

Quantifying and Minimizing the Environmental Impact of Agricultural Plastic Mulch Film Burning

Final Report

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Project Title:

Quantifying and Minimizing the Environmental Impact of Agricultural Plastic Mulch Film Burning

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Project Website

[Hinkley Center Agricultural Plastic Mulch Project website](#)

Project Duration

September 1, 2025 to September 30, 2026.

Abstract

Agricultural plastic mulch film is widely used in Florida to improve crop yield, soil moisture retention, weed control, pest control, and nutrient management. At the same time, used plastic mulch film is difficult to manage after harvest because it is bulky, degraded by sunlight, and heavily contaminated with soil and agricultural residues. Recycling rates remain low, and the soil content of used mulch can be much higher than the contamination level accepted by recycling facilities. In Florida, open burning of polyethylene agricultural plastic is allowed under state law for certain agricultural operations. However, limited data exist on pollutant emissions from realistic burning of field-collected, soil-contaminated plastic mulch film. This project quantified pollutants from controlled burning of agricultural plastic mulch film using a tube furnace reactor and diesel-assisted open burning experiments. The study measured gaseous pollutants, particulate matter, burn residues, and microplastics using real-time aerosol instruments, gas analyzers, filter sampling, stereomicroscopy, and pyrolysis-gas chromatography/mass spectrometry. Results show that burning conditions and plastic type strongly influence modified combustion efficiency, carbon monoxide, nitrogen oxides, sulfur dioxide, particulate matter, and microplastic abundance. Higher combustion temperatures generally reduced carbon monoxide and, under sufficiently ventilated conditions, particulate matter emission factors, while nitrogen oxides and sulfur dioxide generally increased. Sulfur dioxide emissions were unexpectedly high for polyethylene-based materials. The sulfur source was not identified conclusively and may include adhered soil, fertilizer or pesticide residues, film additives or coatings, and other field-derived contamination. Microplastics were detected in all burned residue samples, with most particles larger than 25 micrometers and greater abundance at higher temperatures. No single burning condition minimized all measured pollutants. The results support minimizing open burning where feasible and advancing alternative management options for agricultural plastic mulch.

Key Words

Agricultural plastics; plastic mulch film; open burning; particulate matter; microplastics; emission factor; polyethylene; sulfur dioxide; carbon monoxide; waste management

METRICS REPORTING

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Metrics

1. TAG input on the final report: During the final TAG meeting on September 10, 2026, members provided comments on interpretation of sulfur dioxide emissions, interpretation of source-level pollutant concentrations, practical feasibility of pre-cleaning agricultural plastic mulch, consistency of the Executive Summary with the detailed results, and final recommendations regarding open burning. Tim Townsend recommended evaluating whether the measured sulfur emissions were quantitatively consistent with sulfur present in adhered soil and emphasized that source-level pollutant concentrations should not be interpreted as ambient exposure concentrations. Lisa Wasko DeVetter recommended considering sulfur-containing pesticides and crop-specific pesticide-use records as possible contributors to SO₂ emissions. Samir Elmir similarly recommended additional context when comparing source concentrations with National Ambient Air Quality Standards (NAAQS) and suggested evaluating pre-cleaning as a potential mitigation strategy. He also recommended the team to examine the impact of microplastics on water quality at nearby private wells. Gene Jones identified an inconsistency between the Executive Summary and Results regarding white versus black mulch emissions, emphasized that field washing of mulch film is not a practical management option for Florida growers, and recommended that the final report prioritize alternatives to open burning rather than lower-temperature burning. Tim Townsend supported recommending alternative management strategies. These comments were incorporated into the final report through revisions to the Executive Summary, SO₂ discussion, NAAQS comparison, practical recommendations, and conclusions.
2. Research publications: A peer-reviewed manuscript based on this Hinkley Center project is under preparation. No published article from this project is listed at the time of drafting. The research team is preparing a manuscript summarizing the project findings for submission to Waste Management.
3. Research presentations: The project was presented to the Technical Awareness Group during the TAG meetings. Amir Sharafudin also presented preliminary results in the poster session of the SWANA FL Winter Conference & Hinkley Center Research Forum. Amir Sharafudin will also present the project results at the 2026 Annual Conference for American Association for Aerosol Research. The team also plans to be more involved in the agricultural plastic

community by presenting the findings at the Agricultural Plastics Recycling Conference (APRC) that takes place from August 11 to 13, 2027 in San Diego, California.

4. Citations: No external citations to project publications are available at the time of drafting because project manuscripts are still in preparation.
5. Leveraged funding: The project results are being used to develop future proposals to NSF Environmental Engineering, NSF Combustion and Fire Systems, USDA programs related to sustainable agricultural waste management, Florida DEP, and other agencies. Planned future topics include expanded air and soil pollutant characterization, small-scale waste-to-energy feasibility, and recycling/reuse technologies for soil-contaminated agricultural plastics.
6. New collaborations: The project initiated and strengthened collaboration between the University of Miami and University of Florida, engaged the Southern Waste Information eXchange, involved solid waste and public health stakeholders, and opened discussion with UF Gulf Coast Research and Education Center regarding field soil sampling and possible future field measurements.
7. Use by FDEP or other stakeholders: TAG members and other stakeholders used the project meetings to guide the research toward practical questions, including whether burning conditions can reduce emissions, whether mulch-film properties influence emissions, how sulfur-containing emissions should be interpreted, and how the findings should be translated into management guidance. The team plans to work with Dr. Lisa Wasko DeVetter on developing podcasts and factsheets via USDA's Specialty Crop Research Initiative, which can generate a stronger societal impact. Final TAG feedback directly shaped the report by strengthening source and ambient concentration differences, discouraging impractical field washing as a near-term recommendation, and prioritizing alternative management strategies over optimization of open burning.

ACKNOWLEDGEMENTS

The project team acknowledges the Hinkley Center for Solid and Hazardous Waste Management for supporting this work. We thank Gene Jones and the Southern Waste Information eXchange for providing agricultural plastic mulch film samples and practical insight into agricultural plastic management. We thank the Technical Awareness Group members for their time, review, and suggestions.

Student Researchers

Amir Sharafudin, Ph.D. student in the Department of Chemical, Environmental and Materials Engineering at the University of Miami, conducted combustion experiments, aerosol and gas measurements, and emission factor analysis. His research interests include combustion emissions and air quality measurement.

Kazi Tahsina Habib, Ph.D. student in the Department of Environmental Engineering Sciences at the University of Florida, conducted microplastic sample processing and analysis. Her work focuses on environmental microplastic characterization.

Courtnei Spencer, undergraduate student in the Department of Chemical, Environmental and Materials Engineering at the University of Miami, assisted with project background research, regulatory review, and laboratory activities.

Technical Awareness Group Members

Name	Title/Affiliation	Sector
Gene Jones	CEO, Southern Waste Information eXchange	Private
Sam Sugerman	Sustainability Manager in agricultural sector	Private
Samir Elmir	Division Director, Florida Department of Health Miami-Dade Environmental Public Health and Engineering	Public
Nicholas Ciano	Chief of Resilience Engineering and Environmental Compliance, Department of Solid Waste Management	Public
Elizabeth Kromhout	Environmental Administrator, Florida Department of Environmental Protection	Public
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Lisa Wasko DeVetter	Professor, Small Fruit Horticulture, Washington State University	Researcher
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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
APS	Aerodynamic particle sizer
CO	Carbon monoxide
CO ₂	Carbon dioxide
EF	Emission factor
FDEP	Florida Department of Environmental Protection
GC/MS	Gas chromatography/mass spectrometry
MCE	Modified combustion efficiency
NAAQS	National Ambient Air Quality Standards
NO _x	Nitrogen oxides
NO ₂	Nitrogen dioxide
PE	Polyethylene
PET	Polyethylene terephthalate
PM	Particulate matter
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
Py-GC/MS	Pyrolysis-gas chromatography/mass spectrometry
SMPS	Scanning mobility particle sizer
SO ₂	Sulfur dioxide
TAG	Technical Awareness Group
WTE	Waste-to-energy

EXECUTIVE SUMMARY

Agricultural plastic mulch film is an important material in specialty crop production, particularly in Florida, where mulch films are used in tomato, pepper, eggplant, strawberry, muskmelon, watermelon, and cucumber production. Plastic mulch films improve agricultural productivity by controlling weeds and pests, retaining soil moisture, regulating soil temperature, and improving nutrient uptake. However, after harvest, used mulch film becomes difficult to manage because it is bulky, fragmented, and contaminated with soil, pesticides, fertilizers, and field debris. Soil residue can comprise a large fraction of collected used mulch weight, while recycling facilities generally require much lower contamination levels. These characteristics limit recycling and reuse, making landfilling, stockpiling, in-field burial, and burning common end-of-life pathways.

Open burning of agricultural plastic mulch is a practical disposal method for some growers because it reduces plastic volume and weight. In Florida, state regulations permit open burning of certain polyethylene (PE) agricultural plastics used in crop production. However, open burning can generate air pollutants, residual soil contaminants, and microplastics. Before this project, there were limited data specifically on emissions from realistic burning of field-collected, soil-contaminated plastic mulch film. Existing plastic-burning literature provides important context, but clean plastic burning cannot fully represent used agricultural mulch because soil residue and agricultural contaminants alter combustion temperature, combustion efficiency, residue chemistry, and pollutant formation.

This project was designed to quantify and minimize environmental impacts of agricultural plastic mulch film burning. The research used controlled laboratory combustion systems, including a tube furnace reactor and an open burning reactor. Furnace experiments provide controlled temperature and flow fields, while open burning experiments are intended to represent practical field-burning conditions (diesel fuel-assisted burning). The team measured gaseous pollutants, particulate matter, and burn residues. The University of Florida team analyzed microplastics using stereomicroscopy and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS).

Major progress of this project included establishment of combustion and sampling systems, completion of tube furnace and open burning experiments, microplastic analysis of original and burned samples, collection of air pollutant and microplastics emission data, project website development, and TAG meetings. The project also generated a poster presentation at the SWANA FL Winter Conference & Hinkley Center Research Forum. TAG members provided practical guidance on plastic mulch film specifications, additives, film thickness, field measurement opportunities, health-risk implications, raw plastic sample analysis, metal analysis, and farmer-facing outputs.

Tube furnace experiments at 500, 650, and 800 °C showed that pollutant emissions depended strongly on plastic type, temperature, and air flow. The white/aluminized plastic mulch film was 26 μm (1.0 mil) thick and the black plastic mulch film was 28 μm (1.1 mil) thick. The white/aluminized film generally showed higher combustion efficiency, while the black film generally produced higher CO, NO_x, and SO₂ emission factors under comparable conditions. In contrast, the white/aluminized film generally produced higher particulate matter emission factors. Increasing temperature generally reduced CO emissions and, under sufficiently ventilated conditions, reduced PM emissions, but increased NO_x and SO₂ emissions. SO₂ concentrations and emission factors were unexpectedly high for polyethylene-based materials. The sulfur source was not identified conclusively and may include adhered soil, fertilizer or pesticide residues, film additives or coatings, and other field-derived contamination.

Microplastic analysis showed that microplastics were detected in all burned residue samples, with the majority of particles larger than 25 micrometers. Microplastic abundance increased with temperature. Later microplastic analysis of six sample conditions indicated that white plastic mulch showed higher microplastic occurrence than black plastic mulch, and polyvinyl chloride (PVC) was the predominant polymer identified in burned residue samples, likely due to the inclusion of additional plastic materials in the original plastic mulch. The original plastic samples were dominated by PE, with additional polypropylene (PP) and polymethyl methacrylate (PMMA) detected and approximately one-quarter of the original sample products remaining unidentified by Py-GC/MS. Burned samples contained very low measured polymer mass relative to total residue (<1%), suggesting that most residue may be carbonaceous soot, soil, or other non-polymer material. These results emphasize that burning does not simply eliminate plastic; it can redistribute carbonaceous residues and microplastic-like particles into ash and soil-associated materials, which can lead to soil health implications.

The project has several practical implications. For growers, the results show that plastic type, contamination, and burning conditions strongly affect pollutant emissions, but no single burning condition minimized all measured air and residue pollutants. Therefore, this study does not recommend a preferred open-burning condition. Where feasible, alternative end-of-life management strategies should be prioritized. For waste management professionals, the results highlight the need to improve collection, preprocessing, soil removal, recycling feasibility, and evaluation of controlled energy-recovery options. For regulators, the findings provide a preliminary dataset on a waste stream that is legally and practically important in Florida but not well characterized. For researchers, the data provide a foundation for field validation, sulfur-source identification, exposure assessment, and evaluation of alternative management pathways.

1. INTRODUCTION

1.1 Background and project significance

Plastics play an essential role in modern agriculture, offering numerous environmental and societal benefits. Plastic mulch film, a plastic mulch film that is used to cover the soil (**Figures. 1a and 1b**), comprises approximately 50% of the total mass of agricultural plastics and is extensively used to enhance crop production (Kasirajan and Ngouajio, 2012). The commercial use of plastic mulch film can be traced back to the early 1960s and has been continuously rising. By 2029, the compound annual growth rate of the global plastic mulch film market is estimated to be 7.1%, reaching a value of \$19.5 billion USD (Marketsandmarkets, 2024). Plastic mulch film, mostly made of polyethylene, provides multiple benefits, including weed and pest control, soil temperature and moisture control, and enhanced nutrient uptake. All these benefits translate to an increase in yield, improved water and nutrient use efficiency, and reduced pesticide use. In addition, plastic mulch film can be manufactured at a relatively low price and has been favored for its ease of application due to its lightweight (10 to 20 kg/ha) and flexibility, as well as its high durability. For these reasons, many growers rely on plastic mulch film to grow various specialty crops, such as strawberries, tomatoes, pepper, cucumber, and pumpkin. Specifically in the State of Florida, plastic mulch film is a very important component in successful vegetable production. Mulching is used in the production of nearly all tomato, pepper, eggplant, strawberry, and muskmelon in Florida, as well as most watermelon and cucumber crops. There are nearly 80,000 acres of mulched vegetables in Florida, making Florida a leading state in the use of plastic mulch film (Hochmuth et al., 2002).

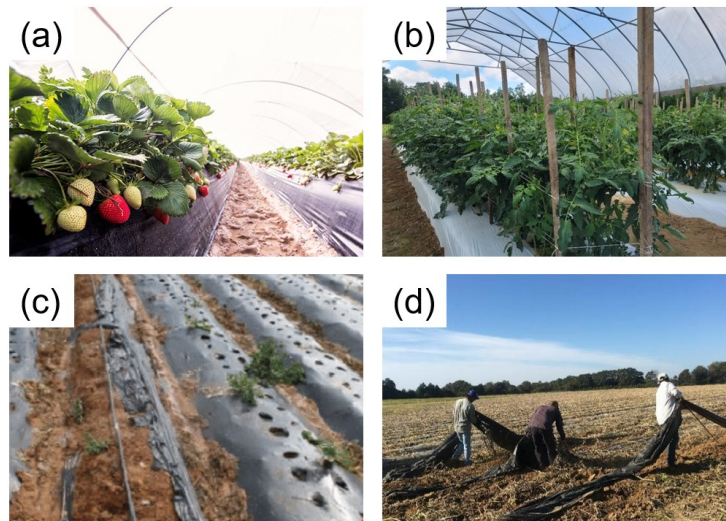


Figure 1. Plastic mulch film being applied in (a) strawberry and (b) tomato growing. (c) Used plastic mulch film after harvesting and (d) removal of plastic mulch film from the farmland.

Photo credit: ucsu.edu

Although plastic mulch film offers several advantages, its use is associated with long-term environmental concerns. Plastic mulch film is resistant to degradation, with its structural decomposition in the environment requiring centuries (Kasirajan and Ngouajio, 2012). Furthermore, microplastics generated from the plastic mulch film in the soil can adhere to plant surfaces or plant roots, potentially affecting food safety (Li et al., 2020). More importantly,

plastic mulch film needs to be reapplied each season due to crop harvesting and subsequent seed planting, yet its reuse and recycling rates remain very low, currently under 10% (Cassou, 2018). This lack of reuse and recycling generates large volumes of plastic waste, leading to challenges in waste management and concerns about plastic pollution (**Figures. 1c and 1d**). Overall, it is difficult to reuse or recycle plastic mulch film because the used plastic mulch film contains a high soil content, which adheres to the plastic mulch film due to its design (**Figure. 2a**). Soil residue can comprise as much as 80% of the total weight of used plastic mulch film, whereas current recycling facilities require significantly lower contamination levels (<5%) (Steinmetz et al., 2016). Moreover, polyethylene (PE) degrades slowly under solar radiation, and the mechanical performance of used plastic mulch film is lower than the new one. Because of the challenges, in the United States, common disposal methods for used plastic mulch film are limited to landfilling, stockpiling, in-field burial, and burning (Moore and Wszelaki, 2016).

Although landfilling appears to be an obvious option for managing plastic mulch film, it is further challenged by the heavy weight and bulk size of the used plastic mulch film (**Figure. 2b**). As soil residue constitutes most of the weight in the used plastic mulch film, growers need to consider the cost of labor for field removal, transportation, and disposal costs at landfills. In Miami-Dade County of the State of Florida, the current tipping fee (the charge for disposing of waste at the landfills) is \$70 per ton. Moreover, since the used plastic mulch film typically arrives at the landfills in large bales or rolls collected by farm machines, landfills also need to excavate larger space to fit the used plastic mulch film.

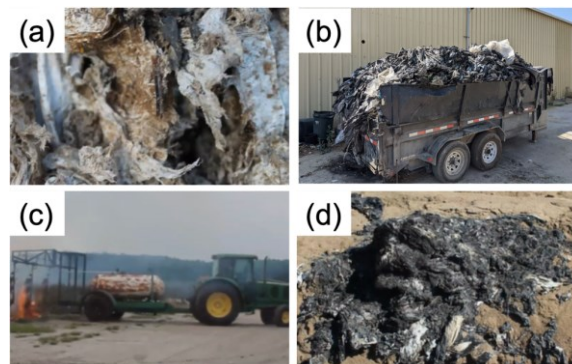


Figure 2. (a) Soil content remains in the used plastic mulch. (b) Collected used plastic mulch has a much larger bulk size compared to unused plastic mulch. (c) In-field burning of plastic mulch after tomato harvesting. (d) Residues remain after the open burning of plastic mulch. Photo credit: Gene Jone, Southern Waste Information Exchange.

Stockpiling and in-field burial can save growers the cost associated with transportation and landfilling the used plastic mulch film, but they are not direct solutions. The used plastic mulch film may undergo degradation, producing microplastics, nanoplastics, and other toxic materials that can be further transported by wind or water or taken up by plants (Yu and Flury, 2021), which could reduce soil health (Ng et al., 2018). Numerous emerging studies have focused on the fate and sink of microplastics (Law and Thompson, 2014; Rochman, 2018), revealing that microplastics can be taken up by organisms, accumulate, and transfer in food chains and have been detected in human food and drinking water (Hernandez et al., 2019; Yang et al., 2015), which poses significant risks to ecosystems and human health (Zhang et al., 2020a; Zhang et al.,

2020b). Moreover, the unburned plastic debris can contaminate nearby water channels or be consumed by livestock and wildlife, posing additional health risks to humans.

Because ideal management methods are lacking, we also rely on incineration to dispose of used plastic mulch film. Incineration can significantly reduce the weight and volume of plastics. Although plastics have a high heating value (46 MJ/kg), much higher than coal (~ 18 MJ/kg), used plastic mulch film is not accepted at waste-to-energy plants because of its high soil content and bulk size, which prevents it from becoming refuse-derived fuel. Therefore, on-site incineration of plastic mulch film and other agricultural plastics is the final option for growers. Although open burning of PE mulch is prohibited in most states, some growers in the Pacific Northwest and Mid-Atlantic regions report engaging in this practice to dispose of their used plastic mulch film (Goldberger et al., 2019). Moreover, in the State of Florida, regulations permit the field burning of agricultural films and plastics (Florida Statutes Title XLVI, Chapter 823.145): “Polyethylene agricultural plastic, ..., which are used in connection with agricultural operations related to the growing, harvesting, or maintenance of crops, may be disposed of by open burning...” Currently, plastic mulch film is either burned in piles that are assisted with gasoline or burned on the farmland assisted with propane flames generated by weed burner tractor attachment (**Figures. 2c and 2d**).

Burning plastic mulch film may lead to environmental concerns on air and soil quality. Air pollutants, such as particulate matter and toxic gaseous (e.g., carbon monoxide and volatile organic compounds), can be generated, especially during the incomplete combustion of the plastic mulch film. Previous studies have reported that the open burning of plastics and other solid wastes can directly release hazardous pollutants into ambient air, including particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}), persistent organic pollutants, and heavy metals (Cheng et al., 2020; Gullett et al., 2010; Hodzic et al., 2012; Jayarathne et al., 2018). Airborne toxic substances can trigger an array of diseases when inhaled by humans and threaten health (Lelieveld et al., 2015). Specifically, the burning of polyethylene was observed to emit larger amount of carbon monoxide when compared to the burning of polystyrene and poly(vinylchloride) (PVC) (Wang et al., 2004). Plastic burning at lower temperatures ($< 300 \text{ }^{\circ}\text{C}$) can produce polycyclic aromatic hydrocarbons that can disperse in the air and accumulate in soil (Wortman and Lovell, 2013). Additional toxic substances can be emitted as heavy metals and 1,4-dioxane (a carcinogen) (Levitan, 2005). Even under high temperatures, where combustion of plastics is considered to be more complete, such as the temperature in waste-to-energy incinerators (above $850 \text{ }^{\circ}\text{C}$), unburned materials still exist in the bottom ash, which contains a considerable number of microplastics (up to 1.02×10^5 microplastics per ton of waste burned) that will negatively impact soil health and crop safety (Shen et al., 2021).

1.2 Project objectives and scope

Although the onsite burning of plastic mulch film is expected to generate an array of air and soil pollutants, until now, there has not been an examination of the pollutant emission associated with plastic mulch film burning. Especially, realistic experiments using soil-contaminated plastic mulch film are needed since the soil content will influence the combustion temperature and associated pollution emission characteristics. In this collaborative project between the University of Miami and the University of Florida, we quantified the pollutants associated with plastic mulch film burning, and we completed the following tasks:

1. Quantify emission factors of air pollutants and microplastics from agricultural plastic mulch film burning using controlled combustion systems.
2. Identify burning conditions and material factors that influence pollutant emission and can inform lower-impact management practices.

By deploying advanced laboratory experimental systems, including the tube furnace reactor and open burning reactor, aerosol and trace gas monitoring systems, and microplastic characterization systems, we will obtain comprehensive knowledge of pollutant emissions and potential environmental and health risks associated with plastic mulch film burning. The findings will benefit the farmers and policymakers regarding the practical management of agricultural plastics.

The study focused on controlled laboratory measurements. The project did not conduct cellular toxicology or quantitative health risk assessment, while TAG members recommended that the emission data could support future health risk modeling. Field measurements were discussed with the UF Gulf Coast Research and Education Center, but logistics prevented field sampling during the reporting period. Therefore, the findings should be interpreted as controlled laboratory results that can guide future field validation. Additionally, future work regarding the soil health impacts and health risk modeling associated with agricultural plastic burning, as well as outreach activities are suggested.

2. METHODS

2.1 Overall experimental design

The project combined combustion experiments at the University of Miami with microplastic analysis at the University of Florida. The selected plastic mulch film samples were burned in two different reactors: a tube furnace reactor and an open burning reactor. A schematic diagram and the photo of the experimental setup are shown in **Figures 3** and **4**. The experiments used two types of field-collected used plastic mulch film (**Figure 5**) obtained from Berry Global Inc. One material was a white/aluminized polyethylene film with a thickness of 1.0 mil, and the other was a black polyethylene film with a thickness of 1.1 mil. The white plastic is a double-layer material and the black plastic is a single-layer material. The white/aluminized and black polyethylene films have densities of $30.9 \pm 0.3 \text{ g/m}^2$ and $31.6 \pm 0.3 \text{ g/m}^2$. The number of layers of the film did not significantly impact the density of the film.

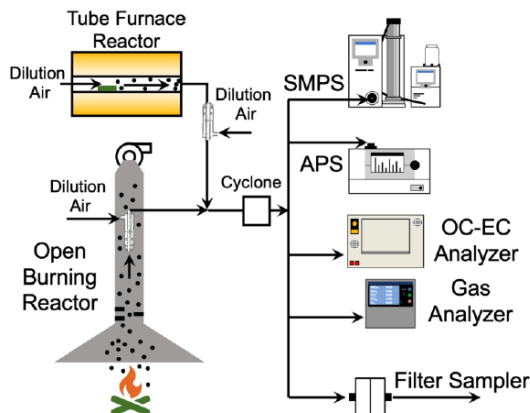


Figure 3. Experimental system for tube furnace and open burning reactor measurements.

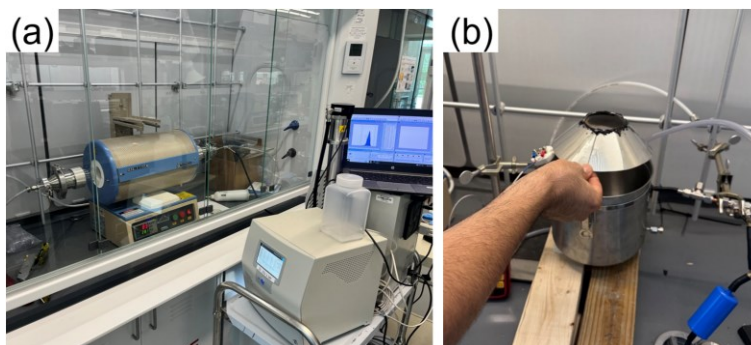


Figure 4. Tube furnace and open burning chamber used in this project.



Figure 5. Plastic mulch films examined in furnace experiments: white/aluminized polyethylene and black polyethylene.

Tube furnace reactor: Tube furnace reactor has the advantage of well-controlled temperature and flow fields, reducing the variation of aerosol measurements in combustion experiments and making it suitable for studying aerosol emissions in solid fuel combustion (Wang et al., 2013; Gao and Wu, 2010; Colom-Díaz et al., 2017; Du et al., 2010; Kajitani et al., 2002). Specifically in this project, the tube furnace reactor can help establish the emission of plastic mulch film burning under different temperatures and flow residence times, which are the parameters that can be controlled in the actual burning practices. Moreover, plastic mulch film is difficult to ignite in open burning, which generally requires the application of propane torches or gasoline, in some cases continuously, to maintain the fire, (Hall et al., 2012; Mcmeeking et al., 2009; Sullivan et al., 2008) which may influence the characterization of plastic mulch film burning emission by itself. The tube furnace reactor does not require such procedures to initiate and maintain the burning.

In this project, plastic mulch film samples were burned in a 5.08 cm-diameter, 0.3 m long quartz tube furnace (Model GSL-1100X-NT-LD, MTI Corp.) with a controllable wall temperature ranging from 100 to 1100 °C. This temperature range is sufficient to plastic burning conditions, since plastics generally self-ignites by 600 °C, while melting and decomposition generally occurs at around 170 °C. Two types of used plastic mulch film samples were examined in the furnace reactor (**Figure 5**). Furnace temperatures of 500 °C, 650 °C, and 800 °C, were used, and after the furnace reached the targeted temperature, the plastic mulch film samples were loaded in crucibles and placed in the furnace during a period of 15 minutes. A longer combustion time was not used as the gas analyzer and PM measurements show that the pollutant emission was minimal after around 10 minutes. Compressed air at a controlled flow rates (0.5, 1, and 2 liters per minute (lpm), corresponding to a flow residence time of 70, 35, and 18 s) were introduced to

the furnace to combust the plastic mulch film samples under different temperatures and residence times. At the exit of the drop-tube furnace, the generated pollutants were sampled by an aspiration-based sampling system, with particle-free air introduced at a flow rate of 15.5 lpm. Each test condition was repeated at least three times to ensure the statistical robustness of the measurement. Table below shows the experimental conditions of the furnace experiments.

Table 1. Summary of tube furnace experimental conditions.

Parameter	Value/Description
Plastic types	White/aluminized PE and black PE agricultural plastic mulch
Representative temperatures	500, 650, and 800 °C in analyzed final datasets
Flow and sampling	Controlled air flow through reactor; diluted sampling downstream
Measurements	CO, CO ₂ , NO _x , SO ₂ , PM size distribution, PM mass, residues, microplastics

Open burning reactor: The open burning experiments were conducted in a laboratory fume hood to simulate small-scale, liquid-fuel-assisted burning of agricultural plastic mulch. Used plastic mulch film samples were placed in a circular crucible. Because the plastic film was difficult to ignite and sustain by itself, diesel was added at 10%, 20%, or 30% of the plastic-mulch mass to assist combustion, reflecting stakeholder-reported field practices in which liquid fuel may be used to initiate burning. A Type-K thermocouple was used to monitor combustion temperature, and gaseous pollutants were sampled from the combustion plume using the dilution sampling system. These experiments were designed as a controlled, field-relevant simulation rather than a direct reproduction of full-scale field burning.

2.2. Air and soil sample analysis

Physicochemical properties of particulate matter: To study the particulate matter in the smoke, we examined the smoke particle size distributions between 10 and 600 nm with a scanning mobility particle sizer (SMPS, Model 3938, TSI Inc.) and between 0.5 and 10 µm with an aerodynamic particle sizer (APS, Model 3321, TSI Inc.). Particulate matter were also collected via a 47 mm-diameter Polytetrafluoroethylene (PTFE) membrane filter (SKC Inc.), then weighed before and after the burning experiment by a microbalance to determine the mass and calculate the mass emission factors of particulate matter. Gas species, including CO, CO₂, NO_x, and SO₂ were monitored by a gas analyzer (Model 310, Testo Inc.) (Patel et al., 2016). A control group without plastic mulch film burning was also conducted to establish the baseline of air and soil pollutant concentrations.

The residue samples of the used plastic mulch film burning were stored and shipped to **Jung's** laboratory at the University of Florida for further microplastics analysis. The shipped particles were recovered from the shipping container (plastic petri dish) using ultrapure water and collected in pre-cleaned beakers. The recovered suspension was then passed through a 25-micrometer metal sieve to separate particles into two size fractions: >25 micrometer and <25 micrometer. The 25-micrometer sieve was selected because it was the smallest mesh size commercially available for this type of separation. Although 25 micrometers is larger than the size range typically considered relevant for inhalation exposure, it allowed us to achieve the finest practical size separation using a commercially available tool. The two size fractions were

subsequently collected and analyzed separately. It should be noted that the procedural blank using a plastic petri dish showed negligible microplastic contamination. The morphology, color, and size of microplastics were characterized using a stereomicroscope (Motic SMZ 171-TLED) with a Moticam BTI10 digital camera (up to 5x magnification). The chemical composition of microplastics was analyzed using pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), which combines a multi-shot pyrolyzer (EGA/PY-3030D, Frontier Laboratories) with an Agilent 8890 GC and Agilent 5977C MS. This technique allowed both identification and quantification of microplastics. **Table 2** below summarizes the pollutant measurements.

Table 2. Pollutants and instruments used in this project.

Pollutant/Property	Instrument or Method	Output
Particle size distribution	SMPS and APS	Number size distribution from nanometer to micrometer range
PM mass	Filter collection and microbalance	Mass concentration and PM emission factor
CO and CO ₂	Gas analyzer	Combustion efficiency and emission factors
NO _x and SO ₂	Gas analyzer	Gaseous emission factors
Microplastics	Stereomicroscope and Py-GC/MS	Particle morphology, size class, polymer identity, and abundance

Emission factors: We used the mass of air and soil pollutants to determine the EFs of plastic mulch film burning-generated pollutants. EF_{*i*} is calculated by (Chen et al., 2007)

$$EF_i = \Delta m_i / \Delta m_b \quad (1)$$

where Δm_i is the increase of mass for pollutant *i*, and Δm_b is the mass of burned plastic mulch film. Smoke pollutants Δm_i is further calculated by

$$\Delta m_i = \Delta C_i \times Q \times t \quad (2)$$

where ΔC_i is the change of concentration in the smoke, *Q* is the flowrate through the stack (corrected to standard conditions), and *t* is the sampling time. Using the above equations, we can determine the EF of PM and pollutant gases. We also examined the modified combustion efficiency under different burning conditions, which can estimates the completeness of the combustion. MCE is defined as the fraction of carbon released as CO₂. MCE was calculated using the following equation,

$$MCE = \Delta[CO_2] / (\Delta[CO_2] + \Delta[CO]) \quad (2)$$

where [CO] and [CO₂] are the concentrations of CO and CO₂.

The obtained measurement results were compared against the physicochemical properties and emission factors of pollutants generated from similar sources established by previous studies on plastic burning (Cruz et al., 2023; Hoffer et al., 2020; Wu et al., 2021) and by the Environmental Protection Agency (EPA) (Epa, 2024b). We used EPA's National Ambient Air Quality Standards (NAAQS) as a standard to further evaluate pollutant concentrations from plastic mulch film burning (Epa, 2024a). The project will establish pollutant levels for various combustion

conditions and burning materials, thereby enabling the provision of recommendations for used plastic mulch film burning practices.

3. RESULTS

3.1 Project website, stakeholder engagement, and milestones

The project website (<https://pmtl.coe.miami.edu/research/hinkleycenter/index.html>) was created to share the project description, project documents, TAG members, TAG meeting recordings, and Hinkley Center acknowledgement. The team established the furnace and open burning reactor systems, calibrated major particulate matter and gas measurement instruments, and finalized sampling protocols. The team completed tube furnace and diesel-assisted open burning experiments, shipped burn residues to the University of Florida, analyzed pollutant data, and held three TAG meetings.

TAG Meeting #1, held on December 4, 2025, included participants from the agricultural plastics sector, Florida DEP, public health, solid waste management, academia, and the Hinkley Center. Key feedback included the need to consider film specifications, additives, thickness, possible field measurements, health aspects, and farmer-facing outputs. TAG Meeting #2, held on May 22, 2026, provided additional technical feedback, including suggestions to use diesel fuel in open burning experiments, analyze raw plastic samples, conduct soil metal analysis, and examine PM trends. TAG Meeting #3, held on September 10, 2026, focused on the final project findings and report interpretation. Members recommended further investigation of the unexpectedly high SO₂ emissions, stronger source-versus-ambient context for the NAAQS comparison, correction of the Executive Summary inconsistency regarding white versus black mulch emissions, recognition that full field washing of mulch film is not a practical near-term management option for Florida growers, and prioritization of alternatives to open burning rather than identification of a preferred burning temperature.

3.2 Modified combustion efficiency (MCE)

From the combustion experiments, we found that MCE depends strongly on the type of the plastic burned (**Figure 6**). The MCE for burning the white/aluminized plastic mulch film was consistently higher than 90%, while the MCE for burning the black plastic mulch film were lower than 85% when less amount of air was provided to the burning. This likely reflects differences in film structure and combustion behavior, where the aluminized plastic mulch film contains less amount of combustible material (PE) that results in more complete combustion even under reduced air flow. The increasing trend of MCE with higher air flow in general agrees with fuel combustion behavior, where more abundant oxygen access results in higher MCE, signifying more complete combustion. In our measurements, combustion temperature was not found to be influencing MCE significantly, indicating that the plastic mulch films could be ignited and combusted at temperatures as low as 500 °C. In our experiments, we did not use further lower temperatures because the burning was minimal at 450 °C.

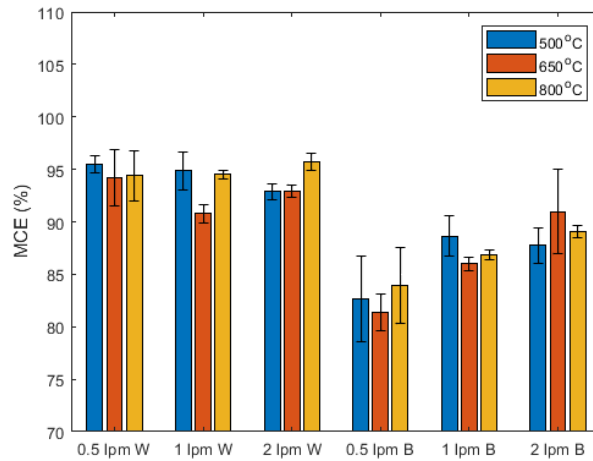


Figure 6. Modified combustion efficiency as a function of burning temperature for white/aluminized and black plastic mulch samples. Each group of three vertical bars represent temperature conditions of 500, 650, and 800 °C from left to right.

3.3 Gaseous pollutant and PM emission factors

The burning experiments showed that the gaseous pollutants and PM emission factors are dependent on the type of the plastic mulch film and the combustion conditions, and there is no consistent trend for different types of pollutants. Results on CO measurements (**Figure 7**) show that burning the black plastic mulch film generated more CO than burning the white/aluminized plastic mulch film, which is consistent with the observations of MCE in **Figure 6**. In general, increasing the burning temperature resulted in the decrease of CO emission, although measurement groups for burning white plastic mulch film under 0.5 and 1 lpm showed a different trend. The EFs for CO observed in this study (10 to 100 g/kg fuel burned) is also consistent with previous literature on plastic burning (Wang et al., 2003).

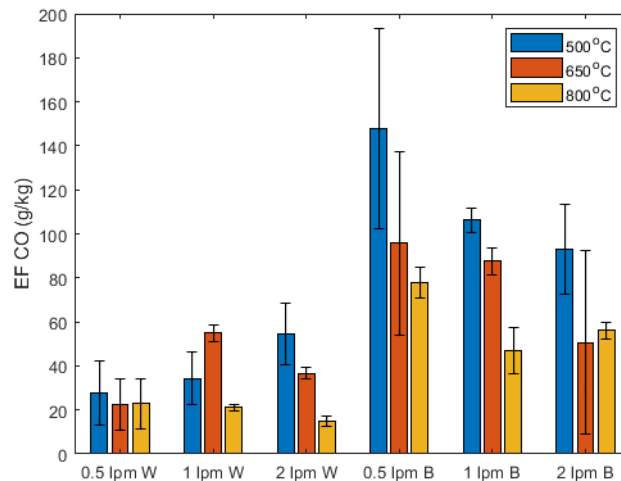


Figure 7. Emission factors of CO as a function of burning temperature for the plastic mulch samples. Each group of three vertical bars represent temperature conditions of 500, 650, and 800 °C from left to right.

Measurements of NO_x (**Figure 8**) showed that burning black plastic mulch film generally emitted more NO_x than burning white/aluminized plastic mulch film. Here, the emission factors are reported as NO₂. NO_x emissions generally increased with furnace temperature. Because the nominal furnace temperatures in this study were below those typically associated with substantial thermal-NO_x formation, the observed NO_x may instead reflect nitrogen-containing components in the field-used mulch, adhered soil, fertilizer or pesticide residues, or other additives; additional elemental analysis is needed to identify the dominant nitrogen source. SO₂ emissions (**Figure 9**) were also unexpectedly high because polyethylene itself does not contain sulfur. The sulfur source could not be identified conclusively in this study. Potential contributors include adhered soil, sulfur-containing fertilizers or pesticides, surfactants or other field-applied chemicals, additives or coatings in the commercial mulch film, and other field-derived contamination. Additional washing experiments using deionized water reduced SO₂ emissions but did not eliminate them, indicating that loosely adhered soil or water-soluble residues alone cannot fully explain the observed sulfur emissions. Future work should quantify sulfur in unused mulch film, washed used mulch film, adhered soil, and combustion residues and evaluate crop-specific pesticide and fertilizer use records to constrain possible sulfur sources.

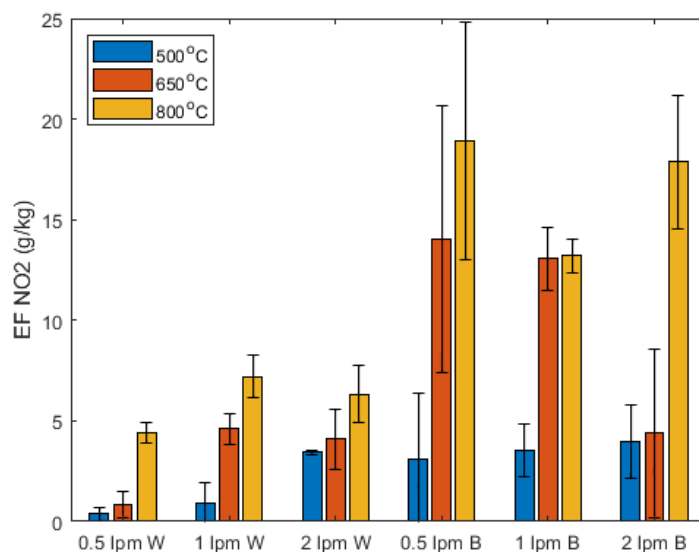


Figure 8. Emission factors of NO₂ as a function of burning temperature for the plastic mulch samples. Each group of three vertical bars represent temperature conditions of 500, 650, and 800 °C from left to right.

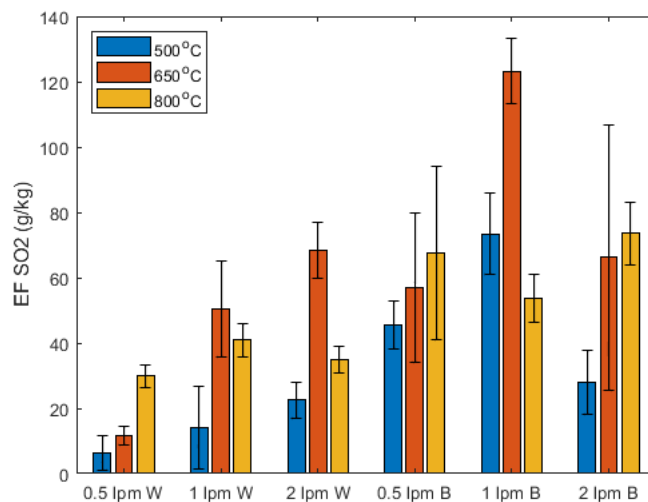


Figure 9. Emission factors of SO₂ as a function of burning temperature for the plastic mulch samples. Each group of three vertical bars represent temperature conditions of 500, 650, and 800 °C from left to right.

Contrary to the gaseous pollutant data, black plastic mulch generated relatively lower PM emission factors than white/aluminized plastic mulch (**Figure 10**). This trend may be associated with differences in material texture, film structure, and combustion efficiency. The aluminized components in the white plastic mulch film may have contributed to the formation of additional PM that is not associated with the gaseous pollutants.

Overall, under well-ventilated conditions with sufficient air flow, the higher combustion temperature leads to lower PM emission factors. However, this trend does not hold under less ventilated conditions (0.5 or 1 lpm air flow). This complexity was identified by the TAG as a key issue because PM emissions are central to practical burning guidance.

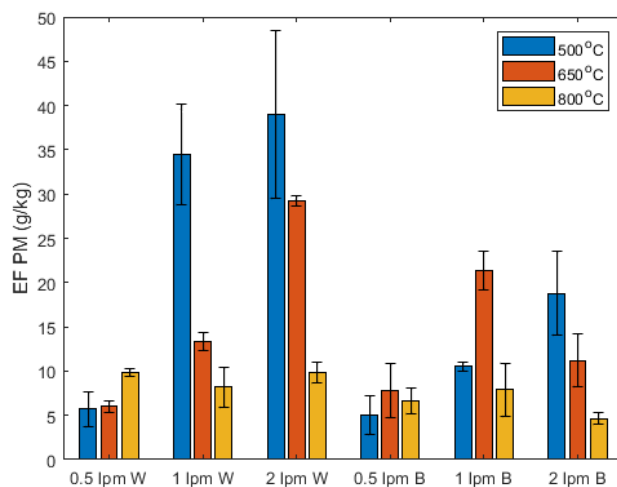


Figure 10. Emission factors of PM as a function of burning temperature for the plastic mulch samples. Each group of three vertical bars represent temperature conditions of 500, 650, and 800 °C from left to right.

As a summary of the gaseous-pollutant and PM measurements, white/aluminized and black plastic mulch films showed distinct emission profiles, and temperature and air flow affected different pollutants in different ways. Higher temperature generally reduced CO and, under sufficiently ventilated conditions, PM, while NO_x and SO₂ generally increased. Because no single condition minimized all measured pollutants, these results should not be interpreted as supporting a preferred open-burning temperature. Instead, they demonstrate the need to consider alternative end-of-life management strategies and to validate laboratory findings under field conditions.

In addition to the furnace experiments, we conducted a limited number of diesel-assisted open burning experiments. Plastic mulch film was placed in a circular crucible, and air pollutants were sampled from the combustion plume above the flame. The film was difficult to burn by itself and tended to extinguish after several seconds, so diesel was added at 10%, 20%, or 30% of the plastic-mulch mass. **Figure 11** shows an image of the open burning experiment. A Type-K thermocouple measured combustion temperatures of approximately 450 to 600 °C after heat-loss correction. These temperatures were lower than those in the furnace experiments, likely because of heat loss to the relatively cool crucible and limited air exchange. The laboratory geometry and scale differ from full-scale field burning. Therefore, these experiments are interpreted as controlled, field-relevant simulations rather than direct reproductions of field conditions.



Figure 11. Picture taken during the open burning of the plastic mulch film. The brown wires are the thermocouple for monitoring the burning temperature, and the stainless tube is the sampling inlet for air pollutant monitoring.

The emission factors of air pollutants during open burning are calculated using a simplified approach, where

$$EF_i = \Delta P_i / (\Delta[CO_2] + \Delta[CO]) \times w_c \quad (1)$$

where ΔP_i is the enhancement of pollutant i compared with background levels and w_c is the carbon content in g/kg. The calculation assumes that burned carbon is converted primarily to CO₂ or CO. A value of 0.856 was used for w_c by assuming that the plastic mulch film was predominantly polyethylene. Using this approach, the emission factors of CO, SO₂, and NO₂

were 38.3 ± 23.9 g/kg, 3.56 ± 1.82 g/kg, and 1.02 ± 1.03 g/kg, respectively. These values were generally consistent with furnace burning results under lower-temperature conditions (**Figures 7 to 10**). Because the open-burning experiments were limited in number and conducted at laboratory scale, the resulting emission factors should be viewed as preliminary and should be validated in future field-scale measurements.

3.4 Contextual comparison with ambient air-quality reference concentrations

Measured source-level concentrations were compared with selected NAAQS values (**Table 3**) only to provide context regarding the relative magnitude of the emissions. This comparison is not intended to represent regulatory compliance, ambient exposure, or health risk. NAAQS values apply to ambient air over specified averaging periods, whereas concentrations measured in this study were obtained directly at or near the combustion source before atmospheric dispersion and dilution. Actual worker and community exposures would depend on distance from the source, wind direction and speed, atmospheric mixing, burn duration, frequency of burning, and personal location relative to the plume. SO₂ was especially high relative to the selected reference value, reinforcing the need to investigate sulfur sources in the used mulch. Therefore, the source concentrations reported here should not be interpreted as concentrations experienced by workers or nearby communities without atmospheric dispersion and exposure analysis.

Table 3. Maximum source-level concentrations of gaseous pollutants and selected NAAQS values shown for contextual reference only.

Pollutant	Maximum concentration	NAAQS reference concentration
CO	343 ppm	9 ppm
NO ₂	21.9 ppm	0.1 ppm
SO ₂	91 ppm	0.075 ppm

3.5 Microplastic abundance and characteristics

Microplastics were detected in all burned residue samples, with the majority of particles larger than 25 micrometers (**Figure 12**). Microplastic abundance generally increased with increasing temperature. For example, the microplastic abundance in the white plastic mulch residue at 585 °C was less than half that observed at 785 °C, as well as that observed in the black plastic mulch residue at the same temperature. Except at 585 °C, white plastic mulch residues generally showed higher microplastic abundance than black plastic mulch residues. PVC was the predominant polymer identified in several burned-residue samples, although PVC was not detected in the original mulch samples. Therefore, the source of the PVC signal remains unresolved and may reflect environmental contamination, sample handling or cross-contamination, or analytical uncertainty. The detected microplastics exhibited various morphologies, including fibers, pellets, and fragments (**Figure 13**). Representative microscopic images also showed numerous gray particles within the burned plastic residues.

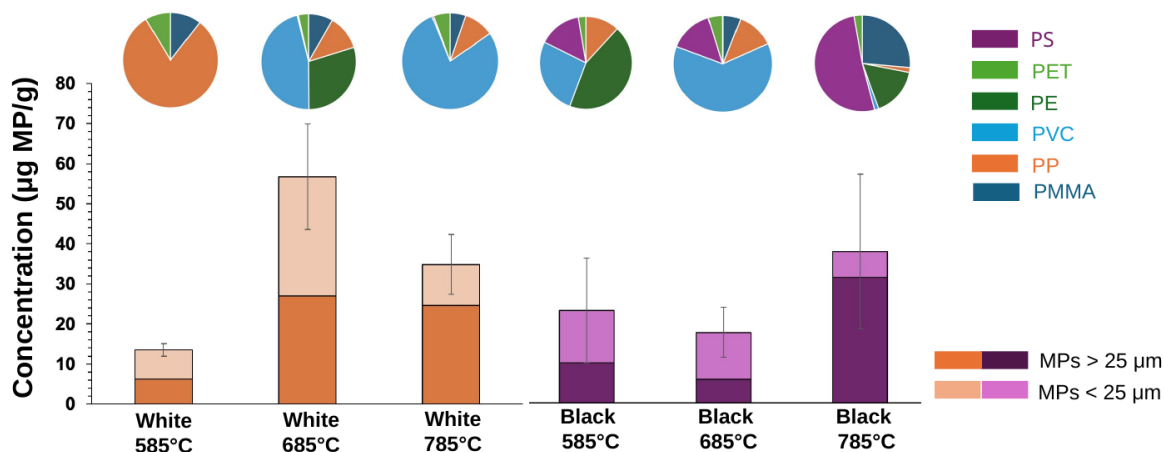


Figure 12. Microplastic abundance and polymer composition in burned plastic mulch residues at 585, 685, and 785 °C. PS, PET, PE, PVC, PP, and PMMA represent polystyrene, polyethylene terephthalate, polyethylene, polyvinyl chloride, polypropylene, and polymethyl methacrylate.

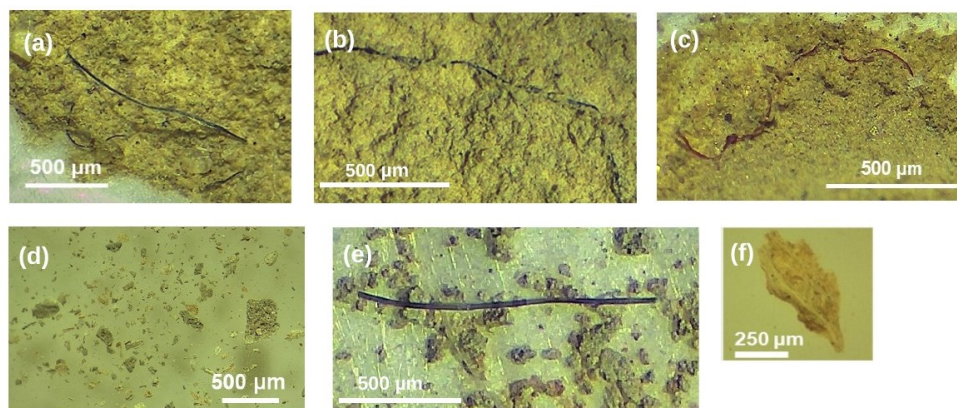


Figure 13. Microscopic images of burned plastic mulch samples. Black plastic mulch: 585, 685, and 785 °C; white plastic mulch: 585, 685, and 785 °C.

3.6 Chemical composition of original and burned samples

According to suggestions from the TAG members during the second TAG meeting, we investigated potential sources of the detected microplastics because the predominant polymer identified in some burned residues was not PE, which is generally considered the major component of agricultural plastic mulch films. As a first step, we analyzed the polymer composition of the original plastic mulch material using Py-GC/MS (**Figure 14**). More than 70% of the material in both plastic mulch samples was identified as polymeric material, with PE comprising the majority, along with smaller fractions of polypropylene (PP) and polymethyl methacrylate (PMMA). The remaining portion of the original samples could not be identified as polymeric material by Py-GC/MS. These results support PE as the predominant polymer in the original mulch while indicating that commercial agricultural mulch materials may contain additional polymeric components or other materials that could contribute to the observed residue composition.

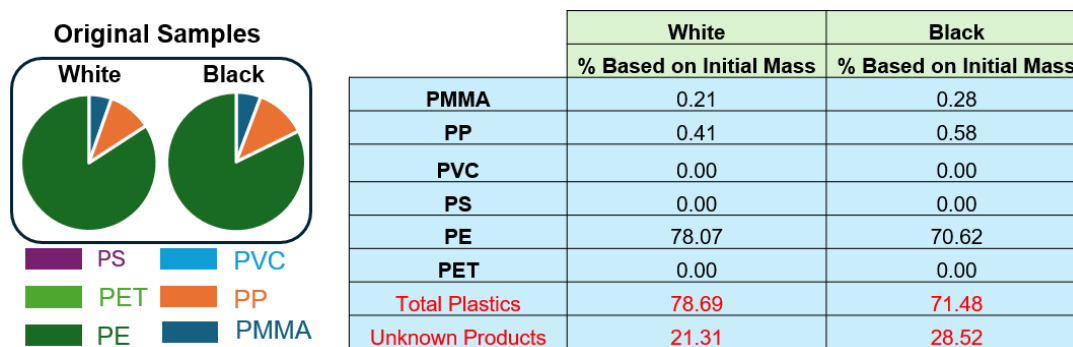


Figure 14. Chemical composition of original plastic mulch samples measured by Py-GC/MS. PS, PET, PE, PVC, PP, and PMMA represent polystyrene, polyethylene terephthalate, polyethylene, polyvinyl chloride, polypropylene, and polymethyl methacrylate.

As a second step, we compared the mass of the detected microplastics with the original mass of the burned plastic mulch to estimate the proportion of the burned material recovered as microplastics (**Figure 14**). The measured polymer mass in the burned residues represented a very small fraction (<1%) of the initial burned plastic mulch mass. Following the analysis, gray-colored residues remained, which is not typically observed during the pyrolysis of PE, as PE generally produces little to no solid residue. In addition, microscopic images of the original burned plastic mulch residues showed abundant gray particles (**Figure 12e**). These observations suggest that substantial portion of the remaining residue may consist of non-polymeric materials, such as carbonaceous residues (e.g., soot) and soil-associated particles. The results further suggest that combustion may have generated or concentrated non-polymeric residues within the burned plastic mulch material.

PVC was not detected in the original mulch samples (**Figure 14**) but was identified among microplastics recovered from some burned mulch samples (**Figure 15**). Because the current data do not identify the source of this discrepancy, the PVC signal should be interpreted cautiously. Potential explanations include environmental contamination, sample handling or cross-contamination, or analytical uncertainty. Additional control experiments using clean, unused polyethylene processed through the same analytical workflow would help determine whether the signal reflects the samples or the analytical procedure.

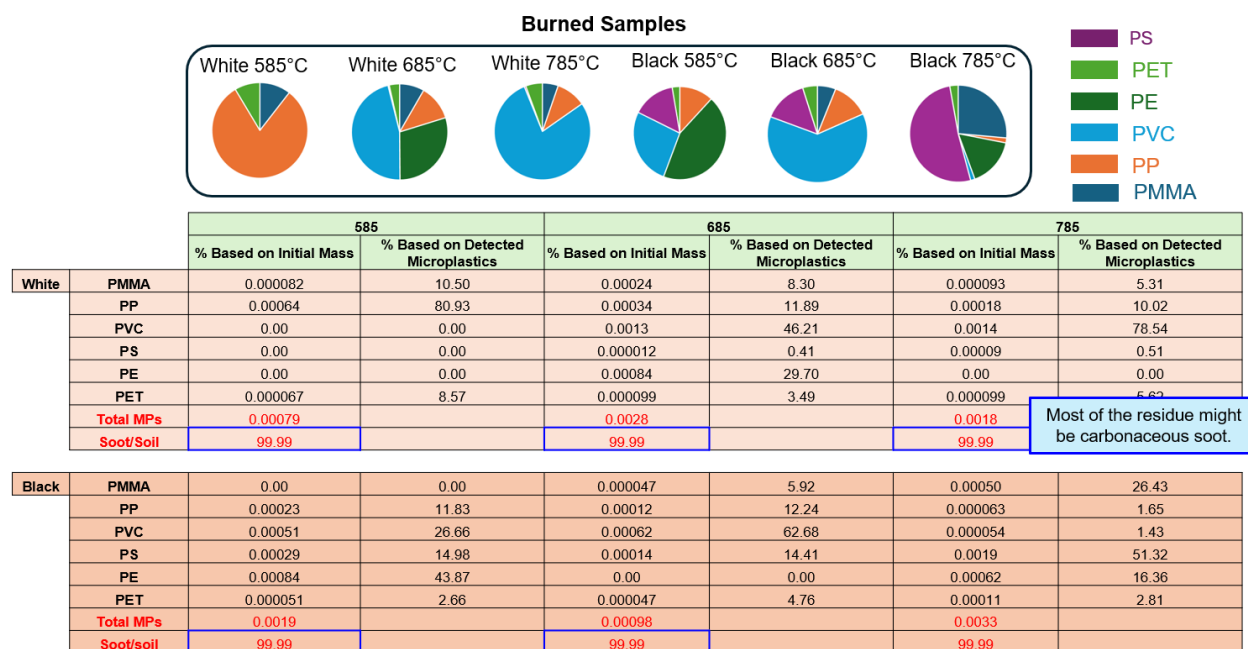


Figure 15. Chemical composition of burned plastic mulch samples measured by Py-GC/MS. PS, PET, PE, PVC, PP, and PMMA represent polystyrene, polyethylene terephthalate, polyethylene, polyvinyl chloride, polypropylene, and polymethyl methacrylate.

3.7 Practical waste management implications

Open burning substantially reduces the volume of agricultural plastic mulch waste but transfers part of the waste burden into gaseous pollutants, particulate matter, and residual microplastics. No single burning condition minimized all measured pollutants simultaneously. TAG members emphasized that the final management recommendations should therefore avoid implying that a particular open-burning condition is environmentally preferable without additional field validation. Alternative management strategies should be prioritized where feasible, including improved collection and preprocessing, soil removal, recycling, appropriately controlled energy recovery, and development of more recyclable or reusable agricultural films. Any alternative must account for high soil loading, low bulk density, transportation cost, and other operational constraints that make agricultural plastic mulch difficult to manage. Additional research should focus on field-scale burning measurements, sulfur-source identification, practical preprocessing methods, and economic comparison of disposal and recovery pathways.

3.8 Summary of findings

Table 4. Summary of major project findings and implications.

Finding	Interpretation	Implication
Higher air flow increased MCE	More complete oxidation occurred at sufficient oxygen	Higher-temperature burning may reduce CO and some gases
Black plastic emits more gaseous pollutants	Film structure and oxygen access likely influenced burning	Film specification must be considered in guidance
SO ₂ emissions were unexpectedly high	Soil, fertilizer, pesticide, or additives may contribute sulfur	Used mulch cannot be treated as clean polyethylene

Finding	Interpretation	Implication
MPs detected in all burned residues	Burning did not eliminate all plastic-related particles	Residue management remains important
Microplastic abundance increased with temperature	Higher temperature may increase fragmentation or residue concentration	Burning optimization must consider both air and residue pollutants

4. CONCLUSIONS

This project generated one of the first controlled datasets on pollutant emissions from burning field-collected agricultural plastic mulch film. The results show that agricultural plastic mulch burning is not equivalent to burning clean polyethylene. Plastic type, film structure, thickness, reflective layers, and contamination can alter combustion efficiency and pollutant emissions. Used plastic mulch can generate gaseous pollutants, particulate matter, and microplastic-containing residues under laboratory-controlled burning conditions.

A key finding is that pollutant emissions from plastic mulch burning depend strongly on both burning conditions and plastic type. Higher temperature did not consistently reduce overall environmental impacts: it generally reduced CO and, under sufficiently ventilated conditions, PM, but increased NO_x, SO₂, and microplastic abundance. Because no single burning condition minimized all measured endpoints, the results do not support recommending a preferred open-burning temperature. Where feasible, alternative end-of-life management strategies should be prioritized.

A second important conclusion is that soil and agricultural contamination likely influence emission chemistry. The unexpectedly high SO₂ emissions cannot be attributed conclusively to a single source. Plausible contributors include adhered soil, fertilizer or pesticide residues, surfactants or other field-applied chemicals, film additives or coatings, and other non-polyethylene components. Washing reduced but did not eliminate SO₂ emissions. Future work should include sulfur mass-balance analysis and direct sulfur measurements in unused film, washed used film, adhered soil, and combustion residues.

For practical use, the project does not support a single universal best burning method because air-pollutant and residue-pollutant trends differ. TAG members also noted that full washing of mulch film before disposal is unlikely to be practical for Florida growers and therefore should not be presented as a near-term field recommendation. The most scientifically defensible recommendation is to minimize open burning where feasible, improve collection and preprocessing options, evaluate recycling and appropriately controlled energy-recovery pathways, and pursue future research that links laboratory emission factors to field measurements and exposure modeling. If open burning continues under existing legal allowances, additional field-scale research is needed before specific operating recommendations can be developed.

Recommendations for future work

1. Conduct field measurements during real agricultural plastic mulch burning to validate laboratory emission factors and characterize downwind exposure.
2. Examine the influence of soil residue on the burning of plastic mulch films.
3. Develop farmer-facing guidance that balances practical constraints, cost, pollutant reduction, personal protection, and residue cleanup.

4. Evaluate practical preprocessing methods, including shaking, dry separation, and electrostatic approaches, to reduce soil contamination and improve recycling or waste-to-energy feasibility. Laboratory washing can be used as a diagnostic method to distinguish contaminant sources, but TAG members noted that full field washing is unlikely to be a practical near-term management option for Florida growers.
5. Use emission factors from this project to support future health risk assessment and air dispersion modeling.
6. Determine the dominant sulfur source through sulfur mass-balance calculations and direct sulfur measurements of unused film, washed used film, adhered soil, relevant agricultural chemicals, and combustion residues.

5. REFERENCES

- Cassou, E.: *Agricultural Pollution - Plastics*, 2018.
- Chen, L. W. A., Moosmüller, H., Arnott, W. P., Chow, J. C., Watson, J. G., Susott, R. A., Babbitt, R. E., Wold, C. E., Lincoln, E. N., and Hao, W. M.: Emissions from laboratory combustion of wildland fuels: Emission factors and source profiles, *Environmental science & technology*, 41, 4317-4325, 2007.
- Cheng, K., Hao, W., Wang, Y., Yi, P., Zhang, J., and Ji, W.: Understanding the emission pattern and source contribution of hazardous air pollutants from open burning of municipal solid waste in China, *Environmental Pollution*, 263, 114417, 2020.
- Colom-Díaz, J., Alzueta, M. U., Fernandes, U., and Costa, M.: Emissions of polycyclic aromatic hydrocarbons during biomass combustion in a drop tube furnace, *Fuel*, 207, 790-800, 2017.
- Cruz, M. B., Saikawa, E., Hengstermann, M., Ramirez, A., McCracken, J. P., and Thompson, L. M.: Plastic waste generation and emissions from the domestic open burning of plastic waste in Guatemala, *Environmental Science: Atmospheres*, 3, 156-167, 2023.
- Du, S.-W., Chen, W.-H., and Lucas, J. A.: Pulverized coal burnout in blast furnace simulated by a drop tube furnace, *Energy*, 35, 576-581, 2010.
- EPA: National Ambient Air Quality Standards (NAAQS) Table, 2024a.
- EPA: AP-42: Compilation of Air Emissions Factors from Stationary Sources, 2024b.
- Gao, X. and Wu, H.: Effect of sampling temperature on the properties of inorganic particulate matter collected from biomass combustion in a drop-tube furnace, *Energy & Fuels*, 24, 4571-4580, 2010.
- Goldberger, J. R., DeVetter, L. W., and Dentzman, K. E.: Polyethylene and biodegradable plastic mulches for strawberry production in the United States: experiences and opinions of growers in three regions, *HortTechnology*, 29, 619-628, 2019.
- Gullett, B. K., Wyrzykowska, B., Grandesso, E., Touati, A., Tabor, D. G., and Ochoa, G. S.: PCDD/F, PBDD/F, and PBDE emissions from open burning of a residential waste dump, *Environmental science & technology*, 44, 394-399, 2010.
- Hall, D., Wu, C.-Y., Hsu, Y.-M., Stormer, J., Engling, G., Capeto, K., Wang, J., Brown, S., Li, H.-W., and Yu, K.-M.: PAHs, carbonyls, VOCs and PM_{2.5} emission factors for pre-harvest burning of Florida sugarcane, *Atmospheric Environment*, 55, 164-172, 2012.
- Hernandez, L. M., Xu, E. G., Larsson, H. C. E., Tahara, R., Maisuria, V. B., and Tufenkji, N.: Plastic teabags release billions of microparticles and nanoparticles into tea, *Environmental science & technology*, 53, 12300-12310, 2019.
- Hochmuth, G., Hocmuth, B., and Olson, S.: New technologies in mulching for vegetable production in Florida, *CITRUS AND VEGETABLE MAGAZINE*, 34-37, 2002.
- Hodzic, A., Wiedinmyer, C., Salcedo, D., and Jimenez, J. L.: Impact of trash burning on air quality in Mexico City, *Environmental science & technology*, 46, 4950-4957, 2012.
- Hoffer, A., Jancsek-Turóczi, B., Tóth, Á., Kiss, G., Naghiu, A., Levei, E. A., Marmureanu, L., Machon, A., and Gelencsér, A.: Emission factors for PM₁₀ and polycyclic aromatic hydrocarbons (PAHs) from illegal burning of different types of municipal waste in households, *Atmospheric Chemistry and Physics*, 20, 16135-16144, 2020.
- Jayarathne, T., Stockwell, C. E., Bhave, P. V., Praveen, P. S., Rathnayake, C. M., Islam, M. R., Panday, A. K., Adhikari, S., Maharjan, R., and Goetz, J. D.: Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): emissions of particulate matter from wood-and dung-fueled cooking fires, garbage and crop residue burning, brick kilns, and other sources, *Atmospheric chemistry and physics*, 18, 2259-2286, 2018.
- Kajitani, S., Hara, S., and Matsuda, H.: Gasification rate analysis of coal char with a pressurized drop tube furnace, *Fuel*, 81, 539-546, 2002.
- Kasirajan, S. and Ngouajio, M.: Polyethylene and biodegradable mulches for agricultural applications: a review, *Agronomy for sustainable development*, 32, 501-529, 2012.
- Law, K. L. and Thompson, R. C.: Microplastics in the seas, *Science*, 345, 144-145, 2014.
- Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., and Pozzer, A.: The contribution of outdoor air pollution sources to premature mortality on a global scale, *Nature*, 525, 367-371, 2015.

Levitan, L.: Reducing dioxin emissions by recycling agricultural plastics: Creating viable alternatives to open burning, 2005,

Li, R. J., Li, L., Zhang, Y., Yang, J., Tu, C., Zhou, Q., Li, Y., and Luo, Y.: Uptake and accumulation of microplastics in a cereal plant wheat, *Chinese Science Bulletin*, 65, 2120-2127, 2020.

MarketsandMarkets: Agricultural Films Market by Type (LDPE, LLDPE, EVA, Reclaim, HDPE), Application (Greenhouse Film (Classic Greenhouse, Low Tunnel), Mulch Film (Black Mulches, Transparent Mulches), Silage Film (Silage Stretch Wrap, Silage Bag) - Global Forecast to 2029, 2024.

McMeeking, G. R., Kreidenweis, S. M., Baker, S., Carrico, C. M., Chow, J. C., Collett Jr, J. L., Hao, W. M., Holden, A. S., Kirchstetter, T. W., and Malm, W. C.: Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory, *Journal of Geophysical Research: Atmospheres*, 114, 2009.

Moore, J. and Wszelaki, A.: Plastic mulch in fruit and vegetable production: Challenges for disposal, Washington State University Extension Fact Sheet FA-2016, 2, 2016.

Ng, E.-L., Lwanga, E. H., Eldridge, S. M., Johnston, P., Hu, H.-W., Geissen, V., and Chen, D.: An overview of microplastic and nanoplastic pollution in agroecosystems, *Science of the total environment*, 627, 1377-1388, 2018.

Patel, S., Leavey, A., He, S., Fang, J., O'Malley, K., and Biswas, P.: Characterization of gaseous and particulate pollutants from gasification-based improved cookstoves, *Energy for Sustainable Development*, 32, 130-139, 2016.

Rochman, C. M.: Microplastics research—from sink to source, *Science*, 360, 28-29, 2018.

Shen, M., Hu, T., Huang, W., Song, B., Qin, M., Yi, H., Zeng, G., and Zhang, Y.: Can incineration completely eliminate plastic wastes? An investigation of microplastics and heavy metals in the bottom ash and fly ash from an incineration plant, *Science of the Total Environment*, 779, 146528, 2021.

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., and Schaumann, G. E.: Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation?, *Science of the total environment*, 550, 690-705, 2016.

Sullivan, A., Holden, A., Patterson, L., McMeeking, G., Kreidenweis, S., Malm, W., Hao, W., Wold, C., and Collett Jr, J.: A method for smoke marker measurements and its potential application for determining the contribution of biomass burning from wildfires and prescribed fires to ambient PM_{2.5} organic carbon, *Journal of Geophysical Research: Atmospheres*, 113, 2008.

Wang, X., Williams, B., Tang, Y., Huang, Y., Kong, L., Yang, X., and Biswas, P.: Characterization of organic aerosol produced during pulverized coal combustion in a drop tube furnace, *Atmospheric Chemistry and Physics*, 13, 10919-10932, 2013.

Wang, Z., Richter, H., Howard, J. B., Jordan, J., Carlson, J., and Levendis, Y. A.: Laboratory investigation of the products of the incomplete combustion of waste plastics and techniques for their minimization, *Industrial & engineering chemistry research*, 43, 2873-2886, 2004.

Wang, Z., Wang, J., Richter, H., Howard, J. B., Carlson, J., and Levendis, Y. A.: Comparative study on polycyclic aromatic hydrocarbons, light hydrocarbons, carbon monoxide, and particulate emissions from the combustion of polyethylene, polystyrene, and poly (vinyl chloride), *Energy & Fuels*, 17, 999-1013, 2003.

Wortman, S. E. and Lovell, S. T.: Environmental challenges threatening the growth of urban agriculture in the United States, *Journal of environmental quality*, 42, 1283-1294, 2013.

Wu, D., Li, Q., Shang, X., Liang, Y., Ding, X., Sun, H., Li, S., Wang, S., Chen, Y., and Chen, J.: Commodity plastic burning as a source of inhaled toxic aerosols, *Journal of Hazardous Materials*, 416, 125820, 2021.

Yang, D., Shi, H., Li, L., Li, J., Jabeen, K., and Kolandhasamy, P.: Microplastic pollution in table salts from China, *Environmental science & technology*, 49, 13622-13627, 2015.

Yu, Y. and Flury, M.: Current understanding of subsurface transport of micro-and nanoplastics in soil, *Vadose Zone Journal*, 20, e20108, 2021.

Zhang, H., Lan, D.-Y., Lü, F., Shao, L.-M., and He, P.-J.: Inhibition of chlorobenzenes formation by calcium oxide during solid waste incineration, *Journal of Hazardous Materials*, 400, 123321, 2020a.

Zhang, Q., Xu, E. G., Li, J., Chen, Q., Ma, L., Zeng, E. Y., and Shi, H.: A review of microplastics in table salt, drinking water, and air: direct human exposure, *Environmental science & technology*, 54, 3740-3751, 2020b.