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Collaborative Efforts to Investigate Emissions From Residential and Municipal Trash Burning in India

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Key Findings

- Research can benefit from collaborations that engage the combined efforts of students in the United States and internationally.
- Commercial drones can potentially be used to measure air quality over industrial areas or municipal dump sites.
- Plastic waste makes up a majority of residential and roadside refuse in Ahmedabad, Gujarat, India.

India in the 21st century is well known for notoriously high levels of particulate pollution. A diverse range of sources contributes to India's air pollution, with common culprits including biomass burning, industrial discharges, power generation, and traffic emissions.[1] One frequently overlooked yet highly prevalent source is trash burning. In Indian cities, 50% to 90% of trash may be collected from homes and businesses, but collected trash ends up in large municipal dump sites (which accumulate 35–45 million tons [~32–40 metric tons] of trash each year across India). Burning is typically the only removal method, as alternative waste management techniques can be costly or difficult to implement.[1] Waste that is not collected and transported to municipal sites is usually burned at or near residences and along roadsides. Since these burning activities often occur in close proximity to people, emissions from trash burning likely are a significant source of daily exposure to particulate matter. Although daily cumulative emissions generated by trash

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burning may be sizable, it is difficult to make representative estimates of emissions from localized burning activities since the locations of burns and the chemical signatures of emissions are highly variable.[2] Hence, residential-level trash burning has not yet been included in existing emissions inventories. In general, trash burning (municipal and nonmunicipal) has become an important focus in recent air-quality studies in India.

Students and researchers at Duke University and RTI International used a partnership with the Indian Institute of Technology (IIT) in Gandhinagar to address this gap in knowledge and to implement novel solutions for monitoring particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) generated by trash-burning activities. This transnational program aimed to give students real-world technical experience and to facilitate a better understanding of the important role that societal and cultural norms play in applying effective engineering solutions.

The local knowledge provided by IIT engineering students and faculty was crucial for effective experimental design and implementation of the presented work. Students generated novel ideas and low-cost approaches to address issues related to trash burning in India, with key projects focusing on (1) potential drone applications for monitoring air quality of large municipal sites with substantial trash-burning emissions and (2) low-cost methods to semiquantitatively assess performance of a small-scale trash combustor. This manuscript outlines these two projects as well as student reflections on the program and the general co-benefits of transnational partnerships in research. In summary, the objective was to investigate trash emissions in India by assessing applications of low-cost sensors and measurement techniques, and to demonstrate how international collaboration offers beneficial contributions to the research process.

Project 1: Assessing Landfill Emissions Using a Commercial Unmanned Aerial Vehicle

Methods of atmospheric data collection historically have relied on the use of ground monitoring stations, satellites, or sensors on balloons and manned aircrafts. Many of these techniques are costly, and some lack precision or are limited by low spatial or temporal resolution, or both. A promising resource with the potential to ameliorate some of these shortcomings is unmanned aerial vehicles (UAVs), or drones. UAVs have been used to measure atmospheric particles and gases since the early 2000s, and have provided researchers with opportunities to collect highly spatially resolved data as well as the capability to safely monitor air quality in areas that are difficult or dangerous to access (e.g., above volcanic plumes, near wildfires, or near industrial sources).[3]

UAVs comprise fixed-wing and rotary-wing aircrafts. As with planes and helicopters, UAVs require a runway or launch pad for takeoff and landing; rotary UAVs are capable of following discontinuous trajectories (i.e., hovering). Rotary UAVs, which are more commercially popular, are small, stable systems that can be transported easily, as the rotors are often removable. As their use has become more commonplace, commercial drones have become lighter, smaller, and more affordable. In addition, they are able to fly for longer durations and can support heavier loads.

Although the use of UAVs for air quality applications has been limited by considerations such as cultural appropriateness and regulatory differences across regions, if those complications can be addressed, there is clear potential for UAVs to improve research methods by increasing spatial mobility, reducing research costs, and shortening sampling time by decreasing the need for trained staff to manually collect data. Commercial drones also have become affordable and relatively simple to use, making them accessible to a wide range of researchers who would otherwise be inhibited by high cost and the lack of technical expertise required by traditional research drones. Hence, UAVs offer numerous potential opportunities to overcome various research barriers. One such opportunity may be using UAVs to safely and efficiently collect emissions data from trash burning.

Given the previously mentioned lack of available data needed to better characterize emissions from trash burning, the joint research team used a commercially available rotary UAV (DJI Phantom 3 Advanced) and sensor package developed at Duke University to measure air quality over residential burning activities as well as over an expansive municipal dump site (the Pirana landfill) in Ahmedabad, Gujarat, India. The sensor package used a light-scattering $PM_{2.5}$ sensor (Plantower PMS3003) that had previously been evaluated against research-grade reference monitors over different seasons and in both low- and high-PM environments (including in urban India).[4] Sensor packages documented minute-averaged concentrations of $PM_{2.5}$, and were powered by a small external battery pack (Figure 1). The UAV itself detected the elevation from ground level and carried a high-resolution camera capable of capturing both still images and video.

Although an initial objective was to measure emissions from trash burning at residential sites across Ahmedabad, the number of spectators the UAV attracted in public spaces limited the intended protocol. Buildings and narrow roadways

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Figure 1. Commercially available rotary unmanned aerial vehicle retrofitted with a low-cost sensor attachment

also posed possible hazards for people and equipment, resulting in the decision to forego residential monitoring. The municipal dump site, however, was located in a less-populated industrialized district. Approximately 80% of the 84-acre (34-hectare) landfill stands 65 to 80 feet (20 to 24 meters) high in solid waste; and more than 3,000 tons (2,700 metric tons) of new trash are added daily.[5] The terrain is characterized by steep slopes and smoldering debris, which self-ignites via slow pyrolysis when the heat generated inside the pile by exothermic reactions exceeds the rate of heat dissipation at the pile's surface. This becomes increasingly likely as landfill volume increases and the surface-to-volume ratio decreases.[6] Given the unstable nature of the site, as well as its sheer size, our team found the benefits of monitoring ambient air quality using a UAV to be clearly evident.

One central apprehension in using air quality sensors on commercial UAVs is the concern that the disruptive airflow caused by the rotary motion of the propellers may inaccurately represent ambient conditions (referred to as the "downwash effect").[7] However, in a recent study that examined pollutant levels in detonation plumes, researchers outfitted a fixed-wing UAV with fans (to simulate the downwash effect of rotary UAVs) and collected pollutant data with and without fan use; no significant differences were observed, indicating that the rotor downwash had minimal impact on pollutant measurements.[8] Thus, we did not expect the airflow from our commercial rotary UAV to significantly impact onboard PM measurements.

Prior field tests demonstrated that the added weight from the sensor package would not compromise UAV performance. Once on site, the student research team stationed the UAV on a roadside that bordered the landfill and then proceeded to complete multiple flight paths. $PM_{2.5}$ levels and site images collected by the UAV during one of these flight trajectories are shown in Figure 2. Over the course of a 10-minute flight, the UAV first traveled at constant elevation (33 feet [10 meters] above ground) along the site perimeter toward a visible plume. It hovered at the plume for 1 minute and then ascended to a height of 175 feet (53 meters) before finally returning to the takeoff location on the roadside. The onboard camera continuously recorded video and helped elucidate sources of observed PM spikes (e.g., vehicle traffic, suspended road dust, smoldering emissions, cigarette smoke from individuals standing nearby). The presence of the camera offers a distinct advantage for sensor systems, which otherwise would be unable to identify the sources of PM spikes that may be observed when retroactively analyzing the data from deployed sensors.

This work demonstrates a proof of concept that UAVs can be used to efficiently assess air pollution at landfills or industrial sites. Although the data presented here represent only a preliminary assessment of the particle emissions generated at the Pirana landfill, more extensive UAV data collection and pollutant modeling could be incorporated in future research efforts to better characterize the site. For example, by adding an onboard sensor for carbon dioxide (CO_2), we could calculate site emission factors. Additional combustion-relevant pollutants also could be measured, such as carbon monoxide (CO) and nitrogen oxides (NO_x). Overall, these data are especially relevant given the number of people working in

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Figure 2. Drone measurements of $PM_{2.5}$ over Ahmedabad dump site

Note: A $PM_{2.5}$ sensor attached to a commercial drone logged pollutant concentrations over the course of a 10-minute flight over a municipal dump site (the Pirana landfill) in Ahmedabad.

close proximity to the Pirana site, and the known contributions of air pollution to adverse health impacts. Further, although recent studies have highlighted the feasibility of collecting high-quality data in diverse environments using sensors on UAVs, the full range of applications of such equipment has yet to be seen.

Project 2: Insights on Localized Trash Burning and Combustor Performance

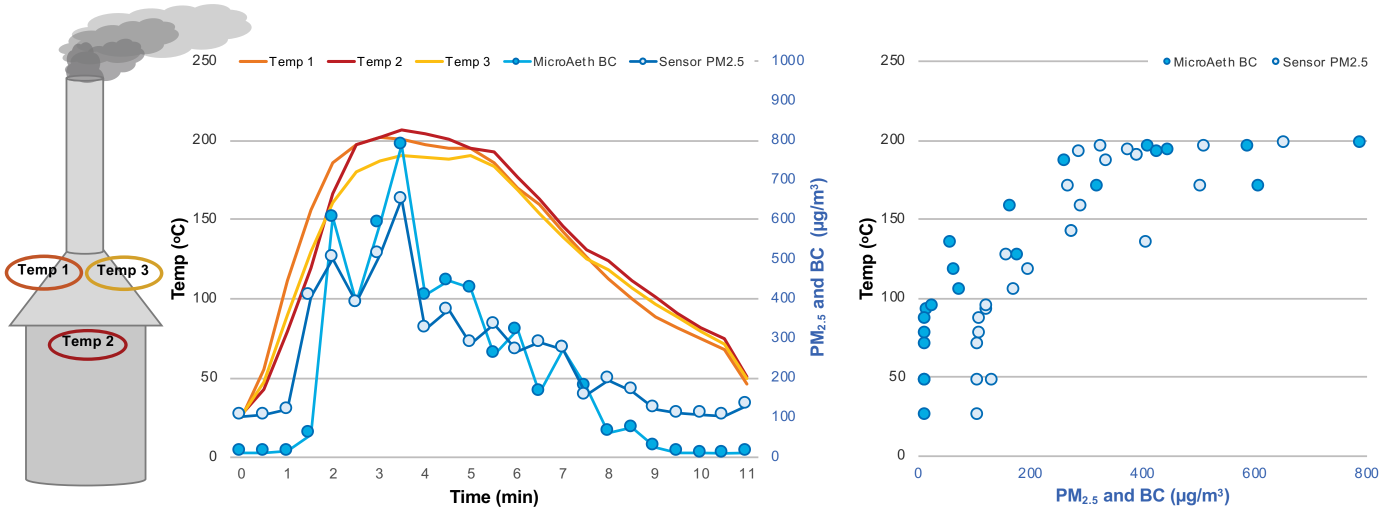
In the field, even small-scale trash burning piles with similar compositions have demonstrated vastly different emissions characteristics, due to variable combustion properties (i.e., lower temperature smoldering or higher temperature flaming).[2] To generate more consistent conditions—and to investigate potential mitigation from introducing small-scale incinerators—students used resources available on the IIT-Gandhinagar campus to construct a simple combustor prototype that could produce comparable combustion properties from one incineration event to the next.

A key step in this project involved in-person observations. Across the city of Ahmedabad, students observed residential and roadside burning practices and visually documented the composition of materials typically burned. Representative samples of trash also were collected at each visited site. The main categories of trash observed in burn piles were plastics, cloth, paper, and biomass.

At visited sites, plastic waste was the most prevalent component, with a site-wide average composition of approximately 60% plastics by volume (about 25% by mass). Of the types of plastic waste observed, approximately half was nonmetalized films (e.g., thin plastic bags), around 35% was metalized films or laminates (e.g., foil-lined food wrappers), and about 15% was harder plastics (e.g., water bottles, lids, containers). Using these proportions, “mixed plastic” piles ($N = 3$) were prepared and then burned in the combustor, and $PM_{2.5}$ and black carbon (BC) emissions were measured 1 foot (30 centimeters) from the stack. Thermocouples attached to the outer body of the combustor documented the temperature change over the course of each burn (Figure 3).

The mixed-plastic results shown in Figure 3 exemplify the types of experiments the students performed. The team assessed additional burn pile compositions ($N = 26$) using this incinerator and sensor setup (including nonplastic trash and homogenous material burns), although plastics were the central focus, due to their abundance.

Figure 3. Averaged black carbon and $PM_{2.5}$ stack emissions from mixed plastic burning events over time



Note: Averaged black carbon and $PM_{2.5}$ stack emissions (circles) from N = 3 "mixed plastic" burning events are shown over time (left-hand plot) and as a function of incinerator surface temperature (right-hand plot). (Mixed-plastic burn piles were composed of 50% plastic films, 35% foil snack wrappers, and 15% polyethylene terephthalate [PET] water bottles). Trendlines show mean temperatures measured by thermocouples, which were located on the outer body of the incinerator, as shown in the left-hand schematic.

To better understand the emissions characteristics of burning plastics, the student researchers burned as separate uniform piles the individual types of plastic (i.e., nonmetalized films, metalized films, and hard plastics represented by shredded plastic bottles) that made up the mixed-plastic piles. Nonmetalized films are typically polyethylene (PE), while metalized plastic wrappers are frequently composed of polypropylene (PP), polyethylene terephthalate (PET), and polyamide (or nylon) films. The foil layer, which is typically aluminum, protects against light and oxygen infiltration. Film packaging for perishable foods may also include polyvinylidene dichloride (PVDC) or ethylene vinyl alcohol (EVOH) as an oxygen barrier.

The students observed that nonmetalized plastic films burned quickly and completely, and rarely increased PM and BC concentrations above ambient levels. Of the three types of plastics burned, the metalized films (i.e., foil food wrappers) burned hottest, which was not unexpected since metalized films tend to be highly flammable. Shredded plastic bottles generated the most emissions and took the longest time to burn out compared with all other pile types (plastic and nonplastic).

Over the course of each burning event, emissions and incinerator temperature followed similar overall trends, with both showing rapid increases in the early stages of the burn when materials first heated up, generating vapors which then widely ignited. The explicit association between temperature and emissions typically followed a logarithmic-style relationship (Figure 3, *right-side* plot), where the lowest temperature points are the ambient PM and BC concentrations (effectively equivalent to the projected *x*-intercept), and plateauing indicates the range of emissions generated near peak temperature. The peak temperature where this plateauing occurs is indicative of the heat that a given fuel source transferred to the incinerator walls, provided that the environmental and incinerator parameters remained constant.

We attributed the wide distribution of emissions occurring at or near peak temperature to incomplete combustion processes, such as the incursion of oxygen from outside the combustor or internal mixing of fuels. For burning events that used identical fuel mixtures, the emissions results convey the variability in the combustion process between runs.

This sensor and thermocouple setup could offer quick insights to incinerator designers. For example, the collected data could highlight how peak emissions increase or decrease as design parameters (such as airflow and fuel type) are altered. Moreover, the low cost of the apparatus offers the advantage of affordability, which is an important consideration for designing trash incinerators at a neighborhood rather than bench or pilot scale.

Summary and Future Benefits

Although trash burning is a common practice across India, measuring emissions has proved challenging, and data that characterize trash burning emissions are limited. To begin to address some of these hurdles, students and researchers in the US and India combined their efforts to investigate potential applications for improving measurements of trash emissions. Importantly, this research greatly benefited from the collaboration between US and Indian students and researchers.

For this effort, the research team exhibited how commercial UAVs with low-cost sensor attachments could be used to estimate air quality over a large municipal dump site. Future efforts could use UAVs to collect highly spatially resolved data over expansive industrial sites. UAV monitoring could be enhanced by incorporating sensors for additional pollutants, such as CO_2, which could be used to estimate site-wide emissions factors.

In addition, the students built a small-scale combustor to observe emissions characteristics of typical compositions of roadside or residential trash piles, and uncovered possible future benefits to using thermocouples and low-cost sensors in iterative small-scale combustor development. This work demonstrated the use of low-cost sensors to measure trash-burning emissions.

Finally, the joint team learned of definitive benefits to collaborating across national borders, including expanding research networks, accessing otherwise unavailable funding sources, sharing resources, and benefiting from resident actors who were well-versed in local languages and societal contexts, which frequently challenge external researchers unfamiliar with local customs. While much of the collaboration was done virtually, there were additional benefits from face-to-face contact, which encouraged the development of collegial relationships that often underpin the successful completion of such research projects.[9]

For example, in the 5 months before the entire group convened in India, students and researchers from Duke, IIT, and RTI held biweekly meetings online to discuss project progress. Duke students assembled and calibrated $PM_{2.5}$ sensors, which were then sent to India, where IIT students conducted preliminary burn tests to preemptively address any challenges that they might encounter while measuring emissions from trash burning. This allowed techniques to be revised and improved before the Duke researchers' arrival in India.

In addition, IIT students used socioeconomic and population data to select a diverse range of wards across Ahmedabad for monitoring emissions, and then explored the wards in person to confirm that the sites were accessible and to talk to residents about local burn practices. During the same period, Duke students designed and constructed trash combustor prototypes to better understand waste combustion properties, and investigated the use of drones for air quality monitoring applications. There were dual benefits in involving undergraduate students with the research process in that (1) time and cost were reduced, in addition to lightening the workload for faculty and senior-level researchers; and (2) the students personally gained valuable experience that cannot be learned in a classroom. For most students, it was a first foray into direct scientific research. All students saw clear benefits from collaborating:

> "We came from different schools, cultures, disciplines, and personal backgrounds, which enabled us to offer a wide variety of assets to the team. It was a rewarding experience because everyone approached the research questions with different strategies and perspectives."
>
> —Emily Shannon (Duke University)

> "Working on this collaborative project also allowed knowledge sharing that wouldn't have been possible sitting in a classroom . . . Interacting with students and professors from different institutions was a learning experience for me. It exposed me to the culture, work ethic, and lifestyle of students in different institutions. For example, the confidence and ability of students at Duke to take calculated risks and go beyond their comfort zone to pursue their passion was something I felt students like me should pursue."
>
> —Ayushman Tripathi (IIT–Gandhinagar)

> "From this experience, I have gained a new understanding and appreciation for cross-cultural and hands-on international partnerships, as the different backgrounds of team members can provide entirely new insights and directions to the project at hand."
>
> —Jaya Pokuri (Duke University)

There are measurable advantages, especially in the hard sciences, for countries such as India with emerging economies to collaborate with countries that historically have had a high scientific impact, such as the United States.[10] Such collaboration increases the scientific impact of research and also tends to increase the number of citations the research receives—in part due to a larger network of people who can access the research; and it can improve research quality and best practices.[10]

As examples, during this initiative, IIT students and researchers were able to incorporate Duke-developed sensor packages with a UAV—equipment that may not have been easily accessible otherwise—and demonstrate the feasibility of using UAV air sensors in industrial settings. Researchers at all three institutions offered a wide range of expertise that laid the foundations for this joint project and has continued to facilitate joint research opportunities. Perhaps most importantly, this initiative brought together students and young professionals who were passionate about solving environmental challenges, and provided them with invaluable exposure to research in a collaborative international setting. Partnerships like this one among Duke, IIT, and RTI offer strong incentives for other institutions to seek out similar collaborations.

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