer programs, where poultry litter is hauled for land application for agronomic purposes. These fossil fuel-intensive transport programs can detract from the overall efficiency of poultry production systems due to the transport inefficiencies associated with hauling low nutrient-density poultry litter long distances. Poultry-litter fueled on-farm thermal conversion processes (PL-TCP) can be used to generate renewable thermal energy for heating poultry houses. Additionally, PL-TCP can potentially enhance nutrient management alternatives by concentrating the phosphorus- and potassium-rich ash co-products to enable reaching more distant markets more efficiently.

However, due to PL fuel properties, scale- and setting-appropriate emission abatement has been a challenge for on-farm PL-TCP. The goal of this project was to assess the total particulate matter emissions abatement for two PL-TCP systems installed at poultry farms in Pennsylvania.

PA Watershed Implementation Plan

In August 2019, the Pennsylvania Department of Environmental Protection finalized the Pennsylvania Chesapeake Bay Watershed Implementation Plan: Phase Three (PA-WIP3). The PA-WIP3 identifies nitrogen, phosphorous and sediment reduction strategies across forestry, agriculture, stormwater and wastewater sectors to meet the target pollution loads delivered to the Chesapeake Bay. The PA-WIP3 specifies seven areas to address nonpoint source pollution from agriculture, including: compliance with erosion and sediment, nutrient management, and conservation plans; improve soil health; expand nutrient management; increase or enhance manure storage facilities; precision feeding practices at dairies; increase forest and grass riparian buffers; and development of integrated systems for excess manure (ISEM). The PA-WIP3 identifies counties with excess manure, including Lancaster and Snyder counties. The goal of this ISEM strategy is to develop coordinated "…systems for removing excess manure (through treatment or transportation) from the Chesapeake Bay watershed." (PA DEP, 2019, p. 62). This strategy seeks to "investigate the incorporation of alternative manure treatment technologies and other potential strategies to address areas of excess manure nutrient generation and capital investment required for implementation of manure treatment systems" (PA DEP, 2019, pp. 160-161). By implementing ISEM-related strategies by the year 2025, the PA-WIP3 projects a reduction in 441,000 pounds of nitrogen and 65,000 pounds of phosphorous, each presented as edge of stream nutrient reduction values, with an estimated annual cost of $3.2 million (PA DEP, 2019).

Poultry Litter as Fuel

Poultry-litter fueled on-farm thermal conversion processes can be used to generate renewable thermal energy for heating poultry houses. Solid-fuel bioenergy sources with high-ash content rich in alkali-earth metals, like poultry litter, tend to have fuel properties that can exhibit problematic reactions for some thermochemical processes and units. Some of the challenges include slagging within combustion chamber, corrosion and fouling of heat exchange surfaces, formation of fine inorganic aerosols via condensation and reactions of alkali-metal vapor in the combustion exhaust gas stream (van Loo & Koppejan, 2008). However, due to variable fuel properties, scale- and setting-appropriate emission abatement has been a challenge for on-farm applications.

Mineral Fuel Additive

A variety of fuel additives exist which have the potential to improve unit operation and maintenance, while also reducing aerosol emissions from solid-fuel bioenergy sources rich in alkali-earth metal ash content. The reaction mechanisms vary based on the thermochemical conversion process, reactor, fuel properties, additive type, among other factors (Wang et al., 2012). However, the general process is that additives can increase ash melting temperature causing less reactive downstream post-combustion processes that result in the formation of particulate matter, among other nuisances.

Conservation Innovation Grant

In 2017, a Pennsylvania Chesapeake Bay Conservation Innovation Grant (CIG) was awarded to Sustainable Chesapeake from the Pennsylvania Natural Resources Conservation Service (NRCS). The project was titled "Reducing Air Emissions from On-farm Poultry Litter-fueled Energy Systems" and conducted from late 2017 through mid 2021 with faculty from the Department of Biological Systems Engineering at Virginia Tech. The purpose of this project was to help address regional nutrient imbalances in high-density animal production regions of Pennsylvania and provide poultry farmers with additional alternative manure management options, and potentially long-term sustainable solutions, for nutrient management and phosphorus recycling. The goal of this project was to improve the environmental performance of innovative, on-farm thermal poultry litter-to-energy technologies that have previously shown promise in terms of on-farm viability.

The project worked with two technology host farmers who each managed their on-farm poultry litter-fueled energy systems installed on their poultry farms in Lancaster and Snyder counties. Project work focused on the evaluation of total particulate matter air emissions from the two systems and the evaluation of emission abatement systems developed by technology providers, installed during the project period. The project sought to reduce total particulate matter air emissions from the two on-farm systems by at least 70% from baseline reference conditions. The following sections summarize the experiences and results gained through this CIG project, to help inform the broader discussion regarding some of the ISEM-related strategies being explored in response to the PA-WIP3, along with the challenges and opportunities related to on-farm poultry litter-to-energy technologies.

Project Challenges

Like any project, during the project period a variety of challenges emerged impacting project timelines and source emission testing opportunities. For this project, some of these challenges included: changes in project personnel and a federal government shutdown in 2018; abatement system installation delays in 2019; COVID-19 travel restrictions during 2020 and 2021; challenges scheduling source testing when ambient temperatures and flock placement schedules permitted, among others. Fortunately, technology host farmers, source emission testers, and technology providers all worked with great flexibility to coordinate and execute the required project work. Additionally, the USDA sponsor and Sustainable Chesapeake worked to address challenges as they emerged to help keep the work on track.

Site Descriptions

Demonstration projects were located in Snyder County at the Klingler Family Farm near Selinsgrove, Pennsylvania and in Lancaster County at the Earl Ray Zimmerman Farm near Ephrata, Pennsylvania. Additional emission testing was performed at technology provider OrganiLock's headquarter facility near Madisonville, KY. Summary descriptions of each location are provided below.

Earl Ray Zimmerman Farm – Lancaster County, Pennsylvania (Location 1)

Location 1 (L1) farm is a 60-acre farm that has two 24,000 sq. ft poultry houses. The farm raises certified-organic broilers on approximately six-week flock cycles resulting on an average of five flock cycles per year per house. The biomass boiler and heat distribution system was installed by Total Energy Solutions (TES) to provide heating for two poultry houses and an adjacent mechanical shop in 2012. The system specified by TES uses a biomass boiler (model CGS-225 and rated at 1.5 MMBtu/hr) is marketed through Triple Green Products (TGP), Morris, Manitoba. The unit has been in operation since its installation with idle periods typically during the summer months when heat demands at the farm are low, and for periodic maintenance or repair.

The farmer uses single-flock bedding, where all of the poultry litter is removed after each flock and replaced with new bedding material prior to the placement of the next flock. Due to the uncertain market and challenges in finding wood shavings, the farmer switched to using giant miscanthus (*Miscanthus x giganteus*), a variety of sterilized warm-season grass native to Asia, as bedding (USDA, 2011). The farmer grows the Miscanthus on eight acres of land. The farmer currently utilizes a forage harvester to cut and chop the miscanthus. The farmer estimates an average yield of 10-12 dry tons per acre, yielding approximately 80 to 96 dry tons per year. The crop is delay-harvested to enhance benefits from in-field storage and translocation of nutrients. Material from each of the periodic harvests is stockpiled in a bay of a three-sided post frame storage building for later use as poultry bedding. When the miscanthus is depleted, the farmer switches to wood chips, typically sourcing these materials in bulk during the summer months when woody biomass prices are often lower.

The farmer places three inches of new bedding material with each flock, where a two-inch base of bedding material is top-dressed with one inch of wood shavings. Typically, from mid-December until mid-July, miscanthus is used for the base material, and wood chips for the remaining periods (Figure 1). Wood shavings are sourced from a local bedding provider that produces shavings from air-dried whole logs (i.e., not a byproduct) with any fine material removed. The bedding material is typically either giant miscanthus with wood shavings or wood chips with wood shavings, except during biannual transition periods, in July and November, where the base material consists of a blend of both wood shavings and giant miscanthus. Actual bedding feedstock utilization rates vary based on flock placement dates, actual length of production period, and duration of downtime between flocks. For example, in 2019 and 2020, five production cycles were initiated each year. During 2019 and 2020, the farmer is estimated to have used 1,111 cubic yards of bedding material per year. Based on the estimated miscanthus harvest yields, approximately, 67% of the volume of bedding material was self-sourced from the miscanthus feedstock during this period.

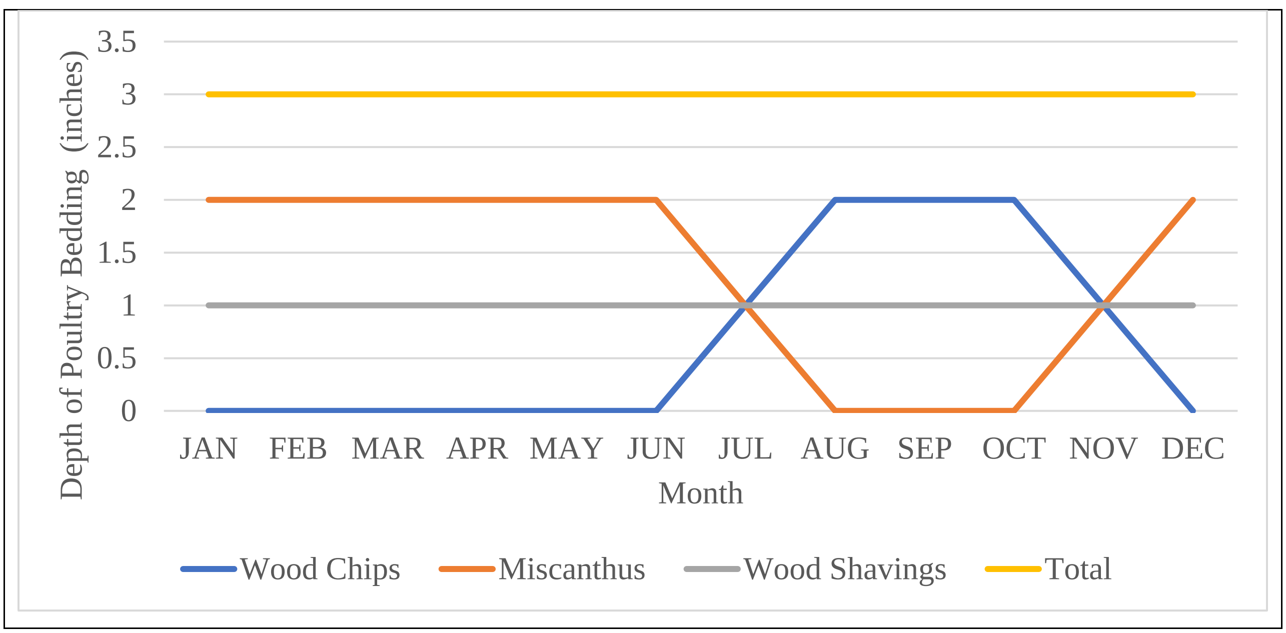

Figure 1: General Poultry Bedding Formulation by Month at Site L1

The poultry litter removed from the previous flock is placed in covered storage in a bay near the fuel feed hopper adjacent to the biomass boiler, once full, additional material is placed in a poultry litter storage bay of a three-sided post frame storage building. A skid-steer loader is used to place fuel into a modified Lanco Litter spreader which serves a fuel hopper. In November 2018, load cells were placed underneath of the fuel hopper to monitor fuel consumption during the project period. Material is automatically delivered into an auger in response to commands from the boiler control system. The fuel-feed auger then delivers fuel to a surge hopper which then supplies the fuel to the boiler. The fuel is combusted in the combustion chamber, heat exchange occurs via a firetube boiler, mounted above the combustion chamber.

Prior to 2019, byproducts of combustion, including gasses and particulate matter, passed through the firetube boiler then through a cyclone before exiting the system via an exhaust stack. Bottom ash, recovered from the combustion chamber, and fly ash, recovered from the cyclone, were collected, comingled, and conveyed via an ash auger system for storage. In January 2020, Triple Green Products installed a new emission abatement system described as the TGP Cyclonic Filter. With this system modification, the exhaust duct routes the gases and particulates exiting the firetube boiler into the TGP Cyclonic Filter abatement system. The TGP Cyclonic Filter uses cyclones and incorporates a bag filter system placed after the cyclones to abate particulate matter. The cyclones, proprietary filter bags and exhaust fan are designed to work in concert. This system can be run in bypass mode when service is required (per email communication from Triple Green Products representative to authors, September 30, 2021). With the new abatement system, bottom ash is recovered from the combustion chamber and augured into a flexible intermediate bulk container (FIBC, “Super Sack”) near the fuel hopper, once full an FIBC is then placed in covered storage. Fly ash is recovered from the TGP Cyclonic Filter system separately and conveyed via an ash auger to a separate FIBC, once full then placed in covered storage.

The system delivers thermal energy for space heating in the two poultry houses and a maintenance garage and for process hot water in power washing equipment. Figure 2 describes how the hydronic heating circuit conveys the hot water from the central boiler to the poultry houses for space heating purposes where heat is then delivered via eight (per house) water-to-air heat exchangers. The heat transfer fluid primarily consists of water with the addition of some boiler protection chemicals.

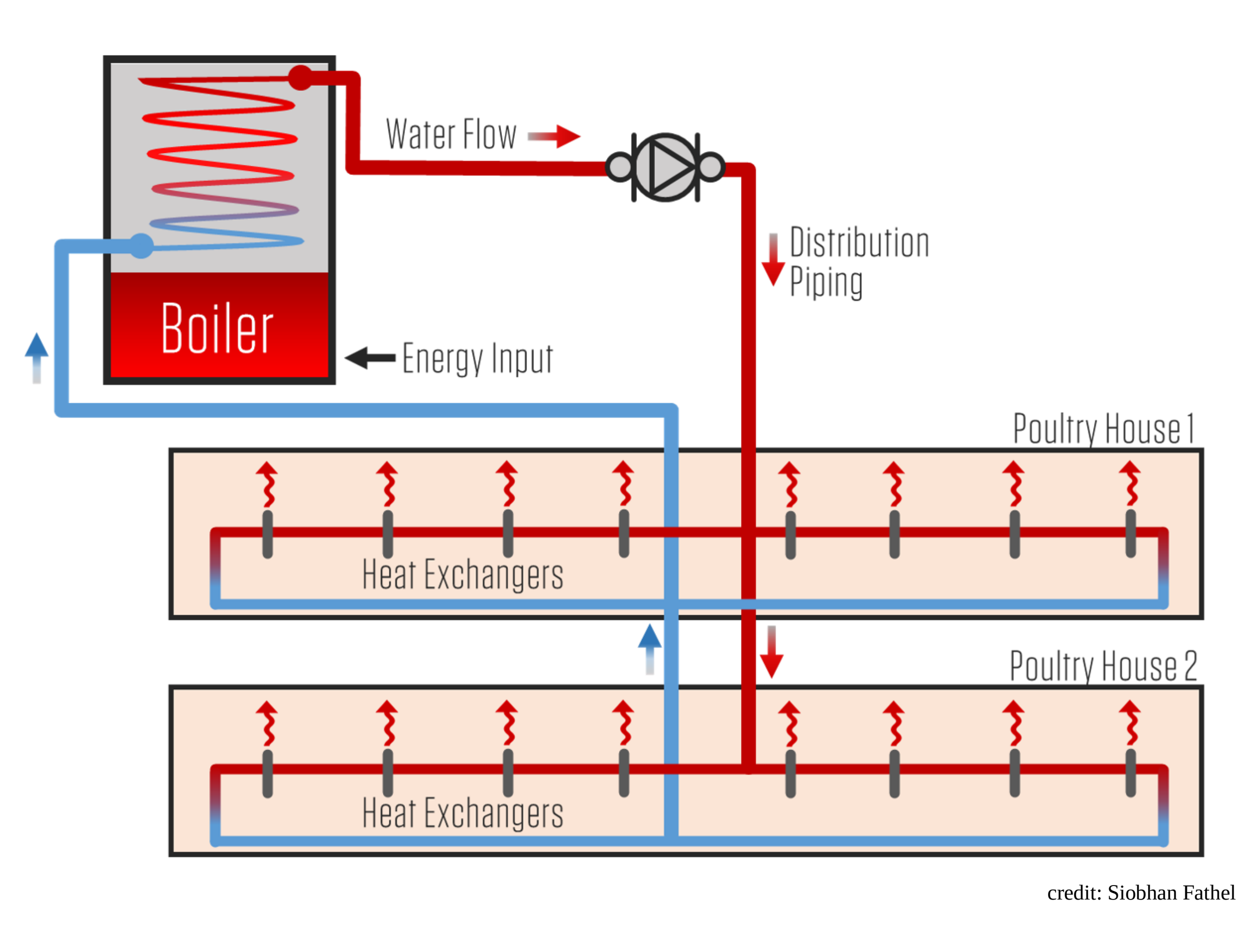

Figure 2: Representation of the Hydronic Heating Circuit at Site L1

The thermal load of the poultry houses is primarily a function of ambient temperature, in-house temperate set points, air exchange requirements and building design properties. Figure 3 describes the in-house temperature set points at L1 for a whole-house brooding program over the course of a flock cycle. Additionally, based on ambient temperatures, the farmer will often pre-condition the new bedding material in the days prior to flock placement to reduce moisture and bring the materials to the required temperature prior to flock placement. The required in-house temperature set point information is programmed into a poultry house controller which monitors actual temperatures across each of the eight zones. When additional heat is required the aperture of zonal valves is opened to increase flowrates and heat delivery. Heat delivery causes the temperature of the thermal storage of the system to lower. When the system temperature reaches a certain point, the boiler control system responds by delivering more fuel into the combustion chamber. This process then generates more thermal energy to be able to deliver more heat until all system temperature set points are satisfied. Figure 4 provides a visualization of the on-farm biomass feedstock-to-bedding-to-boiler-to-byproduct system at L1.

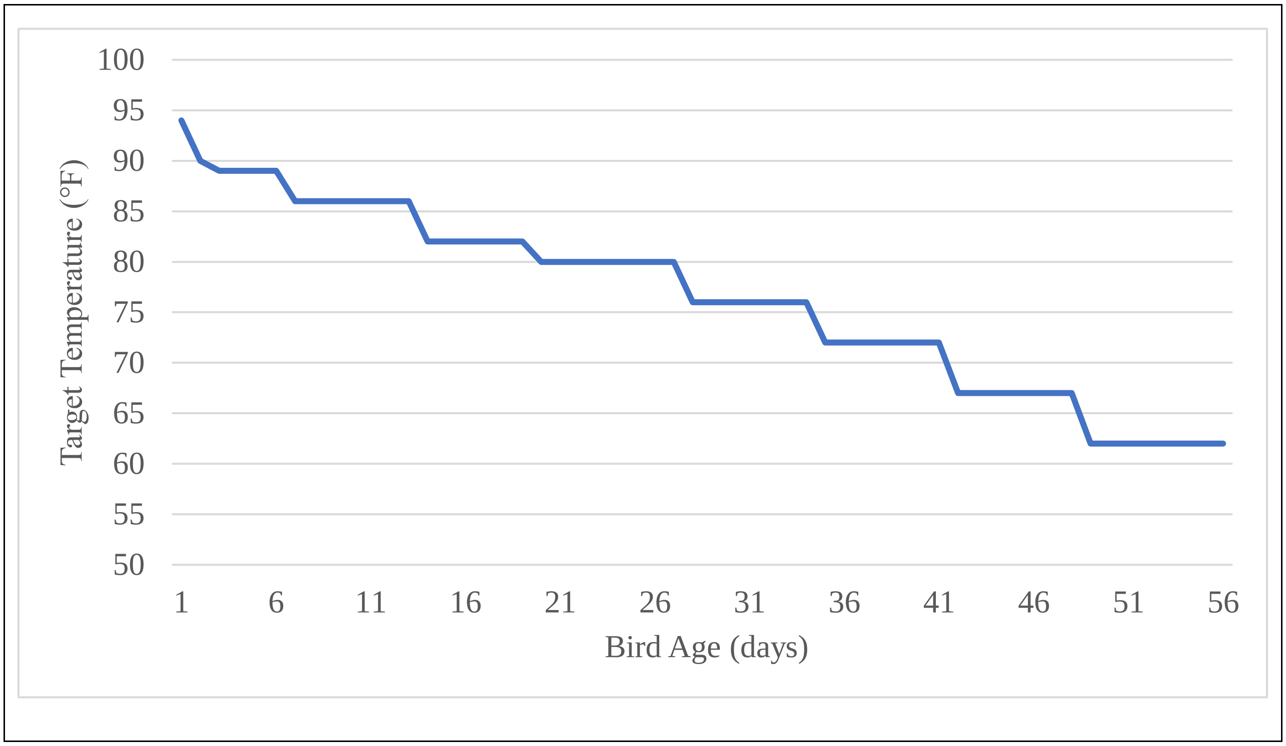

Figure 3: Placement to Growout Target House Temperatures

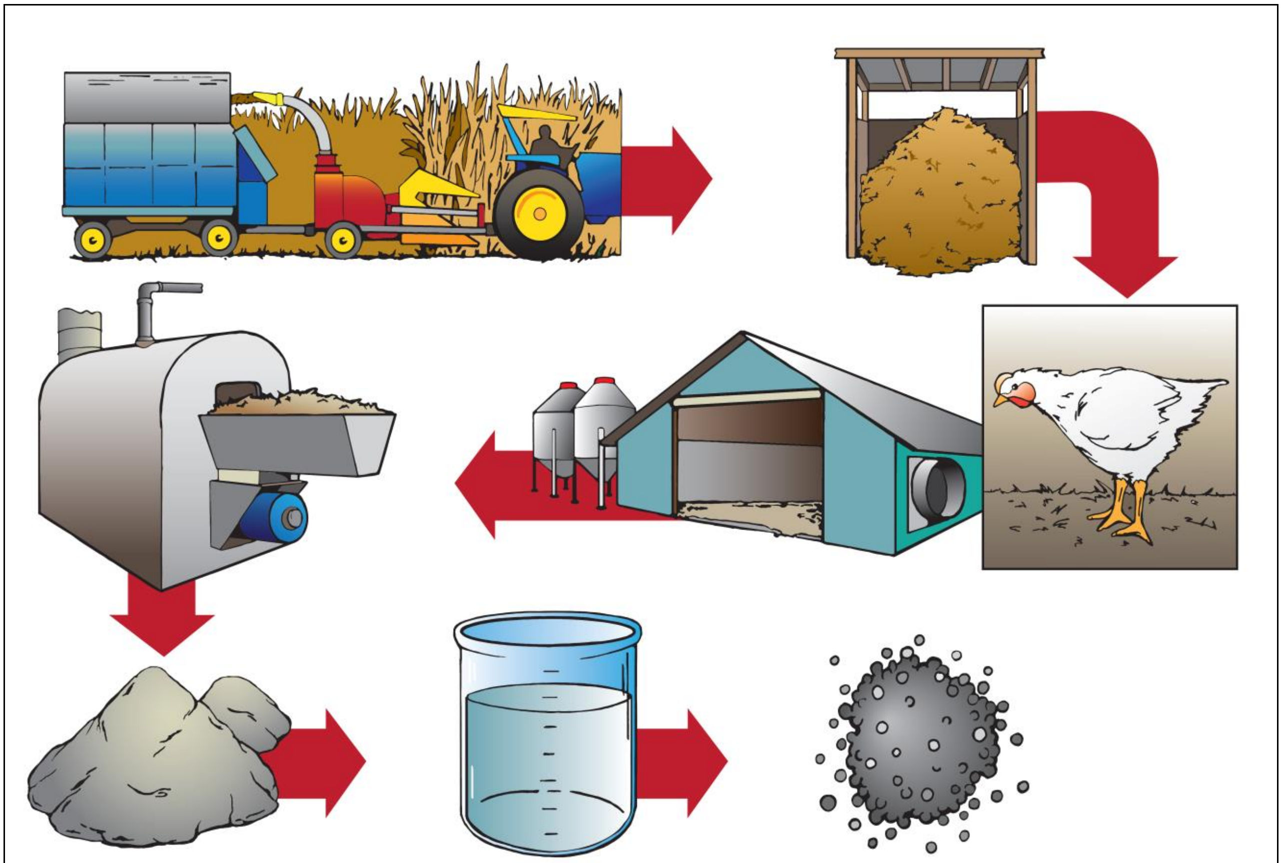

Figure 4: On-farm Biomass Feedstock-to-Bedding-to-Boiler-to-Byproduct System at L1 Showing Co-product Ash Processing for Value-added Product Development

Klingler Family Farm - Snyder County, Pennsylvania (Location 2)

Location 2 (L2) is a poultry farm with three 24,000 square foot poultry houses for antibiotic free broilers, with an average of six-and-a-half flock cycles per year per house. In 2015, the farmer purchased and installed two Bio-Burner BB-500 heating units from LEI Products, a firm now doing business as OrganiLock, to heat two of the poultry houses. The heating units are each rated 0.5 MMBtu/hr and were installed in a mechanical room located between two poultry houses. A skid-steer loader is used to place biomass fuel into one shared cylindrical fuel hopper which is located between the two BB-500s. Within the fuel hopper, a rotating hub sweeps biomass material into the two receiving troughs of the fuel-feed auger systems. The fuel-feed augers automatically deliver fuel to the combustion chamber based on system controller commands and thermal heating requirements. Bottom ash is automatically removed from the combustion chamber via an ash auger system. Periodically, fly ash is manually recovered from an internal trough which receives fly ash from the heat exchange turbulators and integrated cyclone. The fly ash material is removed via a hand-drill powered auger. Byproducts of combustion leave the combustion chamber, pass through the heat exchange turbulators, through the integrated cyclone, then are routed through a vertical stack and exhausted to the atmosphere. A hydronic heating circuit conveys the thermal energy from the heating unit to the poultry house where heat is delivered via water-to-air heat exchangers. The heat transfer fluid consists of a water and propylene glycol solution. Poultry house controllers manage and monitor in-house spacing heating. The heating system is designed for the BB-500s to provide base load thermal heating for the two poultry houses, with higher peak load heating requirements satisfied by propane unit heaters, when conditions require.

Typically, the L2 farm practices single flock litter management, where all poultry litter is removed after each flock and replaced with fresh bedding prior to the next flock placement. In this system the farmer utilizes wood shavings as the sole bedding material, placing approximately three inches of wood shavings throughout each house. During poultry house cleanouts, the farmer would select the relatively drier poultry litter and stockpile it within the poultry litter storage shed for its later use as a fuel source. The wetter poultry litter material (e.g., collected below water lines, etc.) was stored separately for later land application for agronomic purposes on the hay and cropland managed by the farmer.

The farmer would blend clean wood shavings with the single-flock poultry litter for use in the biomass heating system. The blending would occur within the system fuel hopper by placing one skid-steer bucket load of poultry litter followed by one bucket load of clean wood shavings. The turning leaf spring arms along the floor of the fuel hopper, along with the length of the rotating fuel feed auger, would work to blend the two biomass sources prior to their delivery into the combustion chamber. Annually, an estimated 2,889 cubic yards of wood shavings are used as poultry bedding material for the two poultry houses.

In 2018 a wet scrubber was installed at L2 for use as an additional emission abatement device for one of the BB-500 heating units. The wet scrubber was located along the exterior wall of the boiler room. The exhaust stack duct of the BB-500 was routed horizontally, through the exterior wall, to the OrganiLock wet scrubber.

In May 2019, a large secondary forest product manufacturing company (Wood-Mode, Inc.) shut down. This plant had been a large provider of animal bedding material in the area, including for L2. Due to a more limited bedding supply, and increased competition for the remaining materials, bedding prices increased. This shift caused the integrator and farmer for L2 to modify their poultry bedding management practices, shifting to a multi-flock bedding management system in late 2019. With this change, the farmer had difficulty utilizing poultry litter from the multi-flock program within the biomass heating system, without use of the more expensive clean wood shavings. Due to these factors, and the relatively low propane prices during this same period, the farmer has opted to idle the biomass heater since fall 2019. The L2 farmer indicates the system is idled but he would plan to use the biomass heating systems again as market factors change. Some of these factors remain in flux. The local forest product manufacturer is back in production, however, at a lower capacity, and the integrator and farmer have shifted back to single-flock litter management. Additionally, Figure 5 describes propane prices from 2014 to 2021, note that from October 2020 to October 2021 propane prices have increased 154% (EIA, 2021).

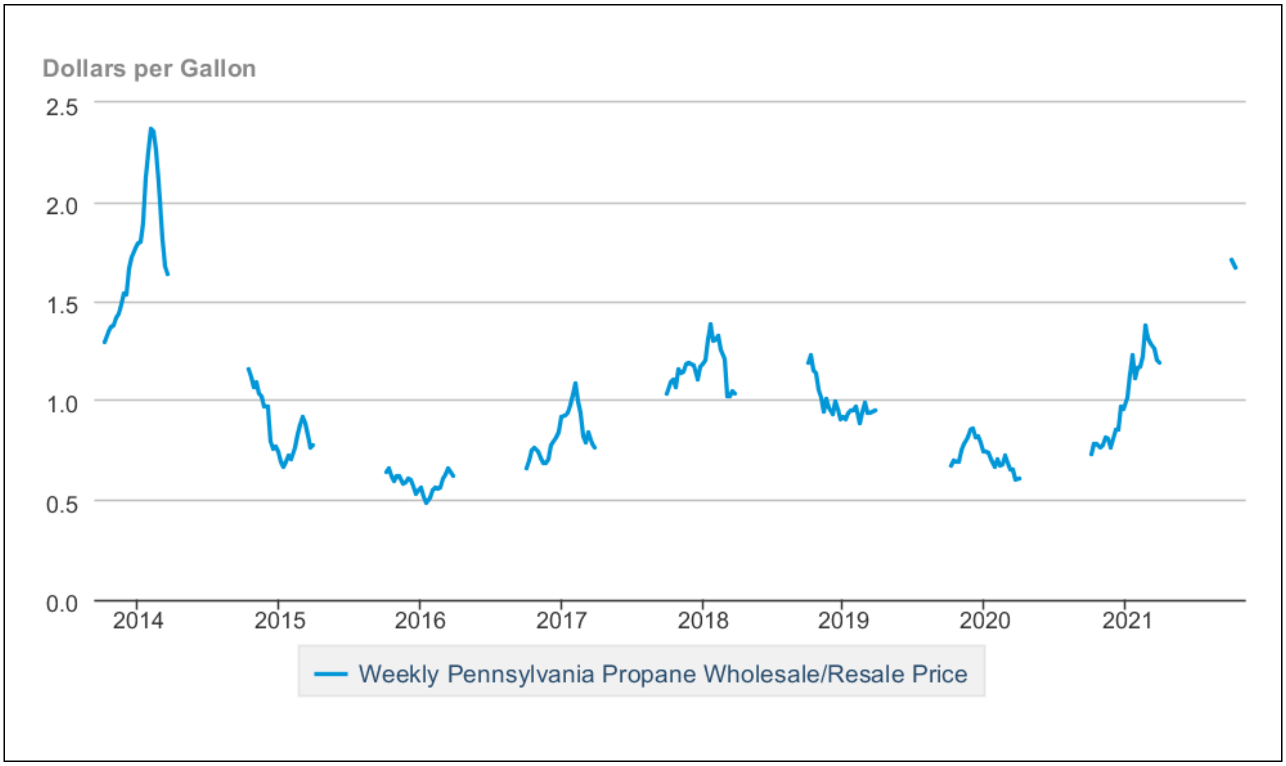

Figure 5: Weekly Pennsylvania Propane Wholesale Price (EIA, 2021)

<u>OrganiLock Headquarter Facility – Madisonville, Kentucky (L3)</u>

The L3 site consists of the OrganiLock company headquarters, including their fabrication, research and development facilities and is located near Madisonville, Kentucky. A Bio-Burner BB-500 heating unit was used with specifications and configuration similar to the on-farm installation at L2. Due to the location of L3, broiler litter from a local farmer was acquired by OrganiLock and stored in FIBCs and was used as the fuel source. Between March 2020 and February 2021, the stored poultry litter was processed through an OrganiLock Biomass Processing System (BPS 200) which hammer milled and dried the material before placing into storage at L3 in FIBCs. Heat generated by the Bio-Burner BB 500 is distributed via a subfloor radiant heating system within the concrete slab of a 7,200 square-foot hoop building. Two rounds of source emission testing were completed at this location using different abatement device configurations, including: wet scrubber abatement (2020) and biochar filtration media (2021). Additionally, testing at the facility enabled a trial of a biomass fuel additive to assess its potential for mitigation of particulate matter emissions.

METHODS

This section summarizes the materials and methods used to perform the project work, including: system configurations, source testing, biomass heating system heat input, feedstock analysis, mineral fuel additive, and host-farmer experiences.

System Configurations

From March 2019 through May 2021, the project assessed 15 different system operational configurations. Table 1 provides a summary of each configuration and indicates the number of source emission tests performed in each scenario. Some abatement technology descriptions are intentionally vague to respect the intellectual property of each technology provider, yet sufficient to convey the general particulate matter abatement strategy employed.

OrganiLock

For the OrganiLock system tests, due to the system design, testing campaigns included replications of the Base Case configuration for use as a reference point to discern effects of the abatement technologies evaluated and minimize effects from different sources of the variable poultry litter fuel. In total, four abatement system designs from this technology provider were assessed during the project (i.e., Abatement A, B, C and D). Two configurations used woody biomass as a reference point to determine particulate matter abated in low ash fuels (i.e., Base Case – Wood, and Abatement D – Wood). Additionally, a series of tests were performed using the base case abatement unit with poultry litter feedstock doped with different levels of a mineral fuel additive (i.e., Base Case + Fuel Additive - 2%, - 5%, and – 10%).

Triple Green Products

For the Triple Green Products system testing campaigns consisted of a Base Case, Abatement I, Bypass Mode, Bypass Gate Slip, and Abatement II. The Base Case was assessed in March 2019 to determine the emissions of the unit with the existing cyclone originally installed in 2012. In January 2020 a new abatement system, described as "TGP Cyclonic Filter System," and stack were installed. In November 2020 a testing campaign assessed the performance of the system with these modifications in Abatement I, Bypass Mode, Bypass Gate Slip modes. During the November 2020 source emission testing, the new lot of ordered filtration media would not securely fit the TGP Cyclonic Filter System. To address this challenge, older filtration media was cleaned and reused during the test (i.e., Abatement I). During the November 2020 source emission test, the system was intentionally run in Bypass Mode, where exhaust gases bypass the filtration media, to assess the abatement effect of the filtration media. Additionally, two source tests were completed while the unit was in an ambiguous system state where the TGP Cyclonic Filter System was neither fully engaged nor fully in Bypass Mode due to some amount of exhaust gas slippage around the diversion mechanism (i.e., Bypass Gate Slip). Finally, in April 2021 a series of source emission tests were completed with the TGP Cyclonic Filter System using new filtration media (i.e., Abatement II).

Table 1: Number of Source Emission Tests by System Configuration and Location

Technology Provider	Configuration	Number of Tests Conducted	Description
OrganiLock	Base Case	9	Integrated cyclone
	Abatement A	3	Integrated cyclone & wet scrubber abatement (v. 2019)
	Abatement B	3	Integrated cyclone & wet scrubber abatement (v. 2020)
	Abatement C	2	Integrated cyclone, wet scrubber abatement (v. 2020) & in situ modification
	Abatement D	6	Integrated cyclone & biochar filtration media
	Base Case – Wood	1	Wood-fired reference test with integrated cyclone
	Abatement D – Wood	1	Wood-fired reference test with integrated cyclone & biochar filtration media
	Base Case + Fuel Additive - 2%	2	Integrated cyclone with 2% fuel additive
	Base Case + Fuel Additive - 5%	3	Integrated cyclone with 5% fuel additive
	Base Case + Fuel Additive - 10%	2	Integrated cyclone with 10% fuel additive
Triple Green Products	Base Case	8	Integrated cyclone
	Abatement I	12	TGP Cyclonic Filter System with re-used filtration media
	Bypass Mode	5	Intentional system state when exhaust gases routed to bypass filter system TGP Cyclonic Filter System

	Bypass Gate Slip	2	Ambiguous system state where TGP Cyclonic Filter System is neither fully engaged nor fully in Bypass Mode due to exhaust gas slippage near diversion mechanism
	Abatement II	19	TGP Cyclonic Filter System with new filtration media
Total Number of Source Emission Tests Performed		78	

Source Testing Methods

Seventy-eight emission tests were completed assessing 15 different abatement system configuration iterations across the two bioenergy systems. Appendix A lists all of the source emission tests performed and each with a unique reference code.

Tests 031020 – 1, 031020 – 2, 031020 – 3, 031120 – 4, 031120 – 5, 031120 – 6, 031120 - 7, and 031120 – 8 were completed by Industrial Air Science (IAS) from Dayton, Ohio. All other tests were completed by Reliable Emission Measurements, Inc. (REM) from Auberry, California and in coordination with the Virginia Tech project team. Furthermore, tests 042721 – 00, 042721 – 01, and 042721 – 02, for selected gaseous pollutants, were completed with the additional coordination of Environmental Source Samplers, Inc. (ESS) from Wilmington, North Carolina.

The Environmental Protection Agency classifies stationary source testing methods as either promulgated, alternative, conditional, or as other. This project followed stationary source emission testing methods promulgated in the *Federal Register* and codified in 40 C.F.R. § 60 Appendix A of the *Code of Federal Regulations* (CFR, 2016), these are described below. Source emission tests were performed in accordance with these methodologies with variations noted in the source testing reports. For the source emission tests conducted solely by Reliable Emission Measurements, Inc. and Virginia Tech, common variations included, using a calibrated Testo 350 combustion gas analyzer to determine stack gas oxygen values and utilizing the Method 202 wet-impinger method to determine condensible particulate matter.

- Method 1A: “Sample and Velocity Traverses for Stationary Sources with Small Stacks or Ducts. The purpose of the method is to provide guidance for the selection of sampling ports and traverse points at which sampling for air pollutants will be performed pursuant to regulations set forth in this part. The applicability is limited to stacks or ducts of less than about 12 inches in diameter.” (CFR, 2016, Method 1A)

- Method 2: “Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube). This method is applicable for the determination of the average velocity and the volumetric flow rate of a gas stream.” (CFR, 2016, Method 2)

- Method 3A: “Determination of Oxygen and Carbon Dioxide Concentrations in Emissions from Stationary Sources (Instrumental Analyzer Procedure). This method is used for measuring oxygen (O_2) and carbon dioxide (CO_2) in stationary source emissions using a continuous instrumental analyzer.” (CFR, 2016, Method 3A)

- Method 4: “Determination of Moisture Content in Stack Gases. This method is applicable for the determination of the moisture content of stack gas.” (CFR, 2016, Method 4)

- Method 5: “Determination of Particulate Matter Emissions from Stationary Sources. This method is applicable for the determination of particulate matter emissions from stationary sources.” (CFR, 2016, Method 5)

- Method 9: “Visual Determination of the Opacity of Emissions from Stationary Sources. Many stationary sources discharge visible emissions into the atmosphere; these emissions are usually in the shape of a plume. This method involves the determination of plume opacity by qualified observers.” (CFR, 2016, Method 9)

- Method 26A: “Determination of Hydrogen Halide and Halogen Emissions from Stationary Sources Isokinetic Method. This method uses isokinetic sampling to collect samples for determining emissions of hydrogen halides and halogens from stationary sources when specified by the applicable subpart." (CFR, 2016, Method 26A)

- Method 202: Condensible Particulate Matter. Tests performed by REM followed the "Method 202 Determination of Condensible Particulate Emissions from Stationary Sources" (Appendix M of 40 CFR part 51 on December 17, 1991 (CFR, 1996)). Tests performed by IAS followed the "Dry Impinger Method for Determining Condensable Particulate Emissions from Stationary Sources" (Appendix A of 40 CFR part 60 on December 21, 2010 (CFR, 2016)). "This method addresses the equipment, preparation, and analysis necessary to measure condensable particulate matter which is measured in the emissions after removal from the stack and after passing through a filter." (CFR, 2016)

Conditional Test Method

- CTM-Method 27: "Procedure for Collection and Analysis of Ammonia in Stationary Sources." (EPA, 1997)

Additionally, a portable combustion gas analyzer (Testo 350) was used during portions of testing to record concentrations of nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and hydrocarbons (C_xH_y). Though existing conditional test methods are used for portable electrochemical analyzers (e.g., CTM-030 and CTM-034) these are typically for use with fossil fuel-fired combustion systems. Therefore, the results from the portable combustion gas analyzer were used for informational purposes in communication with technology providers, or as noted above and in the source emission reports.

Gravimetric analysis was performed on the recovered samples for each of the source emission tests. Particle size analysis for a subset of the samples was performed at the Air Quality Compliance Laboratory, Cotton Production and Processing Research Unit, Agricultural Research Service, USDA (Lubbock, TX) using a Beckman Coulter Multisizer 3 and an LS Particle Size Analyzer. Scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS) was completed for a subset of the samples at the Virginia Tech Institute for Critical Technology and Applied Science's Nanoscale Characterization and Fabrication Lab (Blacksburg, VA).

Biomass Heating System Heat Input

Fuel feed rate was estimated in order to calculate particulate matter emissions in terms of pounds of pollutant per, either, pound of fuel input or, unit of heat input (ERG, 2001).

<u>L1 - Fuel Feed Rate</u>

Load cells were placed under the Lanco Litter fuel hopper to monitor fuel consumption at L1 during the project period. The system by Rice Lake (Rice Lake, WI) consisted of four load cells and mount kits (Model 75016), a data indicator (720i Universal, Model 101230), and a data logger (Go-Between, RS-232-to-USB storage device, Model 153266). The data logger system recorded mass in 5-pound increments at 15-minute intervals. The data indicator also provided a visual display of the instantaneous mass of biomass feedstock within the fuel hopper at any given moment, for use both during timed emission source tests and to aid farmer fuel management. The system was installed in November 2018 and calibrated annually by Apple Valley Scales. This system permitted the estimation of the mass of fuel utilized during, and after, each source emission test.

<u>L2 - Fuel Feed Rate</u>

Fuel hopper load cells were not used at the L2 system due to spatial constraints between the fuel hopper and conveyance system in the mechanical room. Therefore, in order to monitor fuel feed rates during source emission testing, a temporary surge hopper was constructed and mechanically fastened on top of the trough fuel-feed auger jacket. To represent the manner in which the host farmer used the heating system, the two biomass streams, wood shavings and poultry litter, were manually blended in a 1:1 ratio prior to delivery for use as a fuel. In this configuration, the rotating hub within the primary fuel feed hopper was deenergized, and any upstream residual fuel within the fuel feed auger was cleared. During source testing, pre-weighed material was manually fed (via five-gallon buckets) into the fabricated temporary surge hopper and the cumulative mass consumed tracked for the duration of each test. At the completion of each timed source emission test, the volume of any residual material remaining in surge hopper was recorded, and the corresponding mass deducted by application of the bulk density of the material. This process permitted estimation of the mass of fuel utilized during each source emission test. At the completion of source emission testing, the temporary surge hopper was removed and the primary fuel hopper feed mechanism was reenergized to permit automatic fuel delivery and normal system operation by the host farmer.

<u>L3 - Fuel Feed Rate</u>

Similar to L2, fuel hopper load cells were not used at L3 due to spatial constraints between the fuel hopper and conveyance system. Prior to source emission testing, the rotating hub within the primary fuel feed hopper was deenergized. During source testing, pre-weighed material was then manually fed (via five-gallon buckets) directly into the trough of the fuel feed auger system, and cumulative mass tracked for the duration of each source emission test. Any residual material remaining in a five-gallon bucket at the completion of the timed source emission test was re-weighed and this mass deducted. This process permitted estimation of the mass of fuel utilized during a source emission test. At the completion of source emission testing the fuel hopper feed mechanism was reenergized to permit automatic fuel delivery to the heating system.

Feedstock Analysis

Fuel samples were collected to provide a representative sample of the biomass material immediately prior to its use as a fuel within the bioenergy conversion system. At L1 fuel samples were collected from various locations along the face of material prior to its delivery into the receiving fuel feed auger. At L2 fuel samples were collected from the manually blended material destined for delivery to the modified fuel feed system. At L3 fuel samples were collected from the biomass material, stored in FIBCs, used as fuel during each emission test. Additionally, grab samples of virgin biomass sources were collected for analysis prior to their use as a poultry bedding material for reference values. Biomass samples were collected using a material scoop and placed into resealable plastic bags, then placed in temporary storage for later shipment to a laboratory for analyses.

Biomass samples were analyzed for nutrients, moisture, bulk density, mineral and gross calorific value. Samples were analyzed at Brookside Laboratories (BLINC - New Bremen, OH), and additional samples sent to the BioEnergy Testing and Analysis Laboratory at Texas A&M University (BETA - College Station, TX), and the Thermal Analysis Lab at Western Kentucky University (TLA - Bowling Green, KY). Thermal analysis consisted of thermogravimetric analysis which is an analytical technique to assess the change in mass of a sample over time as the material is heated. Table 2 provides a summary of some of the testing methods used by each lab.

Table 2: Laboratory Feedstock Analysis Methods

Parameter	Test Method	Laboratory
Moisture	ASTM E 871 – 82	BETA
	SM2540 G	BLINC
	ASTM D5142 – 04	TLA
Gross Calorific Value	ASTM E 711 – 87	BETA
	ASTM D2015 – 96	BLINC (pre- 2018)
	ASTM D240	BLINC (post – 2018)
	ASTM 5865	TLA
Potassium	EPA 6010	BLINC
	ASTM D3682 – 13	TLA

Mineral Fuel Additive

At L3 three levels of a fuel additive were used during seven source emission tests in the BioBurner BB 500 base configuration. The fuel additive consisted of an aluminosilicate mineral product. The poultry litter was dosed with 2%, 5%, and 10%, by weight (w.b.), with the mineral additive. The two materials were manually blended to create a more homogenous mixture prior to delivery to the fuel feed system and combustion in the biomass heating unit.

Technology Host Farmer Experiences

Farmer experiences operating the biomass heating systems and particulate matter abatement systems were summarized during the project. The human subjects research protocol for this project was authorized by the Virginia Tech Institution Review Board (IRB #18 – 259). A small annual stipend was provided by the project to the farmers to compensate for the additional time in their documenting and later sharing feedback regarding system management experiences and operational and maintenance issues. The farmer experiences were documented and summarized via video interviews. These videos were used to both inform project analysis and for use as future outreach educational extension products for others considering similar biomass heating system applications.

RESULTS

This section summarizes the results from the project assessment work, including: source testing, biomass heating system heat input, feedstock analysis, and host-farmer feedback.

Feedstock Analysis

Table 3 describes the bedding analysis for samples from L1 as analyzed by BLINC. The values in the table illustrate some of the inherent differences among the materials used for animal bedding. For example, in this case, the wood-based bedding materials have lower mineral and potassium values versus miscanthus.

Table 3: Bedding Material Analysis for Biomass Materials Used at L1

Parameter	Wood Chips	Miscanthus	Wood Shavings
Moisture Content (%) $_{w.b.}$	9.37	9.84	18.45
Gross Calorific Value (Btu/lb) $_{w.b.}$	8,109	7,644	7,225
Total Mineral (%) $_{d.b.}$	0.29	1.44	0.48
Potassium (K - %) $_{d.b.}$	0.07	0.20	0.11

Tables 4, 5 and 6 describe the feedstock fuel properties from each site for each source testing period. The tables describe the moisture content, gross calorific value, total mineral, and elemental potassium from the samples with conversions performed per ASTM D3180 – 15 (ASTM, 2015). These values are reported in terms of minimum, maximum, mean and standard deviation for the collected biomass samples.

Table 4: Summary of Fuel Analysis for Source Testing at the L1 Site

Term	Fuel Property	Min	Max	Mean	SD
03-19	Gross Calorific Value (Btu/lb) w.b.	4,599	5,831	4,976	488
	Moisture (%) w.b.	31	36	33	2
	Ash (%) d.b.	16.5	28.4	24.6	4.7
	Potassium (%) d.b.	2.6	3.0	2.8	0.2
11-20	Gross Calorific Value (Btu/lb) w.b.	4,622	7,649	5,506	603
	Moisture (%) w.b.	20	33	27	3
	Ash (%) d.b.	13.3	19.2	16.7	1.6
	Potassium (%) d.b.	2.4	3.0	2.6	0.2
04-21	Gross Calorific Value (Btu/lb) w.b.	5,772	6,572	6,236	261
	Moisture (%) w.b.	24	30	27	2
	Ash (%) d.b.	11.7	17.2	14.1	1.8
	Potassium (%) d.b.	2.3	3.0	2.6	0.2

Table 5: Summary of Fuel Analysis for Source Testing at the L2 Site

Term	Fuel Property	Min	Max	Mean	SD
03-19	Gross Calorific Value (Btu/lb) w.b.	6,338	6,555	6,454	105
	Moisture (%) w.b.	15	17	17	1
	Ash (%) d.b.	7.0	11.0	9.4	1.7
	Potassium (%) d.b.	1.5	1.8	1.6	0.1

Table 6: Summary of Fuel Analysis for Source Testing at the L3 Site

Term	Fuel Property	Min	Max	Mean	SD
03-20	Gross Calorific Value (Btu/lb) w.b.	5,152	5,512	5,292	193
	Moisture (%) w.b.	22	25	24	2
	Ash (%) d.b.	22.6	25.4	24.1	1.4
	Potassium (%) d.b.	3.1	3.2	3.1	0.1
02-21 base	Gross Calorific Value (Btu/lb) w.b.	7,243	7,769	7,491	208
	Moisture (%) w.b.	6	9	7	1
	Ash (%) d.b.	12.7	15.5	14.0	1.1
	Potassium (%) d.b.	2.5	2.7	2.6	0.1
02-21 additive 2%	Gross Calorific Value (Btu/lb) w.b.	7,099			
	Moisture (%) w.b.	8.1			
	Ash (%) d.b.	16.1			
	Potassium (%) d.b.	2.4			
02-21 additive 5%	Gross Calorific Value (Btu/lb) w.b.	7,145	7,391	7,268	174
	Moisture (%) w.b.	7	8	8	1
	Ash (%) d.b.	18.0	18.8	18.4	0.6
	Potassium (%) d.b.	2.4	2.5	2.4	0.1
02-21 additive 10%	Gross Calorific Value (Btu/lb) w.b.	7,396			
	Moisture (%) w.b.	8			
	Ash (%) d.b.	18.4			
	Potassium (%) d.b.	2.2			

Thermogravimetric Analysis

A sample from L1 collected June 2021 was prepared for thermogravimetric analysis (TGA). To prepare the sample the collected material was dehydrated and milled. Two sub samples were prepared. One sample consisted of the processed material, the other sample consisted of the processed material with the addition of an aluminosilicate mineral product doped at 10%, by weight (w.b.), with the additive. Table 7 describes the fuel properties of the two samples used in the TGA.

Table 7: Analysis of Fuel Samples from L1 Used for Thermogravimetric Analysis

Fuel Property	Poultry Litter	Poultry Litter + Mineral Additive
	Sample A	Sample B
Gross Calorific Value (Btu/lb) $_{w.b.}$	7,298	6,490
Moisture (%) $_{w.b.}$	6	5
Ash (%) $_{d.b.}$	13.9	20.1
Potassium (%) $_{d.b.}$	2.8	2.8

Figure 6 is a graphic summary from the TGA of the two samples. The figure describes rates of changes in sample mass and temperature. The processed material (Sample A) is represented by the solid green lines, and the additive-doped material (Sample B) is represented by the dashed blue lines. The difference between the blue and green curves illustrates an effect of the mineral additive with regard to mass. Table 8 describes this information in tabular form as percent mass loss across four temperature intervals. For this sample, when heated from to 68 to 1,472 ºF, Sample A had a total weight loss of 87.97% while Sample B had a total weight loss of 80.64%.

Table 8: Sample Mass Loss Rates Across Four Temperature Intervals

Sample ID	1st Mass Loss (%)	2nd Mass Loss (%)	3rd Mass Loss (%)	4th Mass Loss (%)	Total Weight Loss (%)
	68-302 ºF	302-752 ºF	752-1112 ºF	1112-1472 ºF	68-1472 ºF
A	8.38	51.55	26.96	1.08	87.97
B	7.97	46.13	25.66	0.88	80.64

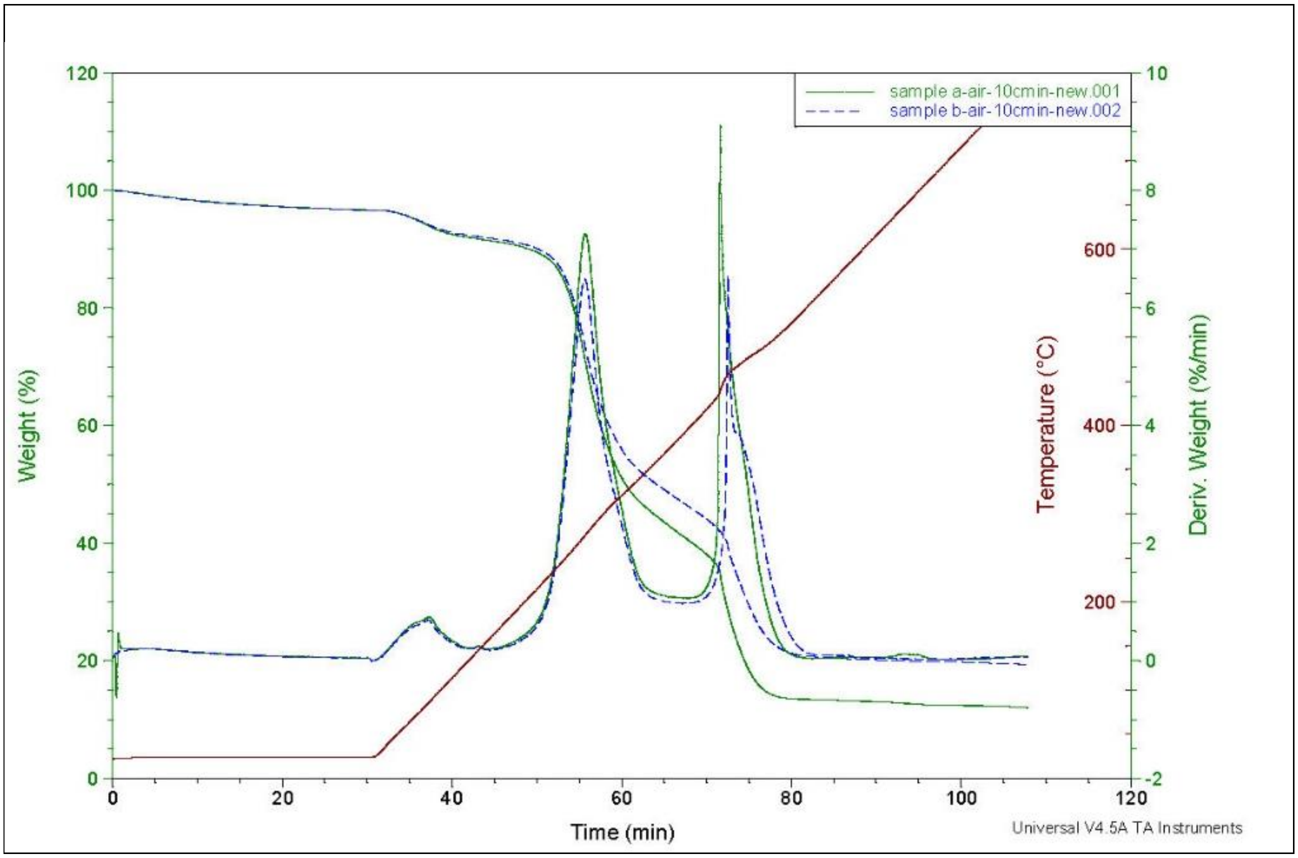

Figure 6: Overlay of TGA Curves for Samples A and B Versus Time Under Air Flow

Biomass Heating System Heat Input

The system fuel feed rates for each source test conducted at L1 are presented in Table 9. These values indicate the range of fuel feed rates, representing heat input rates, during the timed source emission test periods for each testing campaign. The average daily fuel feed rate and the cumulative tons of poultry litter converted from December 17, 2018 through April 30, 2021 at the L1 site as monitored by the system load cell dataloggers are presented in Figure 7. These values indicate the heat input rates of the biomass boiler during this broader time interval. Table 10 describes the system fuel feed rates for each source test conducted at the L2 and L3 sites. The tables note the minimum, maximum, mean, and standard deviation of feed rates by source test configuration.

Table 9: Triple Green Products – Heating System Input

Configuration	Term	Site	# Tests Performed	Fuel Feed Rate (lb/hr) w.b.			
				Min	Max	Mean	SD
Base Case	03-19	L1	8	210	312	265.8	34.90
Abatement I	11-20	L1	12	62	202	148.8	43.71
Bypass Mode	11-20	L1	5	236	276	261.4	15.90
Bypass Gate Slip	11-20	L1	2	38	182	110.0	101.82
Abatement II	04-21	L1	19	64	216	148.7	40.66

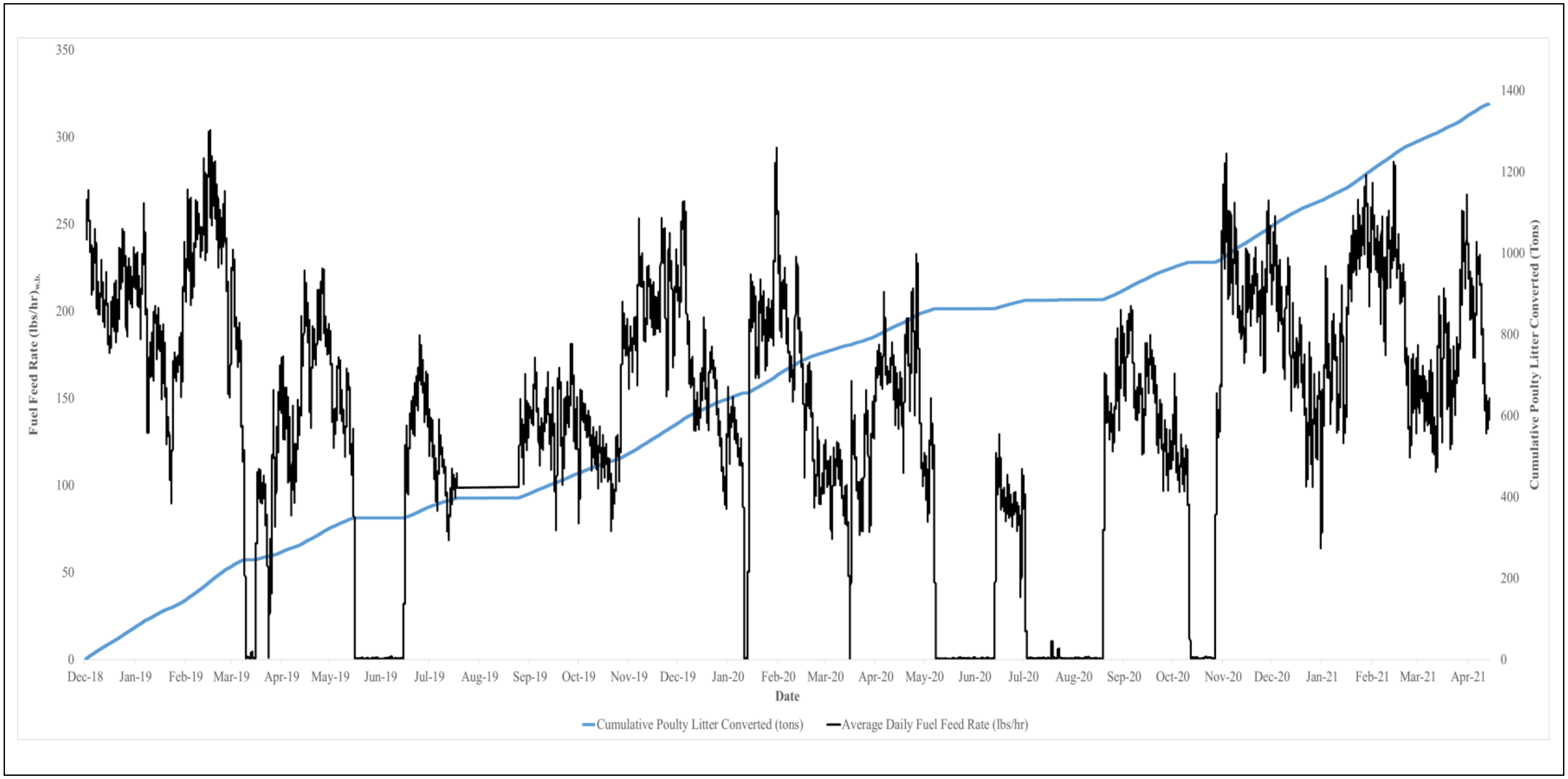

Figure 7: Average Daily Fuel Feed Rate & Cumulative Tons of Poultry Litter Converted from December 17, 2018 through April 30, 2021 at the L1 Site as Monitored by System Load Cell Dataloggers

Table 10: OrganiLock – Heating System Input

Configuration	Term	Site	Number of Tests Performed	Fuel Feed Rate (lb/hr) w.b.			
				Min	Max	Mean	SD
Base Case	03-19	L2	3	53	55	54.0	1.00
	03-20	L3	3	91	111	99.7	10.24
	02-21	L3	3	50	56	54.0	3.46
Abatement A	03-19	L2	3	48	54	51.7	3.21
Abatement B	03-20	L3	3	81	105	91.3	12.34
Abatement C	03-20	L3	2	84	84	84.0	0
Abatement D	02-21	L3	6	52	58	54.3	2.16
Base Case – Wood	02-21	L3	1	53			
Abatement D – Wood	02-21	L3	1	58			
Base Case + Fuel Additive - 2%	02-21	L3	3	50	56	52.4	3.37
Base Case + Fuel Additive - 5%	02-21	L3	2	56	65	60.3	6.36
Base Case + Fuel Additive - 10%	02-21	L3	2	54	57	55.2	2.19

Source Testing

Source emission testing occurred in 2019 at the L1 and L2 sites, in 2020 at the L1 and L3 sites, and again in 2021 at the L1 and L3 sites. Summary information describing this series of emission tests is described below.

For base case testing during 2019 at L1 (e.g., 030119 – 1 through 030219 – 8) it was difficult to determine the effective stack diameter due to the varying thickness of a particulate matter cake lining the inner stack wall effecting flow rate calculations. Therefore, the effective stack diameter was estimated at both 8” and 12” diameters, in this report the average values are reported and used to determine the mass emission rates for the L1 reference base case.

As noted in Appendix A, some tests were anisokinetic and some were less than 60-minute duration. During some of the unabated tests (e.g., 030119 – 2, 030119 – 3, 030119 – 4, and 030119 – 7) the filter media used in the Method 5 analysis became heavily loaded with particulate matter, to the extent that, for certain runs, it was not possible to maintain isokinetic sampling conditions. Some of the emission tests consisted of a series of shortened-tests (i.e., < 60-minutes). For instance, shortened run times were used to mitigate the high loading of particulate matter on the filter media (e.g., 030219 – 5, 030219 – 6, 030219 – 7, 030219 – 8, 031120 – 4, 031120 – 5, 111620 – 13, 111620 – 14, 111620 – 15, and 111620 – 16). While in other situations, shortened sample times were performed to mitigate issues from sub-freezing temperatures causing icing within the series of impinger sockets in the later portions of 60-minute tests (e.g., 030219 – 5, 030219 – 6, and 030219 – 8). In each of these cases, the results, for isokinetic runs with shortened test periods, were converted for expression to an hourly basis. In other situations, certain equipment issues occurred during the emission test, including: a long piece of biomass material lodged in the fuel surge hopper which impeded fuel delivery during the sample period (e.g., 111520 - 11), in situ abatement system modifications (e.g., 031120 – 7 and 031120 – 8), and a system bypass switch mechanism failed to seal properly (e.g., 111720 – 17 and 111720 – 18). Additionally, two tests were performed using woody biomass as a fuel source (e.g., 021021 – 1 and 021121 – 11) for use as reference point regarding an abatement systems ability to mitigate particulate emissions from high-ash versus low-ash fuels. Appendix A provides comments for each test, and unless otherwise noted, tests consisted of isokinetic sampling durations of approximately one hour.

Table 11 and Table 12 describe the number of source emission tests conducted for each system configuration and the number of tests, and their corresponding test reference code (from Appendix A), included in summarizing the total particulate matter source emission results for each configuration. Five sources tests are not included in the particulate matter emissions summary data, including: four anisokinetic source tests (i.e., 030119 – 2, 030119 – 3, 030119 – 4, 030119 – 7), one source test with a blocked fuel-feed mechanism (i.e, 111520 - 11), and a source test which only measured selected gaseous pollutants (i.e., 042721 – 00). For the OrganiLock system the results from each test performed are included in the summary results for each configuration.

Table 11: Triple Green Products

Configuration	Term	Site	Number of Tests Conducted	Number of Tests Included	Source Test Reference Codes of Included Tests
Base Case	19-Mar	L1	8	5	030119 – 1 030219 – 5 030219 – 6 030219 – 8
Abatement I	20-Nov	L1	12	11	111320 – 1 111320 - 2 111320 - 3 111420 - 4 111420 - 5 111420 - 6 111420 - 7 111420 - 8 111520 - 9 111520 - 10 111720 – 19
Bypass Mode	20-Nov	L1	5	5	111620 - 12 111620 - 13 111620 - 14 111620 - 15 111620 – 16
Bypass Gate Slip	20-Nov	L1	2	2	111720 – 17 111720 – 18
Abatement II	21-Apr	L1	19	18	042721 – 01 042721 – 02 042721 – 03 042721 – 04 042721 – 05 042821 – 06 042821 – 07 042821 – 08 042821 – 09 042821 - 10 042821 - 11 042821 - 12 042921 - 13 042921 - 14 042921 - 15 042921 - 16 043021 - 17 043021 – 18

Table 12: OrganiLock

Configuration	Term	Site	Number of Tests Conducted	Number of Tests Included	Source Test Reference Codes of Included Tests
Base Case	19-Mar	L2	3	3	030519 – 1 030519 – 2 030519 – 3
	20-Mar	L3	3	3	031120 – 4 031120 – 5 031120 – 6
	21-Feb	L3	3	3	021021 - 2 021021 - 3 021021 - 4
Abatement A	19-Mar	L2	3	3	030619 – 4 030619 – 5 030619 – 6
Abatement B	20-Mar	L3	3	3	031020 – 1 031020 – 2 031020 – 3
Abatement C	20-Mar	L3	2	2	031120 – 7 031120 – 8
Abatement D	21-Feb	L3	6	6	021021 - 5 021121 - 6 021121 - 7 021121 - 8 021121 - 9 021121 – 10
Base Case – Wood	21-Feb	L3	1	1	021021 - 1
Abatement D – Wood	21-Feb	L3	1	1	021121 – 11
Base Case + Fuel Additive - 2%	21-Feb	L3	2	2	021321 – 17 021321 – 18
Base Case + Fuel Additive - 5%	21-Feb	L3	3	3	021221 – 12 021221 – 13 021221 – 14
Base Case + Fuel Additive - 10%	21-Feb	L3	2	2	021221 – 15 021221 – 16

Emission Concentration (Grains of Total Particulate Matter per Dry Standard Cubic Foot)

Table 13 summarizes the results of total particulate matter emission concentration, expressed at 7% Oxygen, for source testing with the Triple Green Products system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. For reference, the table also includes mean stack flowrate (dscf/minute) for each configuration. The emission concentration for the Base Case configuration is estimated as 2.303 TPM-gr/dscf (7%-O_2) and for the Abatement II configuration is estimated as 0.103 TPM-gr/dscf (7%-O_2).

Table 13: Triple Green Products - Total Particulate Matter Emission Concentration

Configuration	Term	Site	Number of Tests Included	Mean Stack Flowrate (dscf/min)	Grains per Dry Standard Cubic Foot (gr/dscf 7%-O_2)			
					Min	Max	Mean	SD
Base Case	19-Mar	L1	4	429	1.717	2.844	2.303	0.608
Abatement I	20-Nov	L1	11	532	0.044	0.260	0.103	0.059
Bypass Mode	20-Nov	L1	5	1,100	1.336	2.576	1.942	0.440
Bypass Gate Slip	20-Nov	L1	2	585	0.424	0.425	0.425	0.001
Abatement II	21-Apr	L1	18	599	0.059	0.286	0.103	0.050

Table 14 summarizes the results of total particulate matter emission concentration, expressed at 7% Oxygen, for source testing of the OrganiLock system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. The emission concentration for the Base Case (2021) configuration is estimated as 1.639 TPM-gr/dscf (7%-O_2) and for the Abatement D configuration is estimated as 0.566 TPM-gr/dscf (7%-O_2).

Table 14: OrganiLock - Total Particulate Matter Emission Concentration

Configuration	Term	Site	Number of Tests Included	Mean Stack Flowrate (dscf/min)	Grains per Dry Standard Cubic Foot (gr/dscf 7%-O_2)			
					Min	Max	Mean	SD
Base Case	19-Mar	L2	3	417	0.639	0.823	0.752	0.099
	20-Mar	L3	3	491	1.478	2.239	1.919	0.395
	21-Feb	L3	3	312	1.566	1.718	1.639	0.076
Abatement A	19-Mar	L2	3	509	0.320	0.736	0.553	0.213
Abatement B	20-Mar	L3	3	470	0.878	1.814	1.234	0.507
Abatement C	20-Mar	L3	2	642	0.658	0.710	0.684	0.036
Abatement D	21-Feb	L3	6	629	0.284	0.677	0.566	0.155
Base Case – Wood	21-Feb	L3	1	331	0.170			
Abatement D – Wood	21-Feb	L3	1	778	0.024			
Base Case + Fuel Additive - 2%	21-Feb	L3	2	344	1.362	1.371	1.367	0.006
Base Case + Fuel Additive - 5%	21-Feb	L3	3	323	1.033	1.260	1.175	0.123
Base Case + Fuel Additive - 10%	21-Feb	L3	2	299	0.777	0.857	0.817	0.057

Mass Emission Rate (Pounds of Total Particulate Matter per Hour)

Table 15 summarizes the mass emission rate of pounds of total particulate matter per hour for testing with the Triple Green Products system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. The mass emission rate for the Base Case configuration is estimated as 5.210 TPM-lb/hr and for the Abatement II configuration is estimated as 0.158 TPM-lb/hr.

Table 15: Triple Green Products - Pounds of Total Particulate Matter per Hour

Configuration	Term	Site	Number of Tests Included	Mass Emission Rate of Total Particulate Matter (lb/hr)			
				Min	Max	Mean	SD
Base Case	19-Mar	L1	4	2.423	7.084	5.210	2.193
Abatement I	20-Nov	L1	11	0.058	0.306	0.144	0.069
Bypass Mode	20-Nov	L1	5	2.822	5.745	4.934	1.201
Bypass Gate Slip	20-Nov	L1	2	0.483	0.711	0.597	0.161
Abatement II	21-Apr	L1	18	0.109	0.262	0.158	0.038

Table 16 summarizes the mass emission rate of pounds of total particulate matter per hour for testing with the OrganiLock system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. Figure 8 describes the abatement effects of the mineral additive on the mass emission rate of total particulate matter at four mix levels (0%, 2%, 5% and 10%). The mass emission rate for the Base Case (2021) configuration is estimated as 1.162 TPM-lb/hr and for the Abatement D configuration is estimated as 0.766 TPM-lb/hr.

Table 16: OrganiLock - Pounds of Total Particulate Matter per Hour

Configuration	Term	Site	Number of Tests Included	Mass Emission Rate of Total Particulate Matter (lb/hr)			
				Min	Max	Mean	SD
Base Case	19-Mar	L2	3	0.668	0.927	0.823	0.137
	20-Mar	L3	3	0.907	1.251	1.098	0.175
	21-Feb	L3	3	1.037	1.248	1.162	0.111
Abatement A	19-Mar	L2	3	0.418	0.962	0.724	0.278
Abatement B	20-Mar	L3	3	0.453	1.054	0.688	0.321
Abatement C	20-Mar	L3	2	0.507	0.525	0.516	0.013
Abatement D	21-Feb	L3	6	0.355	0.984	0.766	0.226
Base Case – Wood	21-Feb	L3	1	0.118			
Abatement D – Wood	21-Feb	L3	1	0.039			
Base Case + Fuel Additive - 2%	21-Feb	L3	2	1.004	1.068	1.036	0.045
Base Case + Fuel Additive - 5%	21-Feb	L3	3	0.743	0.805	0.776	0.031
Base Case + Fuel Additive - 10%	21-Feb	L3	2	0.426	0.470	0.448	0.031

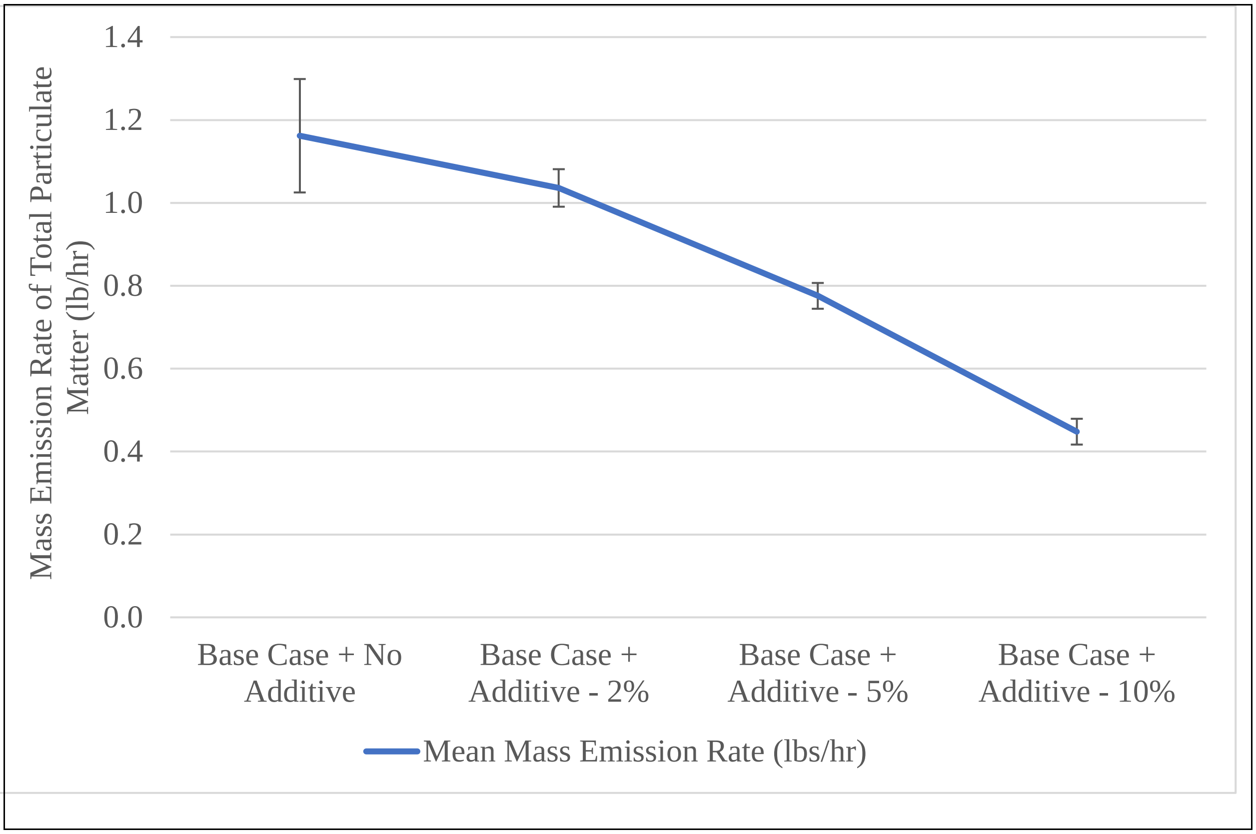

Figure 8: Abatement Effects of the Mineral Additive on the Mass Emission Rate of Total Particulate Matter (lb/hr) at Four Mix Levels (0%, 2%, 5% and 10%)

<u>Emission Factor (Pounds of Total Particulate Matter per Unit of Energy Input)</u>

Table 17 summarizes the mass emission rate of pounds of total particulate matter per unit of energy input for testing with the Triple Green Products system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. The emission factor for the Base Case configuration is estimated as 3.851 TPM-lb/MMBtu and the emission factor for the Abatement II configuration as 0.187 TPM-lb/MMBtu.

Table 17: Triple Green Products – Total Particulate Matter Emission Factor

Configuration	Term	Site	Number of Tests Included	Total Particulate Matter per Unit of Energy Input (TPM-lb/MMBtu)			
				Min	Max	Mean	SD
Base Case	19-Mar	L1	3*	2.319	5.921	3.851	1.861
Abatement I	20-Nov	L1	11	0.085	0.454	0.198	0.130
Bypass Mode	20-Nov	L1	5	2.172	4.060	3.403	0.733
Bypass Gate Slip	20-Nov	L1	2	0.710	2.309	1.509	1.131
Abatement II	21-Apr	L1	18	0.106	0.417	0.187	0.081

* Test #030219 – 5 is not included in the calculated emission factor due to a feed rate measurement error

Table 18 summarizes the mass emission rate of pounds of total particulate matter per unit of energy input for testing with the OrganiLock system. The table reports values from each testing configuration in terms of minimum, maximum, mean and standard deviation. The emission factor for the Base Case (2021) configuration is estimated as 2.885 TPM-lb/MMBtu and the emission factor for the Abatement D configuration is estimated as 1.887 TPM-lb/MMBtu.

Table 18: OrganiLock – Total Particulate Matter Emission Factor

Configuration	Term	Site	Number of Tests Included	Total Particulate Matter per Unit of Energy Input (TPM-lb/MMBtu)			
				Min	Max	Mean	SD
Base Case	19-Mar	L2	3	1.882	2.660	2.366	0.422
	20-Mar	L3	3	1.544	2.598	2.116	0.533
	21-Feb	L3	3	2.472	3.207	2.885	0.376
Abatement A	19-Mar	L2	3	1.199	3.106	2.206	0.958
Abatement B	20-Mar	L3	3	0.815	2.459	1.491	0.860
Abatement C	20-Mar	L3	2	1.140	1.181	1.161	0.029
Abatement D	21-Feb	L3	6	0.862	2.526	1.887	0.571
Base Case – Wood	21-Feb	L3	1	0.288			
Abatement D – Wood	21-Feb	L3	1	0.090			
Base Case + Fuel Additive - 2%	21-Feb	L3	2	2.322	2.535	2.428	0.151
Base Case + Fuel Additive - 5%	21-Feb	L3	3	1.816	2.176	2.044	0.198
Base Case + Fuel Additive - 10%	21-Feb	L3	2	1.075	1.121	1.098	0.033

Visible Emissions

Due to weather, sun angle, among other site factors, visibility measurements were not performed for each particulate matter test. The table reports values from each testing configuration indicating the number of opacity tests and in terms of mean and standard deviation. Table 19 summarize the results from the visible emissions measurements conducted during source testing with the Triple Green Products system at L1.

Table 19: Triple Green Products – Visible Emissions

Configuration	Term	Site	Number of Tests Included	Opacity (%)	
				Mean	SD
Base Case	19-Mar	L1	1	55	n/a
Abatement I	20-Nov	L1	8	0	0.2
Bypass Mode	20-Nov	L1	2	76	2.8
Bypass Gate Slip	20-Nov	L1	2	32	24.2
Abatement II	21-Apr	L1	17	1	2.1

Table 20 summarize the results from the visible emissions measurements conducted during source testing with the OrganiLock system at L2 and L3.

Table 20: OrganiLock – Visible Emissions

Configuration	Term	Site	Number of Tests Included	Opacity (%)	
				Mean	SD
Base Case	19-Mar	L2	1	10	n/a
	21-Feb	L3	2	41	3
Abatement A	19-Mar	L2	1	2	n/a
Abatement D	21-Feb	L3	5	11	4
Base Case + Fuel Additive - 2%	21-Feb	L3	2	42	10
Base Case + Fuel Additive - 5%	21-Feb	L3	3	34	3
Base Case + Fuel Additive - 10%	21-Feb	L3	2	27	22

<u>Additional Gaseous Pollutants at Site L1</u>

Table 21 describes emissions for selected pollutants at site L1. Three tests were conducted for sulfur dioxide (SO_2), nitrogen oxides (NO_x), and carbon monoxide (CO). Values from these three tests are reported in terms of minimum, maximum, mean and standard deviation for each pollutant. One single test was performed for hydrogen chloride (HCl) and one for ammonia (NH3).

Table 21: Triple Green Products –Emission Factors for Additional Analytes

Configuration	Term	Pollutant	Number of Tests Performed	Pollutant per Unit of Energy Input (lb/MMBtu)			
				Min	Max	Mean	SD
Abatement II	21-Apr	SO_2	3	0.120	0.150	0.140	0.017
		NO_x	3	0.140	0.290	0.233	0.081
		CO	3	0.540	1.490	1.097	0.496
		HCl	1	.066			
		NH_3	1	.0192			

Particle Analysis

The results from particle sizing analysis from the Beckman Coulter Multisizer are provided below. Table 22 describes the number of filters included in the particle sizing analysis, their geometric median and geometric standard deviation in microns for the Triple Green Products system at the L1 site. The average geometric median particle size for the Base Case was 4.81 µm and for the Abatement II configuration was 3.02 µm.

Table 22: Triple Green Products – Particle Sizing Analysis

Configuration	Term	Site	Filters Included in Analysis	Geometric Statistics (µm)	
				Average Median Value	Average Geometric Standard Deviation
Base Case	19-Mar	L1	4	4.81	2.00
Abatement I	20-Nov	L1	11	2.11	1.13
Bypass Mode	20-Nov	L1	5	4.06	1.76
Bypass Gate Slip	20-Nov	L1	2	3.17	1.99
Abatement II	21-Apr	L1	18	3.02	1.69

Table 23 describes the number of filters included in the particle sizing analysis, their geometric median and geometric standard deviation in microns for the OrganiLock system for tests at the L2 and L3 sites. The average geometric median particle size for the Base Case (2021) was 4.05 µm and for the Abatement D configuration was 3.59 µm.

Table 23: OrganiLock – Particle Sizing Analysis

Configuration	Term	Site	Filters Included in Analysis	Geometric Statistics (µm)	
				Average Median Value	Average Geometric Standard Deviation
Base Case	19-Mar	L2	2	3.43	1.48
	21-Feb	L3	4	4.05	2.15
Abatement A	19-Mar	L2	2	2.77	1.50
Abatement D	21-Feb	L3	6	3.59	2.05
Base Case – Wood	21-Feb	L3	1	3.33	1.88
Abatement D – Wood	21-Feb	L3	1	2.19	1.34
Base Case + Fuel Additive - 2%	21-Feb	L3	2	3.70	1.93
Base Case + Fuel Additive - 5%	21-Feb	L3	3	4.64	1.99
Base Case + Fuel Additive - 10%	21-Feb	L3	2	4.17	1.68

A subset of samples from the 19-Mar term from sites L1 and L2 were analyzed via scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS). Following installation of the abatement system in January 2020 at L1, a bottom ash and fly ash sample were collected and also analyzed via SEM-EDS. Figures 9, 11, 13, and 15 provide magnified images from the SEM analysis. Figures 10, 12, 14, and 16 provide the EDS spectra graphs from the area of interest with each image. Additionally, selected EDS data from the higher-ranking elements (by atomic ratio) of each sample are included in Tables 24, 25, 26, and 27. Based on the atomic ratios of the analyzed samples from both the L1 and L2 filters the particulate matter compounds are primarily comprised of oxygen, chlorine and potassium elements. The bottom ash sample is primarily comprised of oxygen, calcium and phosphorous elements, while the fly ash sample is primarily comprised of oxygen, potassium, and calcium elements. The SEM-EDS analysis described in this section, enables a “snap shot” of groups of, or even individual, particles to determine their elemental analysis across different forms and sizes of particulate. The particle sizing coupled with SEM-EDS can help inform effective emission abatement strategies based on the size and species of particulate.

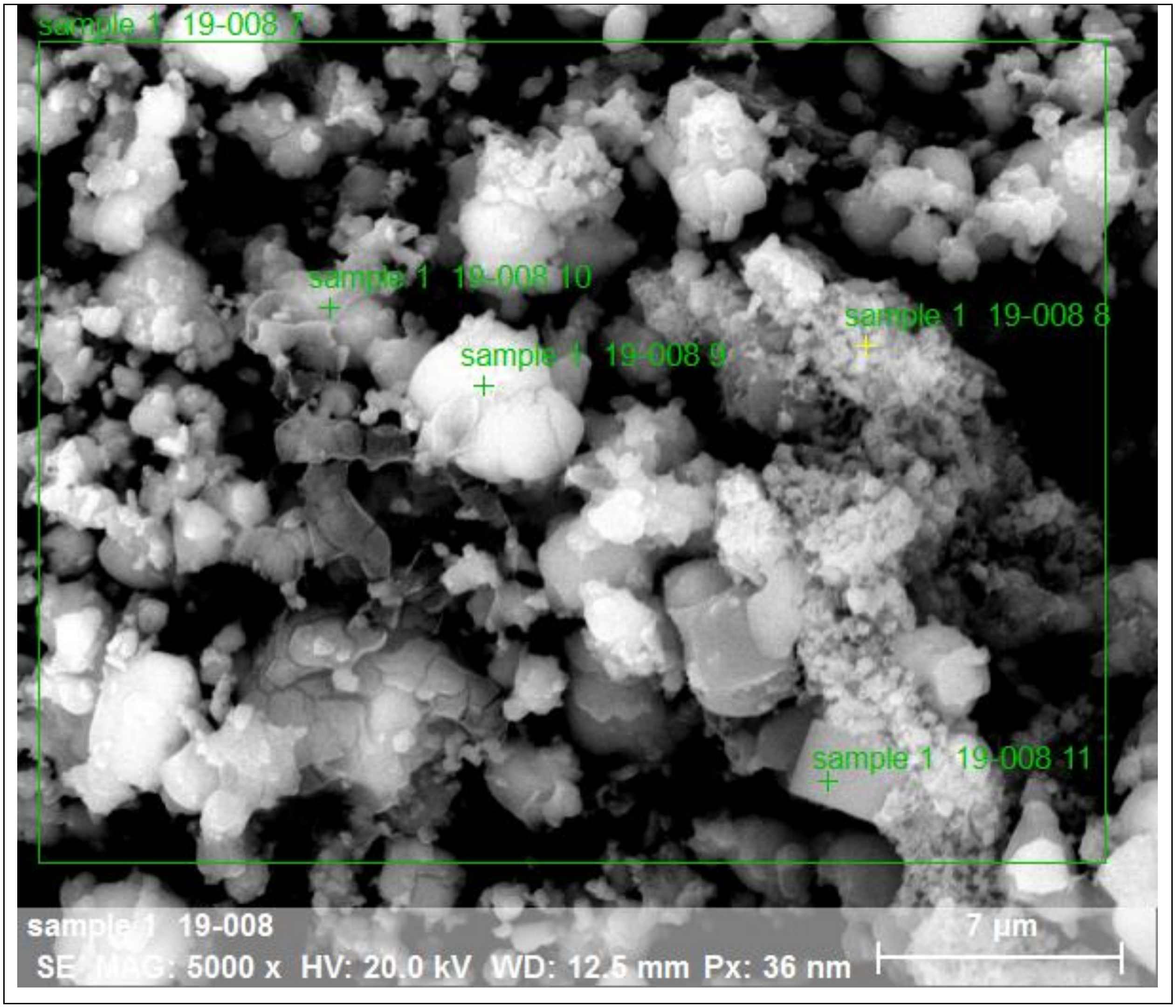

Figure 9: Filterable Particulate Matter at 5000x Magnification from Run 030119 – 4 from L1

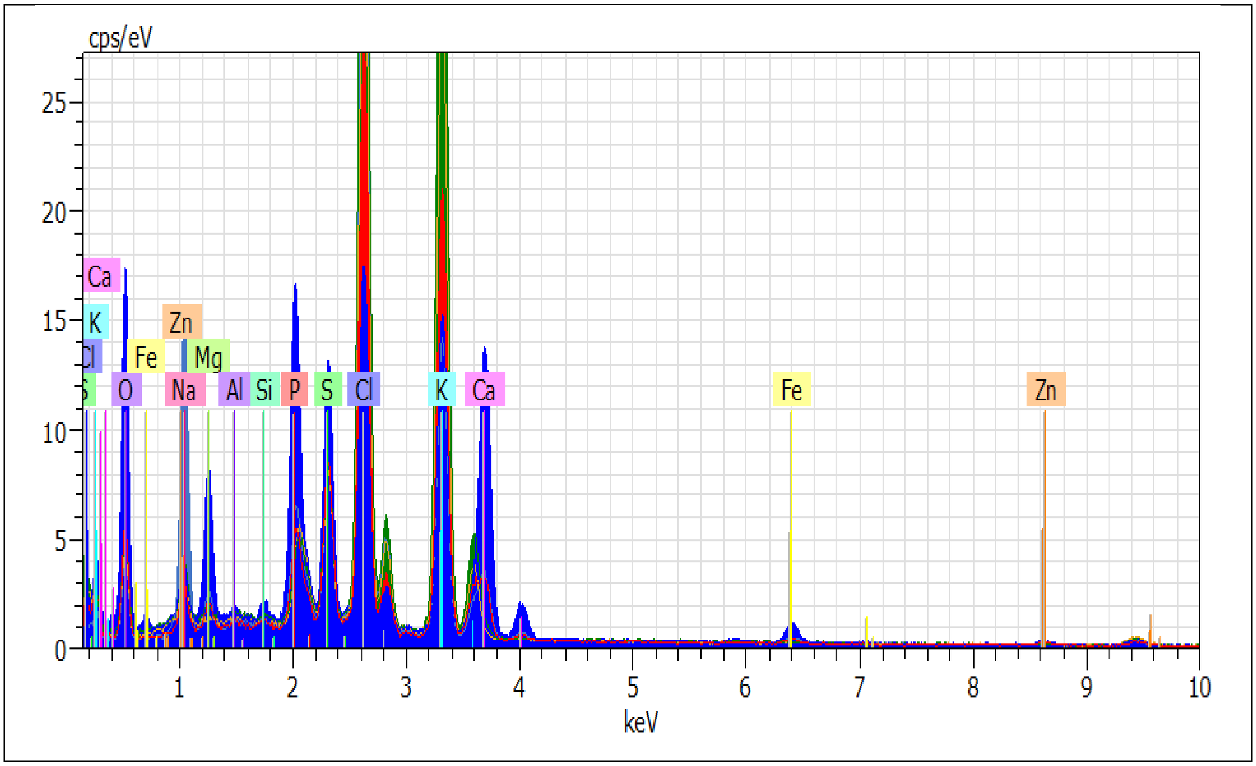

Figure 10: Graph of EDS Spectra from Run 030119 – 4 from L1

Table 24: Elemental Spectra by Atomic Percent from Run 030119 – 4

Statistic	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Fe	Zn
Mean	48.58	4.51	2.24	0.73	0.50	4.38	3.82	18.58	16.96	4.33	0.58	0.94
SD	9.84	5.69	1.59	0.00	0.00	1.28	0.58	7.67	9.15	2.10	0.16	0.23

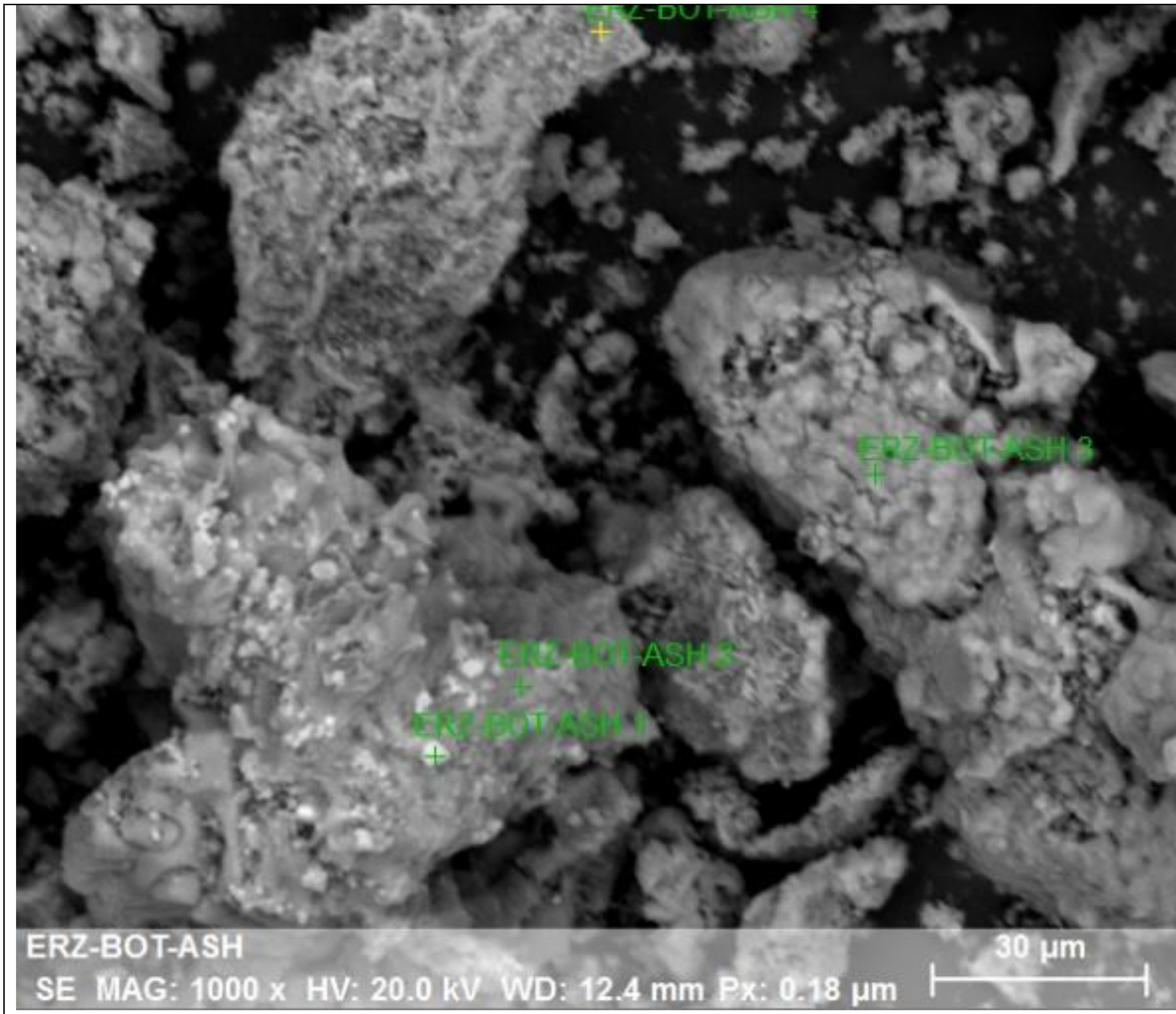

Figure 11: Bottom Ash at 1000x Magnification from L1

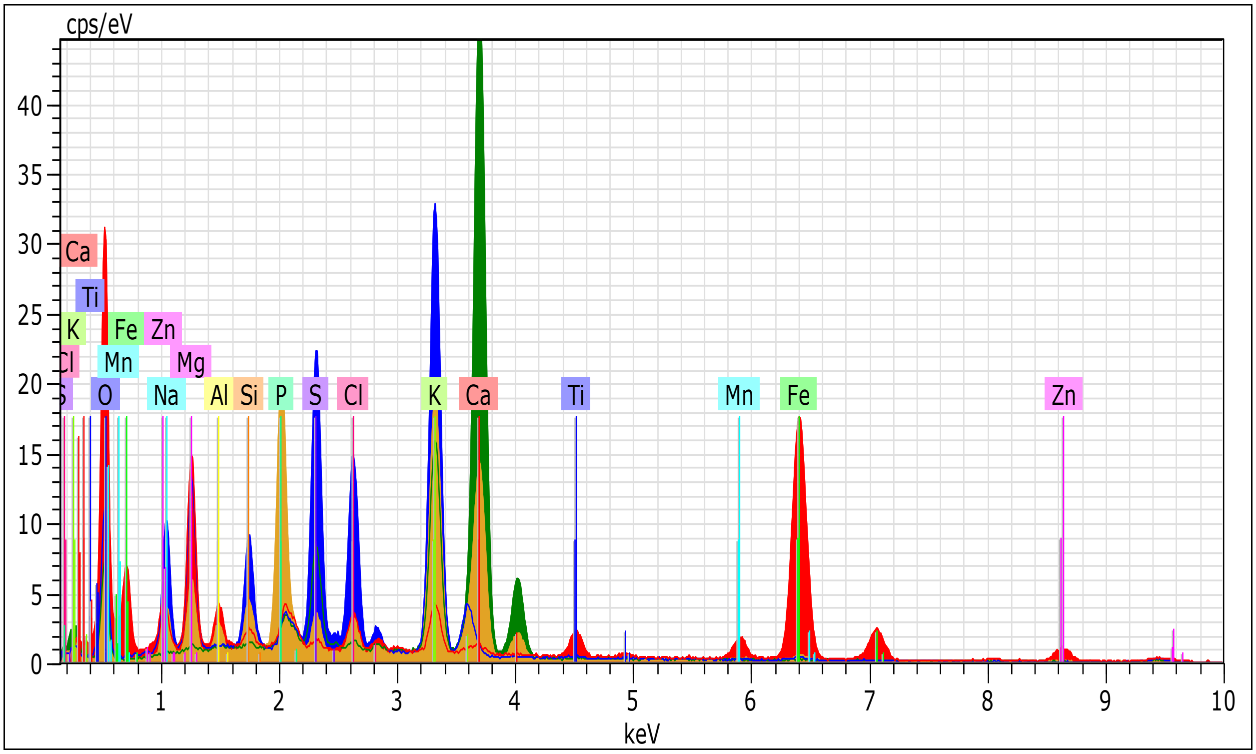

Figure 12: Graph of EDS Spectra of Bottom Ash from L1

Table 25: Elemental Spectra by Atomic Percent of Bottom Ash from L1

Statistic	O	Na	Mg	P	S	Cl	K	Ca	Fe	Zn
Mean	56.69	3.95	7.49	10.67	2.99	2.94	8.97	20.38	5.67	2.39
SD	4.94	3.29	3.81	0.00	3.19	2.59	6.39	12.59	9.00	0.00

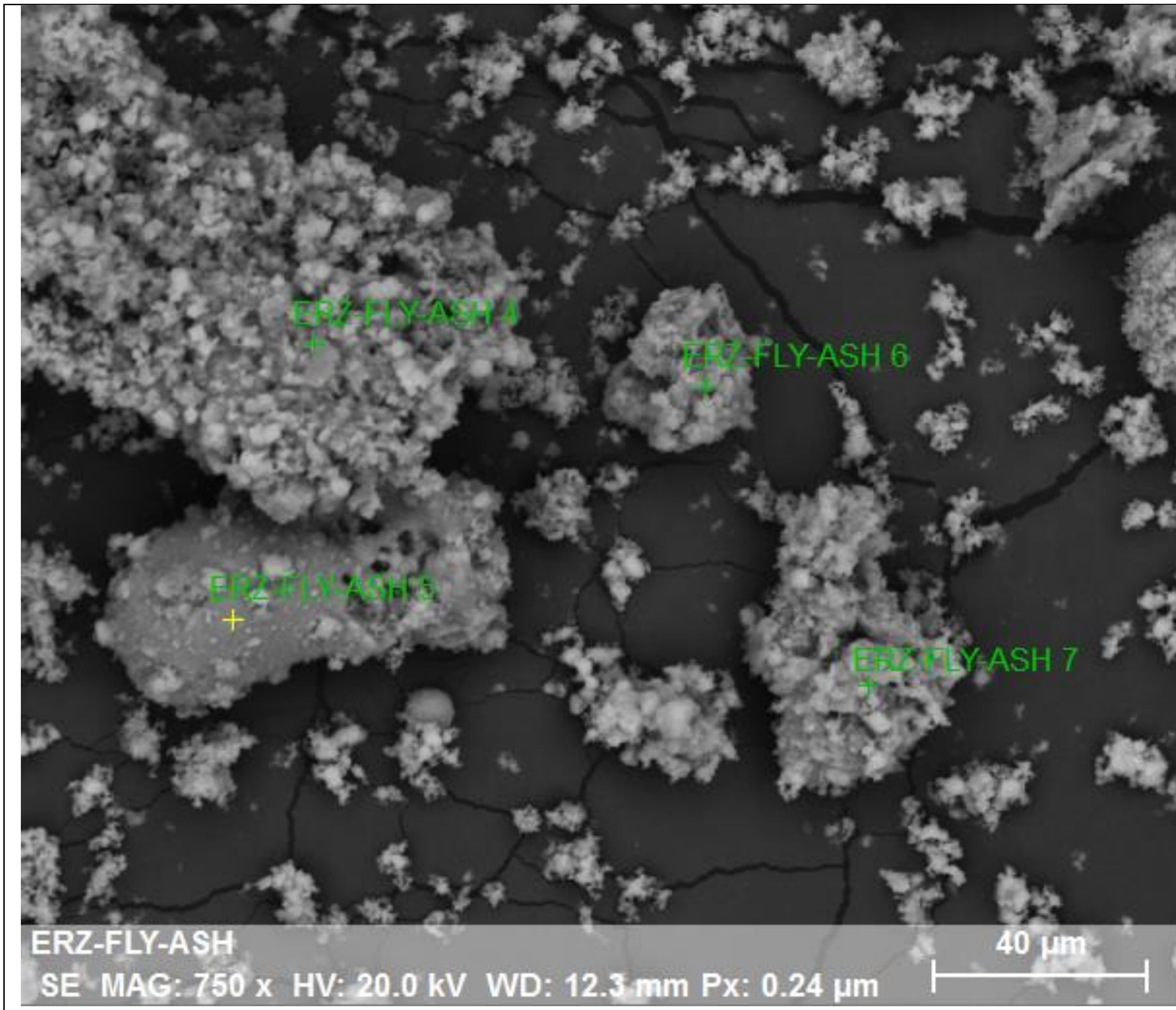

Figure 13: Fly Ash from Abatement Device at 750x Magnification from L1

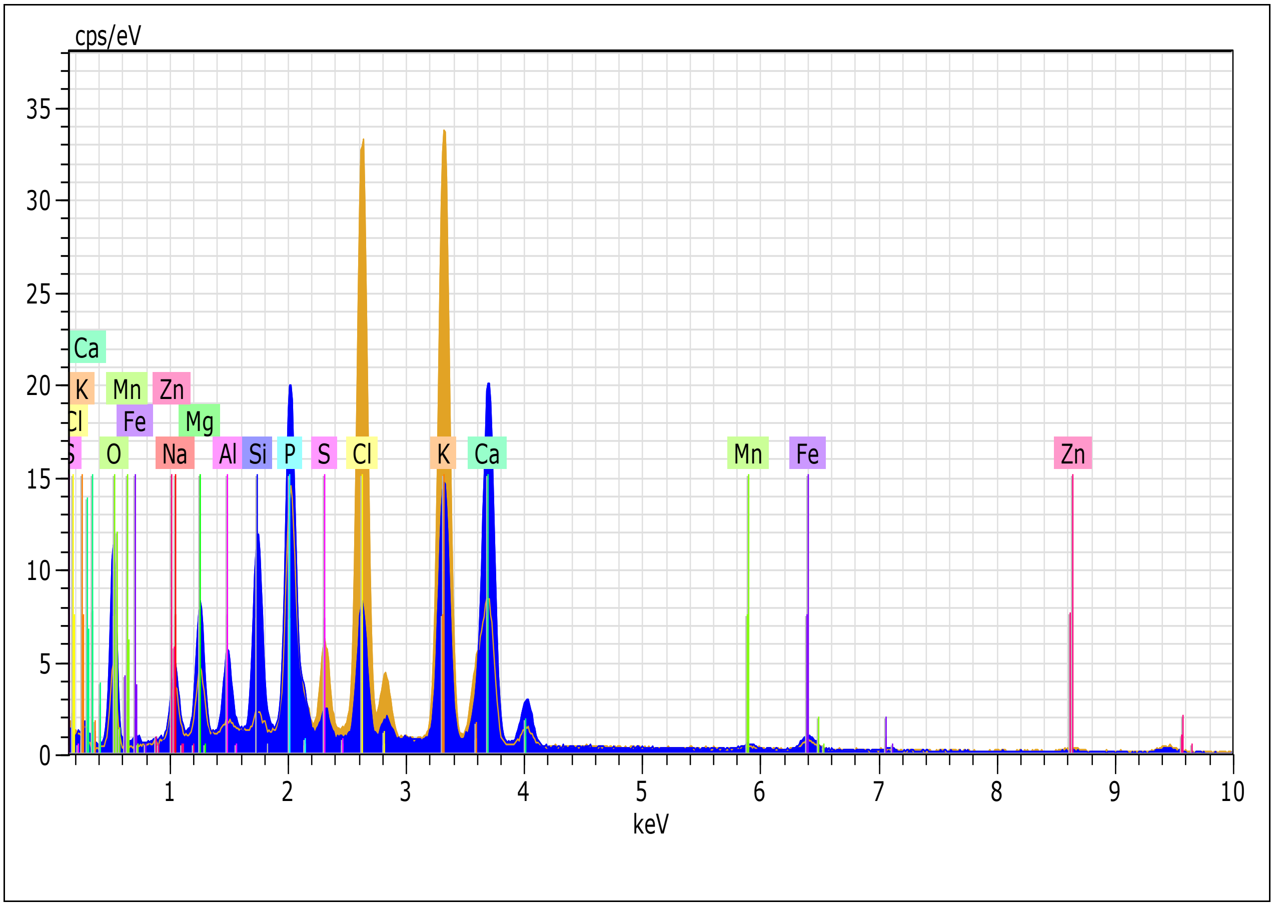

Figure 14: Graph of EDS Spectra of Fly Ash from Abatement Device from L1

Table 26: Elemental Spectra by Atomic Percent of Fly Ash from Abatement Device from L1

Statistic	O	Na	Mg	Al	Si	P	S	Cl	K	Ca
Mean	46.09	2.92	4.36	4.06	3.26	8.24	2.84	7.00	13.36	9.77
SD	7.08	1.26	2.55	2.46	2.44	2.78	1.66	6.5	6.39	4.09

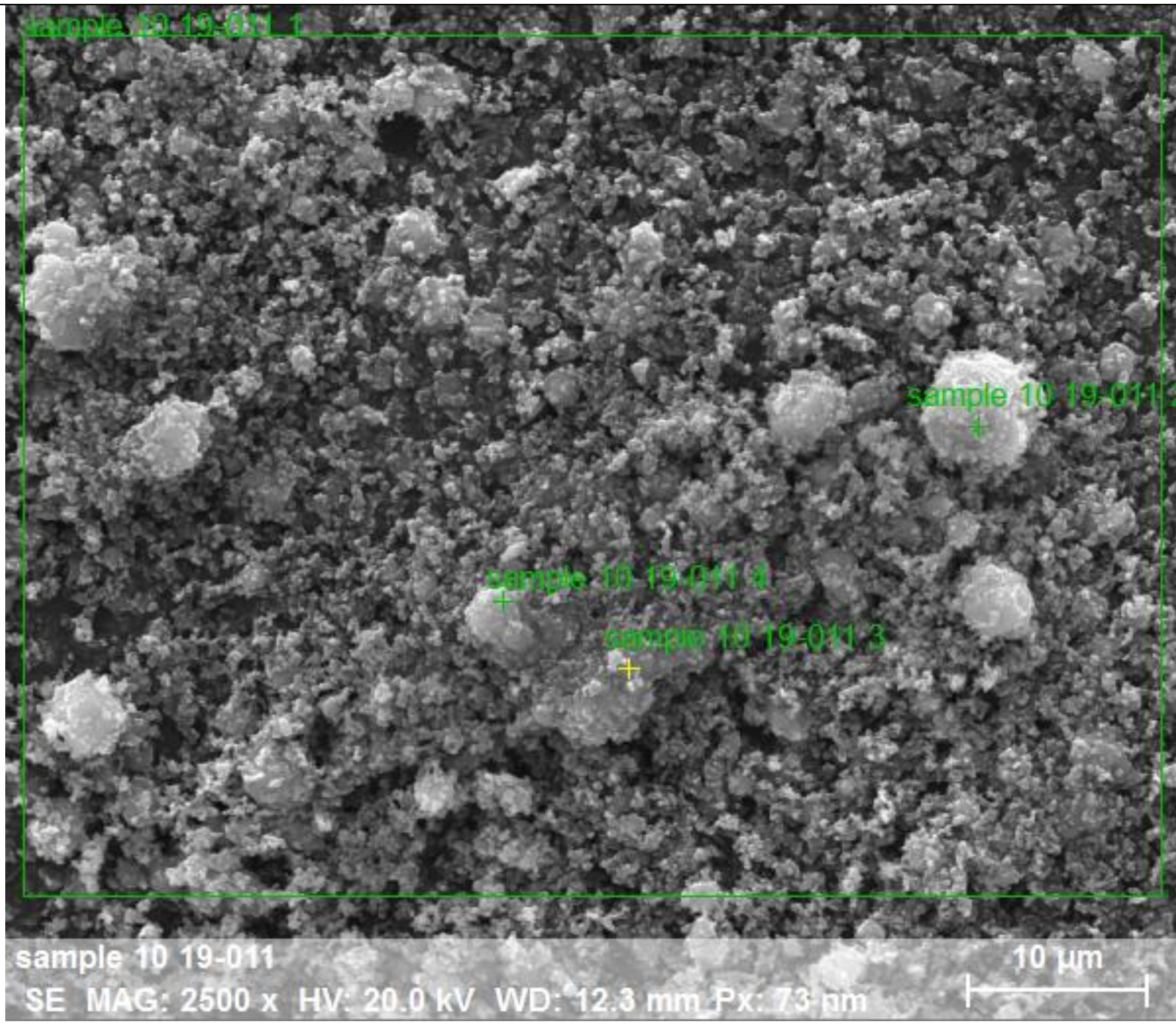

Figure 15: Filterable Particulate Matter at 2500x Magnification from Run 030519 – 2 from L2

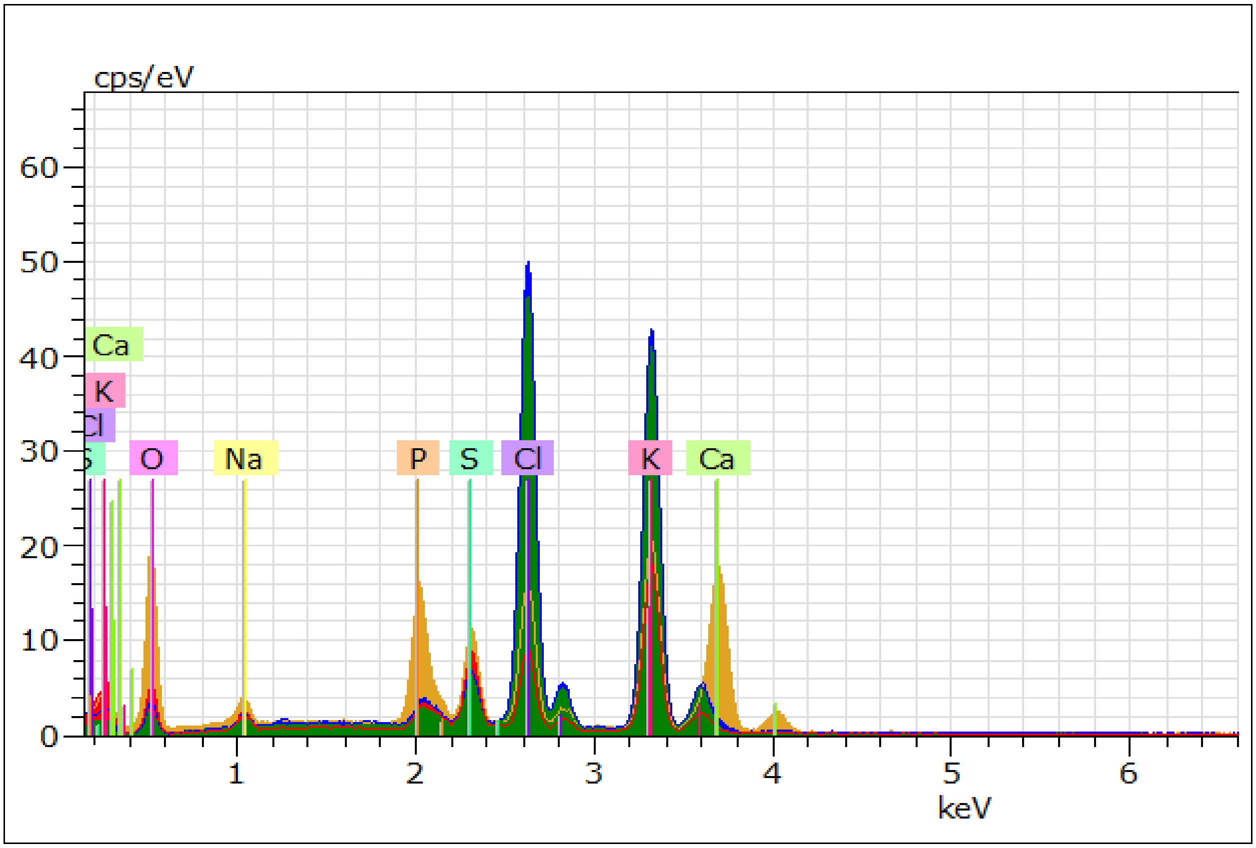

Figure 16: Graph of EDS Spectra from Run 030519 – 2 from L2

Table 27: Elemental Spectra by Atomic Percent from Run 030519 – 2 from L2

Statistic	O	Na	P	S	Cl	K	Ca
Mean	50.94	1.70	4.59	3.66	16.51	23.84	8.83
SD	18.45	0.94	0.00	1.68	11.83	12.85	0.00

Figure 17 provides pictures of the Method 5 filter media with the filterable particulate matter catch from the L3 site for wood with the cyclone (021321 – 1), and the poultry litter-fired runs with cyclone only (021321 – 4), wet scrubber (021321 – 5), and with mineral additive at 2% (021321 – 18), 5% (021321 – 12), and 10% (021321 – 15) mix levels. Visually the poultry litter-fueled runs tend to be whiter in appearance due to the potassium-rich fine aerosol filter cake. Whereas, the filter from the wood-fueled run has a darker appearance likely due to the soot loading from unburned carbon captured in the fly ash and the relatively low ash levels of the wood fuel, including potassium, as compared to the poultry litter fuel. The effects of the mineral additive impact the visual appearance of the filter cake collected on the filter media.

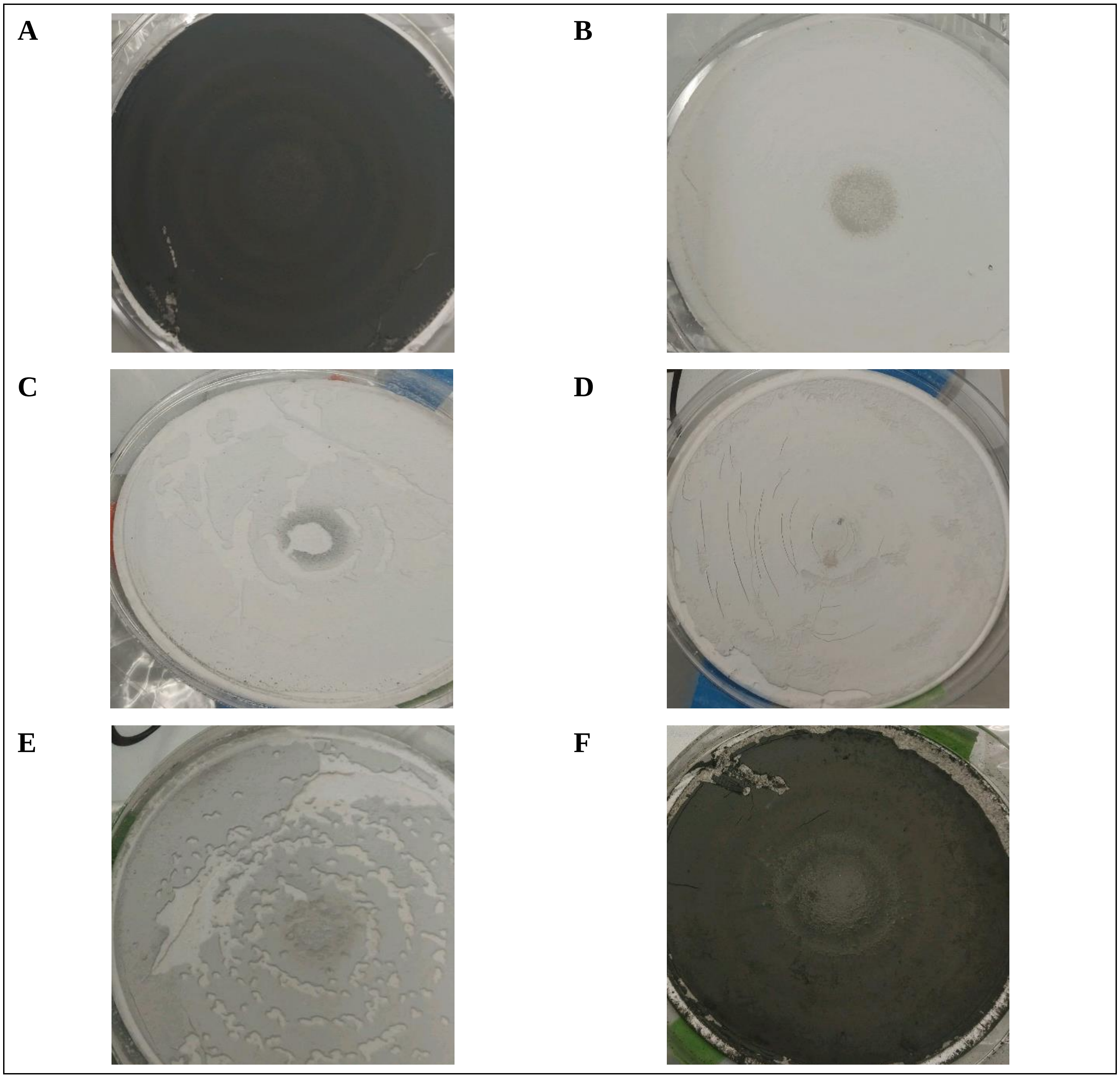

Figure 17: Pictures of Filter Media with Filterable Particulate Matter Catch for Wood with Cyclone (A), and Poultry Litter-Fired Runs with Cyclone Only (B), Wet Scrubber (C), and with Mineral Additive at 2% (D), 5% (E), and 10% (F)

Technology Host Farmer Experiences

Three videos, listed below in Figure 18, were developed to document and share farmer experiences operating the on-farm bioenergy systems. The intent of these videos is to help inform potential future adopters of these technologies via sharing of the first-hand operational experiences of the two technology host farmers. The first video in the series, titled "What is it

Like to Heat with On-farm Bioenergy?” was developed in collaboration with the *Farm Energy Answers* project funded by the National Institute of Food and Agriculture’s Beginning Farmer and Rancher Development Program through project work led by Penn State University (PI: Dr. Ciolkosz.) with collaboration from Virginia Tech and other regional land grant universities. The other videos were developed directly from CIG project funds with videography services provided by Bramble Films of State College, PA with aerial footage provided by the Virginia Tech project team.

	**What is it Like to Heat with On-farm Bioenergy?** In this video hear first-hand experiences from a poultry farmer using poultry-litter biomass to heat his poultry houses at site L1. Created as part of the "Energy Answers for the Beginning Farmer and Rancher" Program
	**General Operation and Maintenance Considerations for an On-farm Poultry Litter-to-Energy System: A Farmer’s First-Hand Experience.** In this video hear first-hand experiences from a poultry farmer regarding what is involved in day-to-day operation and maintenance of an on-farm bioenergy system at site L1.
	**Experiences Selecting, Installing and Managing an On-farm Poultry Litter-to-Energy System: A Farmer’s First-Hand Experience.** In this video hear first-hand experiences from a poultry farmer regarding selecting, installing, and managing an on-farm bioenergy system to heat two poultry houses at site L2.

Figure 18: Listing of Videos Created for Broader Educational Outreach Purposes

At the L1 site the farmer describes some challenges regarding the operation of the installed abatement device, including:

- The farmer replaces the filter media after approximately eight weeks of runtime during portions of the winter heating season.
- At approximately the fourth week, the farmer places the system in bypass mode for one day. During this time the system air purge is run using compressed air to remove some of the particulate matter loaded on the filter media. After this daylong purge process, the unit is again placed in full abatement mode.
- The farmer has also observed that around week six there are often holes in portions of the filter media effecting abatement system performance.
- Additionally, due to the increased exhaust gas flow restrictions imposed by the abatement device, the system is unable to be operated at the higher fuel feed rates of the pre-2020 period, or as compared to when the abatement device is operated in bypass mode. Though, as of Fall 2021, the farmer at L1 indicates the bioenergy system has still been able to meet all of his heating needs.

The abatement device (Abatement A) installed at L2 was removed in 2019 and not re-installed due to the idling of the on-farm bioenergy system and the subsequent abatement system modifications by the manufacturer at L3. Thus, farmer experiences in operating the OrganiLock abatement system are limited.

DISCUSSION

This project focused on reducing total particulate matter and visible emissions from two on-farm poultry litter-to-energy systems by 70% relative to their base case condition. Emission reductions are calculated as the percent change from the base case reference to the final abated values.

Table 28 provides the abated emissions for the Triple Green Products system for the base case from 2019 (i.e., Base Case) and the 2021 abated case (i.e., Abatement II). Triple Green Products reduced emission concentrations by 96%, mass emission rate by 97%, the energy input emission factor by 95%, and visible emissions by 98%.

Table 28: Total Particulate Matter Emissions for Triple Green Products

Parameter	Base Case	Abated	Percent Change (%)
Emission Concentration (gr/dscf - 7% O_2)	2.303	0.103	96
Mass Emission Rate (lb/hr)	5.210	0.158	97
Emission Factor (lb/MMBtu)	3.851	0.187	95
Opacity (%)	55	1	98

Table 29 provides the abated emissions for the OrganiLock system for the base case (i.e., Base Case) the abated case (i.e., Abatement D), as measured in 2021. OrganiLock reduced emission concentrations by 65%, mass emission rate by 34%, the energy input emission factor by 35%, and visible emissions by 72%.

Table 29: Total Particulate Matter Emissions for OrganiLock

Parameter	Base Case	Abated	Percent Change (%)
Emission Concentration (gr/dscf - 7% O_2)	1.639	0.566	65
Mass Emission Rate (lb/hr)	1.162	0.766	34
Emission Factor (lb/MMBtu)	2.885	1.887	35
Opacity (%)	41	11	72

This project evaluated abatement system strategies to reduce total particulate matter and visible emissions from on-farm poultry litter-to-energy systems. One of the systems was able to surpass the project goal of 70% reduction in emissions across all parameters (i.e., concentration, mass emission rate, emission factor, and opacity).

While the project goal was achieved with emission improvements greater than 70% realized, questions remain regarding on-farm poultry litter-to-energy systems. Some of these questions relate to the longer-term environmental and economic performance of these systems. For example, it is important to better understand the impact the additional time and cost associated with the operation and maintenance of abated systems has on the overall project viability. Additionally, due to the variability of biomass fuels, failure to follow combustion best practices, or adequately maintain abatement systems, can result in increased pollutants. Each of these questions has implications for the technology host farmers at L1 and L2, and more widely too, as the potential for broader adoption is explored.

Future Work

Some potential areas for additional investigation are described below.

- Optimizing Abatement Systems

  Each abatement system represents additional capital, operation and maintenance costs to the farmer. Additional work is needed to understand the costs associated with each abatement strategy. Certain abatement strategies require more maintenance upkeep than others. Additional work is needed to evaluate optimal abatement coupling to minimize system capital cost and minimize operational and maintenance cost. Furthermore, system configurations should be explored which are robust with regard to delayed abatement system maintenance.

- Benchmarking Fuel Properties

  Poultry litter is a variable fuel in terms moisture content, major and minor ash components, and gross calorific value. These values change based on bedding material, litter management practices, among other factors. Additional work should develop common fuel property metrics based on common ranges of poultry litter values. This information would also likely provide a beneficial resource in non-hazardous secondary material (NHSM) documentation for section 112 requirements of the *Clean Air Act*. For example, development of slagging indices for poultry litter (as compared to other forms of biomass feedstocks) can help inform decision making in evaluating poultry litter properties from a location considering on-farm poultry litter-to-energy. This type of information would also help inform farmer-technology provider conversations and, hopefully, help minimize surprises due to the variable nature of poultry litter fuel versus a technology provider's fuel specifications for a specific thermal conversion process.

- <u>Evaluating Fuel Additives</u>

  Use of mineral additive appears to have had an effect in reducing mass emission rate at L3 from 1.162 lb/hr for the base case to 0.448 lb/hr for the 10% additive fuel mix, a reduction of 61%. However, additional work is needed to: replicate these trials, understand the ash-bed chemistry mechanisms with additive-doped poultry litter, evaluate the system technical and economic performance implications (including abatement system impacts), to determine optimal doping levels and mechanisms, and explore potential scale- and setting-appropriate implementation strategies.

- <u>Estimation of Emission Factors</u>

  In addition to the data from the source emission tests, the determination of emission factors is sensitive to the energy content of the fuel and determination of fuel feed rate. A challenge can be that different laboratories often use different methods for determination of gross calorific value and report the results on different bases. Additionally, the determination of fuel feed rate can be challenging based on the design of the bioenergy system. These factors can complicate the determination, and the uniform interpretation of, emission factors. Additional work is needed to explore the impact of different bomb calorimetry methods on determination of gross calorific values from poultry litter fuel samples, and determine the impact on the calculation of emission factors. Similarly, work will explore the sensitivity to fuel feed rate estimations, and their impact on calculation of emission factors. The development of "F-Factors", which represent the ratio of flue gases generated to the caloric value of the fuel combusted, for poultry litter fuel may help address some of these challenges, and be an aid for non-instrumented on-farm systems (CFR, 2013). These issues are particularly of interest for uniform comparison between systems and in areas with emission factor-based regulations.

- Techno-Economic Assessment

  Development of a detailed techno-economic analysis (TEA) would help discern project viability to determine where and when these systems are more appropriate. For example, such a TEA can be illustrative to evaluate the impact from: the potential reduced equipment life due to the corrosive properties of chlorine-rich biomass fuels, participation in ecosystem service markets (e.g., nutrient credit trading, thermal renewable energy certificates, etc.), service provider performance contracting mechanisms, and overall system efficiency impacts to the point-of-use energy costs. Additionally, the development of a probabilistic TEA would help explore viability within the context of dynamic policies and markets (e.g., options for poultry litter, propane prices, potential co-product market prices, etc.).

- Broader Adoption

  When compared to propane-based heating systems, on-farm poultry litter-to-energy systems typically require more farmer time to manage and operate. The TEA mentioned above can help evaluate the financial viability of adopting a bioenergy system in terms of energy-cost savings, among other financial factors. However, it is also important that the TEA incorporate farmer-time constraints regarding bioenergy system operation. These farmer cultural-practice components of the TEA are also needed to help inform the appropriate adoption of these bioenergy systems. For example, there may be instances when the adoption of the bioenergy system makes financial sense for a particular farmer, however, the farmer may have time constraints which would preclude successful system adoption. Because of this, on-farm poultry litter-to-energy systems are not suitable for all locations and potential adopters should seek to learn from both the successful, and the unsuccessful, projects.

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APPENDIX

Appendix A: Listing of Source Emission Tests Performed

Test Count	Reference Code	Technology Provider	Configuration	Location	Comments
1	030119 – 1	Triple Green Products	Base Case	L1	
2	030119 – 2	Triple Green Products	Base Case	L1	Anisokinetic
3	030119 – 3	Triple Green Products	Base Case	L1	Anisokinetic
4	030119 – 4	Triple Green Products	Base Case	L1	Anisokinetic
5	030219 – 5	Triple Green Products	Base Case	L1	41-minute sample, feed rate error
6	030219 – 6	Triple Green Products	Base Case	L1	20-minute sample period
7	030219 – 7	Triple Green Products	Base Case	L1	Anisokinetic; 20-minute sample period
8	030219 – 8	Triple Green Products	Base Case	L1	20-minute sample period
9	030519 – 1	OrganiLock	Base Case	L2	
10	030519 – 2	OrganiLock	Base Case	L2	
11	030519 – 3	OrganiLock	Base Case	L2	
12	030619 – 4	OrganiLock	Abatement A	L2	36-minute sample period
13	030619 – 5	OrganiLock	Abatement A	L2	36-minute sample period
14	030619 – 6	OrganiLock	Abatement A	L2	36-minute sample period
15	031020 – 1	OrganiLock	Abatement B	L3	
16	031020 – 2	OrganiLock	Abatement B	L3	
17	031020 – 3	OrganiLock	Abatement B	L3	
18	031120 – 4	OrganiLock	Base Case	L3	20-minute sample period
19	031120 – 5	OrganiLock	Base Case	L3	39-minute sample period
20	031120 – 6	OrganiLock	Base Case	L3	
21	031120 – 7	OrganiLock	Abatement C	L3	In situ modified with demister
22	031120 – 8	OrganiLock	Abatement C	L3	In situ modified with demister
23	111320 – 1	Triple Green Products	Abatement I	L1	
24	111320 - 2	Triple Green Products	Abatement I	L1	
25	111320 - 3	Triple Green Products	Abatement I	L1	
26	111420 - 4	Triple Green Products	Abatement I	L1	

27	111420 - 5	Triple Green Products	Abatement I	L1	
28	111420 - 6	Triple Green Products	Abatement I	L1	
29	111420 - 7	Triple Green Products	Abatement I	L1	
30	111420 - 8	Triple Green Products	Abatement I	L1	
31	111520 - 9	Triple Green Products	Abatement I	L1	
32	111520 - 10	Triple Green Products	Abatement I	L1	
33	111520 - 11	Triple Green Products	Abatement I	L1	Fuel feed blockage
34	111620 - 12	Triple Green Products	Bypass Mode	L1	
35	111620 - 13	Triple Green Products	Bypass Mode	L1	30-minute sample period
36	111620 - 14	Triple Green Products	Bypass Mode	L1	30-minute sample period
37	111620 - 15	Triple Green Products	Bypass Mode	L1	30-minute sample period
38	111620 - 16	Triple Green Products	Bypass Mode	L1	30-minute sample period
39	111720 - 17	Triple Green Products	Bypass Gate Slip	L1	System bypass gate failed to seal
40	111720 - 18	Triple Green Products	Bypass Gate Slip	L1	System bypass gate failed to seal
41	111720 – 19	Triple Green Products	Abatement I	L1	
42	021021 - 1	OrganiLock	Base Case - Wood	L3	
43	021021 - 2	OrganiLock	Base Case	L3	
44	021021 - 3	OrganiLock	Base Case	L3	
45	021021 - 4	OrganiLock	Base Case	L3	
46	021021 - 5	OrganiLock	Abatement D	L3	
47	021121 - 6	OrganiLock	Abatement D	L3	
48	021121 - 7	OrganiLock	Abatement D	L3	
49	021121 - 8	OrganiLock	Abatement D	L3	
50	021121 - 9	OrganiLock	Abatement D	L3	
51	021121 – 10	OrganiLock	Abatement D	L3	30-minute sample period
52	021121 – 11	OrganiLock	Abatement D - Wood	L3	30-minute sample period

53	021221 – 12	OrganiLock	Base Case + 5% Fuel Additive	L3	
54	021221 – 13	OrganiLock	Base Case + 5% Fuel Additive	L3	
55	021221 – 14	OrganiLock	Base Case + 5% Fuel Additive	L3	
56	021221 – 15	OrganiLock	Base Case + 10% Fuel Additive	L3	
57	021221 – 16	OrganiLock	Base Case + 10% Fuel Additive	L3	
58	021321 – 17	OrganiLock	Base Case + 2% Fuel Additive	L3	
59	021321 – 18	OrganiLock	Base Case + 2% Fuel Additive	L3	
60	042721 – 00	Triple Green Products	Abatement II	L1	SO2, NOx, CO, HCl & NH3
61	042721 – 01	Triple Green Products	Abatement II	L1	TPM + SO2, NOx, CO
62	042721 – 02	Triple Green Products	Abatement II	L1	TPM + SO2, NOx, CO,
63	042721 – 03	Triple Green Products	Abatement II	L1	
64	042721 – 04	Triple Green Products	Abatement II	L1	
65	042721 – 05	Triple Green Products	Abatement II	L1	
66	042821 – 06	Triple Green Products	Abatement II	L1	
67	042821 – 07	Triple Green Products	Abatement II	L1	
68	042821 – 08	Triple Green Products	Abatement II	L1	
69	042821 – 09	Triple Green Products	Abatement II	L1	
70	042821 - 10	Triple Green Products	Abatement II	L1	
71	042821 - 11	Triple Green Products	Abatement II	L1	
72	042821 - 12	Triple Green Products	Abatement II	L1	
73	042921 - 13	Triple Green Products	Abatement II	L1	
74	042921 - 14	Triple Green Products	Abatement II	L1	
75	042921 - 15	Triple Green Products	Abatement II	L1	

76	042921 - 16	Triple Green Products	Abatement II	L1	
77	043021 - 17	Triple Green Products	Abatement II	L1	
78	043021 - 18	Triple Green Products	Abatement II	L1	