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India: Crop Residue: A Burning Problem

I was visiting my grandmother over Thanksgiving break, and as soon as we disembarked at New Delhi's Indira Gandhi International Airport, I started to cough. We were surrounded by thick smog. Later, as we were sitting in her living room with the windows closed and an air purifier running in the background, she told us we were lucky our plane had been able to land. This time of year, flights are often diverted because the visibility on the runway is too low. Schools shut down, offices close, and the city comes to a standstill. This hazardous air pollution is not from vehicle and factory emissions, but from crop stubble burning in the agricultural belt north of the city.

India, with a population of about 1.46 billion, is the world's most populated country (UN estimates). Two thirds of its people live in rural areas. The average household size is ~4.4 people (Census NFHS data). Family structure, as well as educational and job opportunities can differ greatly between rural and urban settings. Urban families are mostly nuclear whereas rural families are multigenerational. It is common for three generations of a family to live together to help with elder and childcare. In rural areas jobs are agriculture-based, with monthly earnings of $120-$180 depending on the harvest. Lack of jobs and economic uncertainty has led to rural youth migrating to urban cities. In urban areas jobs are mostly in manufacturing, trade, transport, and services, with monthly earnings of around $180-$300. Bigger cities offer well-paying jobs in multinational corporations for highly skilled and educated workers. Families in states like Punjab also rely on remittances from relatives in Canada, the United Kingdom, the United States, and the Gulf countries.

Government initiatives through the years have vastly improved infrastructure, including universal access to toilets, clean potable water, and electricity (though power cuts can be common). Mobile phones are widespread, and internet access is improving rapidly. Roads are generally well-maintained, and highways connect major cities. Still, there is still a big rural-urban divide when it comes to infrastructure, education, healthcare, and economic opportunities.

A typical Indian diet is plant and dairy based. Staple foods are wheat rotis and paranthas, rice, and lentils. Dairy is widely consumed in the form of milk, cottage cheese (panner), and yogurt, and seasonal vegetables include cauliflower, spinach, potatoes, and okra. Non-vegetarian options include chicken, fish, and goat, but these can be limited due to cost and religious beliefs. The cow is considered sacred by the Hindu majority and consumption of beef is banned. There is a nutrition gap where calories are sufficient but protein, vitamins, and minerals like iron are lacking, causing childhood anemia and growth stunting

India is the second largest agriculture-based economy in the world. The agricultural sector is the largest employer, consisting of about 40% of India's workforce (FAO data). About 50% of land is arable, but farm holdings are small, and family-based (World Bank). The average holding size is only 2.6 acres,

compared to 400-500 acres of a typical Iowa farm. It can be hard to make a profit because of limited mechanization, decreased productivity, and limited access to markets and finance.

Major crops include rice, wheat, cotton, and sugarcane. India is self-sufficient in staples like wheat and rice and even has a 20% export surplus. Despite this 40% of the population suffers from moderate to severe food insecurity. This is about 307.7 million people (FAO data). This is India's '*paradox of plenty*.' India's Public Distribution System, which is meant to channel subsidized grain to the poor, is riddled with leakage. Wheat and rice are calorie-dense but nutritionally shallow. More than half of poor Indian households rely on cereal as their primary protein source. Unique to India, with its Hindu majority, are religious dietary restrictions, which result in large numbers of people being vegetarian or strictly vegan. This, combined with inadequate protein from non-animal sources, can exacerbate protein deficiency.

For a predominantly agriculture-based economy, sustainable management of agricultural waste can be a challenge. This is especially true for India in the context of rice and wheat crop stubble. India has a crop cycle of rice in the summer and wheat in the winter. Rice is water intensive, so by law, rice planting can only happen after the monsoons, typically late June, to save ground water. Once rice is harvested by early November, wheat sowing begins within 2-3 weeks so that the yield can be protected before temperatures rise in the spring. There is a very short window to turn the crops around. After harvesting rice, about 8-10 inches of stubble remains on the field. Crop residue is a natural resource that can contribute to soil stability and fertility by being ploughed directly into the soil and being composted. It can also increase irrigation efficiency by holding onto ground water and helps prevent topsoil erosion. But the fastest and cheapest way to get rid of rice stubble is to burn it. The domino effect of crop stubble burning on public health and food insecurity is the focus of my essay.

Geographically, India has the Himalayan Mountain ranges in the north leading down to the Indo-Gangetic plain. Seasonal climate patterns exacerbate the problem of air pollution from stubble burning. This is particularly problematic in the months of October to December. The capital, Delhi, is downwind from the northern farming states of Punjab and Haryana, and as the post monsoon winds shift northwesterly, they blow smoke directly toward it. November also brings on temperature inversion. The nights become cooler, but the ground is still warm from the day. A layer of warm air traps the cooler air near the ground and acts like a lid, trapping smoke. The particulate matter from vehicle exhaust and factory emissions also clings to the smoke further preventing it from dispersing upwards. As a result, these pollutants accumulate close to breathing level. As the air flows, pollution spreads to neighboring countries like Pakistan, Nepal, and Bangladesh.

India is a federal parliamentary republic with a central (federal) government and state governments. Agricultural policy is formulated at both the national and state level. The central governing party controls environmental policy, subsidies, and farm laws, but regional parties often control state governments. To tackle the pollution from burning crop residue that affects the capital Delhi but starts in the northern states of Punjab and Haryana, there needs to be political co-operation between the federal and state governments. This involves taking decisions that can work against narrow self-interests of powerful regional voting blocks.

Food insecurity from stubble burning arises from the complex interplay of its impact on soil, air, water, labor, and household health and economics.

About 25% of total crop residue is burnt on the farm and it releases carbon dioxide, black carbon (soot), and other greenhouse gases. This causes climate change and weather disruption and contributes to global warming. Heat stress causes irregular rainfall. This increases drought risk, which is especially devastating in a country like India which relies heavily on monsoon rains. Furthermore, the smoke and particulate matter reduce sunlight reaching crops. Lower solar radiation slows photosynthesis in winter wheat and vegetables planted right after the rice harvest. Unpredictable harvests lead to unstable food availability.

Crop residue burning also releases particulate matter (PM). These lightweight particles, classified as PM 2.5, stay suspended in the air, and they can travel long distances with the wind. When inhaled, they cause lung problems and enter the blood stream. PM in Delhi from crop residue burning is 17 times that from all other sources such as vehicle emissions, garbage burning, and industrial activity (Ministry of Earth Sciences; SAFAR). The WHO standards for permissible levels of PM 2.5 in the air is 5 ug/m3, but levels of 90 or greater are not uncommon in Delhi during the winter. The public health implications are immense. The Global Burden of Disease study reported that over 1.6 million premature deaths were attributed to long-term exposure to air pollution in India in 2019, accounting for 17.8% of total deaths. Lost output from premature deaths and morbidity attributable to air pollution accounted for economic losses of US $36.8 billion, 1.36% of India's gross domestic product (India State-Level Disease Burden Initiative Air Pollution Collaborators). PM increase risk of respiratory diseases including asthma and cardiovascular diseases. Sick agricultural laborers can't work the fields and sick household earners lose income exacerbating "*medical impoverishment*."

Children exposed to high particulate matter show stunted growth and impaired nutrient absorption. Even when food is available, their bodies utilize it less effectively. This is undernutrition driven by pollution rather than by lack of calories.

Crop stubble burning releases nitrogen oxides and volatile organic compounds that react with sunlight to form surface level ozone. When wheat plants breathe, ozone enters through their pores "*stomata*" and damages the plant's photosynthetic machinery, causes leaves to yellow and decay prematurely, and forces the plant to divert energy from making grain to repairing oxidative damage. Counterintuitively, irrigated or watered wheat is affected more, since the pores are open more widely and therefore more of the ozone can enter. The net effect is smaller grains, fewer grains per head, and lower overall yield. It is estimated that wheat production losses in 2021 from surface ozone pollution could have fulfilled the wheat requirements of 11.4 million people (Dewan and Lekhani).

Heat from burning causes continuous deterioration in soil fertility by depleting the bacteria and fungi in the soil and removing substantial amounts of organic matter. The carbon-nitrogen equilibrium of soil is lost. The lower the soil fertility, the lower the crop yield. Farmers must use more chemical fertilizer, irrigate more, and spend more on soil restoration. The higher the input costs, the higher the food prices. All the above factors set up a cycle of food insecurity that can be difficult to break.

Since 2015, burning residue is banned and punishable by fines but clearly this has not worked. Innovative solutions include The Harnessing the power of Agricultural Residues through Innovative Technologies (HARIT) project, launched in 2019, which aims to encourage farmers to use a new stubble-clearance tool called the Happy Seeder. The machine cuts and lifts the straw while simultaneously sowing the next crop. This process leaves the residue on the soil surface where it decomposes naturally,

improving soil moisture and organic matter. The limiting factor is its cost ($1200-$3000) though the government offers subsidies to help cover part of it (The Nature Conservancy India).

Another strategy would be to financially incentivize farmers to not burn crop residue through the Payment for Ecosystems Services Program. A 2024 study by the Economic Growth Center and the Yale School of Economics found that financial incentives in the form of partial upfront payments reduced crop residue burning by around 10% (Yale Economic Growth Center and Inclusion Economics). Upfront cash helps build trust and eases liquidity issues like money needed to rent machinery like the Happy Seeder.

My solution involves using specialized satellite technology to identify areas of crop stubble burning coupled with strict on the ground local law enforcement.

Orbital satellites can be polar or geostationary. A polar satellite is closer to the earth and flies roughly north-to-south over the poles while the Earth rotates underneath it. Most polar satellites use a special path called a sun-synchronous orbit. This means they cross over the exact same spot at the same local time every day so if one pass happens at 1:30 PM (daytime) the next will be at 1:30 AM (nighttime). This makes their ground checks rather predictable; a fact that has been noticed by farmers in India. Geostationary satellites are nearly six earth radii out, fixed at the same spot and collect data every ten minutes; better frequency comes at the cost of worse resolution.

Satellite data was first used in the 1970s to monitor plant health and biomass by calculating a number called The Normalized Difference Vegetation Index (NDVI). Red light is absorbed by green leaves, near-infrared light is bounced back by healthy plants and the normalized ratio helps remove variables like sun angle, time of day, season, terrain slope, and atmospheric haze. Values range from minus one to plus one. High values mean thick, green, healthy plants; Low values mean bare soil, water, or dead plants. The limitation is harvested, burned, plowed, or drought-stressed all read as "less vegetation" (Rouse et al.). Currently, NDVI values are followed sequentially, and post-burn tracking looks for an abrupt drop in the NDVI value.

Tracking fires in real time seems like a better strategy than following the NDVI number, and so in the early 2000s, optical satellites began to be fitted with thermal sensors to enhance their ability to detect active fires. These include MODIS (on NASA's Aqua/Terra) and VIIRS (on Suomi-NPP and NOAA-20). Active fires are much hotter than surrounding fields and show up as anomalies in thermal-infrared bands. Infrared imagers detect these heat anomalies, giving a fire count for an area and distinguishing fires by intensity. Each fire pixel carries coordinates, which are then matched against land records to identify the specific plot and owner. The state of Punjab where the problem is quite acute, runs control rooms that flag incidents in near-real time and notify the Sub-Divisional Magistrate, who dispatches a team to the field. Penalties and sanctions including baring a farmer from taking loans against the land, selling or mortgaging it, or holding a gun license.

Using the above approach, the official thermal fire counts dropped dramatically, yet air pollution in Delhi remained severe. The actual burnt area had only decreased by 25% to 35% (International Forum for Environment, Sustainability and Technology). While polar satellites provided resolution and global coverage, it came at the cost of predictable checks which for India are between 11:30-2:30 pm. To slip detection, farmers have now shifted burning to between 4 and 6 pm; the polar orbiters that have the resolution to see individual fields simply aren't overhead then, and the geostationary satellite that is watching continuously has too coarse a resolution for a two-hectare plot. Currently, optical satellites are

the preferred way to aerially monitor crop stubble burning in India. We need an approach that helps us look closely at what is left on the ground rather than catching fires in real time.

Assessing burnt areas on the ground helps quantify the problem better than the thermal fire count. The Normalized Burn Ratio (NBR) is a satellite remote sensing index specifically designed to highlight burnt areas and estimate fire severity. It is better than NDVI (Normalized Difference Vegetation Index) for fire analysis because it uses Shortwave Infrared (SWIR) and Near-Infrared (NIR) bands, making it directly sensitive to burnt soil, char, and moisture loss rather than just live green chlorophyll. NBR is custom-built to detect fire scars and char. Burned material absorbs NIR light and strongly reflects SWIR light, which are the exact opposite reactions seen in healthy plants. Combining these two bands maximizes the spectral contrast of a fire zone. NBR's inclusion of SWIR helps isolate the distinct moisture loss and mineral ash signature left by fire. By comparing pre-fire and post-fire NBR images specialists can accurately grade burn severity across light, moderate, and high categories (McCarty et al).

Since northern India suffers from heavy smog, haze, and cloud cover during the October to November harvest, we need to combine the NBR with a tool that can penetrate clouds and smoke and see even at night. My solution is Radar.

All weather radar satellites send microwave signals down to Earth and measure the signal that bounces back. Tall stubble reflects radar signals strongly. Post burning the surface appears smoother and darker. Radar sensors detect this change in backscatter, allowing scientists to identify burned areas even when smoke or clouds are present (Kumari et al.). Currently radar is used for flood mapping, deforestation surveillance, and ground deformation monitoring that results from earthquakes or fault movements.

Synthetic Aperture Radar (SAR) is uniquely positioned to fill the gaps from optical and thermal sensors that get blocked by thick smoke, haze, or cloud cover. SAR actively emits microwave signals and measures the backscattered echo, meaning it maps the terrain clearly day or night through any atmospheric obstruction. Burning alters the physical structure of a field. It changes the micro-topography, moisture, and roughness of the soil and remaining residue. SAR backscatter intensity drops or shifts distinctively when uniform stubble is converted into smooth ash or bare charred soil. Pre- and post-fire SAR comparisons can also accurately estimate the volume of crop residue left on fields and the proportion consumed by fire by measuring biomass changes over time.

Radar data is already available from satellites such as Sentinel-1 and NISAR minimizing equipment costs. Since radar images are harder to interpret, India will need to invest in machine learning models that need advanced computing, specialized software, and trained analysts. This should not be difficult for a technology intensive country like India. The Council on Energy, Environment and Water and academic institutions are testing machine learning foundation models trained specifically on Indian agricultural landscapes to automate radar burn scar detection down to the individual plot level (Ignatious et al.).

Despite its advantages, radar imagery is not yet a standalone real-time enforcement tool. While radar can see through smoke, satellites like Sentinel-1 only pass over the same spot in India every few days, making it difficult to generate immediate daily alerts. Differentiating a partially burnt field from a

fully harvested field that was manually cleared remains difficult, keeping current algorithm accuracy around 60% for specific field conditions.

A hybrid model combining radar burn scar tracking, geostationary satellites for continuous daytime viewing, and low-altitude night-flying drones to monitor fields in real-time would be ideal. Also, rather than implement radar monitoring nationwide, India could start with pilot programs in areas where stubble burning is common like Punjab and Haryana and pair radar satellites with optical-thermal sensing satellites. Better still, the government could integrate radar monitoring with incentive programs like subsidies for the Happy Seeder machines and the Payments for Ecosystem Services program to confirm compliance. Given the complexity of the problem and limitations of each specific solution a complementary approach that works to each technology's strengths and covers individual weaknesses is needed.

Farmers burn crop stubble because they feel pressurized to grow more food and grow it faster; yet this threatens the very ecosystems that agriculture depends on. Solutions include incentive programs like the upfront partial payment for ecosystems, technology like the happy seeder and stringent laws coupled with strict on the ground enforcement supported by data from optical satellites enhanced by all weather radar sensing.

In conclusion, crop residue burning impacts the environmental and agricultural sectors with long term negative consequences for the economy and public health. It undermines sustainable agricultural practices and exacerbates food insecurity by affecting the quality of soil, air, water, and the workforce's health, which in turn adversely impacts the quality and quantity of food produced. We need creative solutions and partnerships between different agencies to help solve this burning problem.

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