RESEARCH PAPER

Air Pollution and Greenhouse Gas Emissions from the Agricultural Sector in South and Southeast Asia

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Cover page photo: Tribhuvan University, Nepal

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Executive Summary

In recent decades, high air pollutant concentrations in South and Southeast Asian countries have meant that they consistently dominate top positions in world rankings of the poorest air quality. The sources of these air pollutants vary from country to country, province to province, and city to city. However, a constant underlying source, particularly in agrarian communities during the dry/post-harvest season, is the burning of biomass waste such as straw left behind in fields from the cultivation of rice crops. While quick and efficient, burning can negatively impact climate, human health, soil health, and economies while accentuating geographical disparities and having disproportionately large adverse consequences for vulnerable groups including rural women and children. Furthermore, these fires can easily spread to become uncontrollable wildfires, which both ravage the landscape and add immense amounts of Greenhouse Gases and air pollutants to the atmosphere.

The practice of biomass burning of post-harvest straw residue is a particular phenomenon occurring in these sub-regions, rooted in traditional practices, and continued due to a lack of awareness or the resources to make changes needed to protect their communities from the harmful effects of air pollution. Recommended solutions to provide the appropriate interventions to prevent open biomass burning are as follows:

1. **Cooperation**

For the two sub-regions to successfully combat climate change, cooperation is necessary between countries, local governments and sectors, wherein harmonized standards are set and pacts are made to strive towards global goals. Political will, government leadership, an intersectoral approach and coordination among nations and partners are critical to ensure the effectiveness and efficiency of the measures.

2. **Monitoring and Modelling**

Air pollution comes from various sources, and because of that, the first step in air quality management needs to be source identification and appointment through measuring and monitoring. Next, innovative data modelling and the deployment of emerging technologies to identify air pollution hotspots are necessary to formulate informed and efficient policies.

3. **Sustainable Agricultural Mechanization**

Sustainable agricultural mechanization is a critical step to increasing food security, protecting livelihoods, and combating climate change. Sustainable agricultural mechanization technologies range from hand tools and techniques such as no-till farming to more sophisticated means, such as equipment which converts bio-waste to bio-gas or bio-char, and to advanced technologies in which power sources are diversified. Further promotion of mechanization is needed throughout the agricultural sector, from large commercial production farms to smallholder farms that are often family-run. However, smallholder farms will need the maximum support in this transition, as they face the most economic and societal barriers.

By finding ways to avoid open biomass burning and reduce the amount of air pollutants and GHGs emitted from unsustainable agricultural practices, countries can save lives, protect the environment, and improve the overall productivity of their agriculture sectors. It will help uphold their commitment to the 2015 Paris Accords while contributing toward the attainment of the Sustainable Development Goals.

1. Introduction

"Improving the quality of the air we breathe is absolutely necessary to our health and well-being. It is also critical to food security, climate action, responsible production, and consumption – and fundamental to equality. In fact, we can't talk about the 2030 Agenda for Sustainable Development unless we are serious about air quality."

--- *Helena Molin Valdés, Head of the United Nations Environment Programme (UNEP) and Head of the Climate and Clean Air Coalition Secretariat from 2013 to 2021 (UNEP, 2022)*

Exposure to air pollution is now considered the greatest environmental risk to human health, with around seven million premature deaths attributed to it annually, including over 700,000 children (GBD, 2020). Air pollution is intrinsically linked to climate change because air pollutants tend to be emitted alongside greenhouse gases (GHGs), such as carbon dioxide (CO_2). In addition, some air pollutants can modify the Earth's climate on timescales that are much shorter than GHGs. Moreover, air pollution can undermine economic growth due to the cost of illness and loss of labour, and can act to damage plants and impede growth, thus depleting crop yields. The consequences of air pollution further stratify existing inequalities, impacting vulnerable groups the most dramatically due to economic, social, and geographic disparities.

Air pollution comes from a wide variety of sources, the main sources typically include industrial processes, residential cooking and heating (particularly involving solid-fuel combustion), transport, power generation, agricultural activities, construction, and natural sources (such as volcanos, desert dust, and biological sources). In South and Southeast Asia, another major source of air pollutants, such as Particulate Matter (PM), is the agricultural practices of burning to dispose of post-harvest waste and to clear land for the next planting season.

This Research Paper, Air Pollution and Greenhouse Gas Emissions from the Agricultural Sector in South and Southeast Asia, hereby known as the 'Paper', examines why agricultural biomass burning is a crucial issue for two sub-regions within the Asia-Pacific region, namely South and Southeast Asia, and how these emissions impact climate change, health, environment, and economy, particularly in the Least Developed Countries (LDCs). The Paper explores some of the fundamental reasons air quality issues persist and offers solutions, including leveraging regional cooperation, advanced monitoring techniques, and efficient mechanization.

Reducing air pollution emissions from the agricultural sector will help countries uphold their commitment to the 2015 Paris Accords and other global conventions and standards to tackle climate change. It will also contribute toward the attainment of the Sustainable Development Goals (SDGs) enshrined in the 2030 Agenda for Sustainable Development, particularly SDG 2 (Zero Hunger) target 2.4 (ensure sustainable food production systems), SDG 1 (No Poverty) target 1.4 (poor have equal access to appropriate new technology), SDG 12 (Responsible Consumption and Production) target 12.2 (promote efficient use of natural resources), and SDG 13 (Climate Action) target 13.1 (strengthening adaptive capacity to climate-related hazards).

This Paper uses the 2021 WHO Guidelines on Air Pollution. Since 1987, WHO has periodically issued health-based air quality guidelines to assist governments and civil society reduce human exposure to air pollution, the last update came after a 15-year hiatus and was released in September 2021 (World Health Organization, 2021). In this recent update, the WHO dramatically tightened their air quality guideline (AQG) levels (Table 1) based on emerging evidence on the health impacts of air pollution exposure, even for short amounts of time. In the case of PM2.5 exposure, they have cut recommended levels in half, lowering the average maximum exposure from ten micrograms per cubic meter per year to five. They also tightened the limits for gaseous air pollutants (i.e., nitrogen dioxide (NO_2)), cutting it down by one-quarter of previous recommendations, from 40 to 10 micrograms per cubic meter.

Currently, most countries in the two sub-region exceed the old maximum recommended amounts regularly – therefore, they must work twice as hard to meet the new limits. To rise to this new challenge, swift, immediate action is required in South and Southeast Asia to avoid the dramatic and worsening consequences of dirty air.

Table 1: Recommended AQG levels and interim targets

Pollutant	Averaging time	Interim target				AQG level
		1	2	3	4	
$PM_{2.5}$, µg/m³	Annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15
PM_{10}, µg/m³	Annual	70	50	30	20	15
	24-hour[a]	150	100	75	50	45
O_3, µg/m³	Peak season[b]	100	70	–	–	60
	8-hour[a]	160	120	–	–	100
NO_2, µg/m³	Annual	40	30	20	–	10
	24-hour[a]	120	50	–	–	25
SO_2, µg/m³	24-hour[a]	125	50	–	–	40
CO, mg/m³	24-hour[a]	7	–	–	–	4

[a] 99th percentile (i.e. 3–4 exceedance days per year).
[b] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

Source: World Health Organization (2021)

This Paper is intended for the farming sector members and change agents (i.e., lead farmers, CSOs, local enterprises, extension personnel), policymakers responsible for agriculture and air quality management, and the environmental community.

2. Air Pollution in South and Southeast Asia

Globally 17 billion years of life are lost yearly due to air pollution, with an average of 2.2 years lost per person. This is greater than the effects of infectious diseases like tuberculosis and HIV/AIDS or behavioural killers like cigarette smoking and unsafe war combined (Greenstone, 2022). In Southeast Asia, that average jumps to 3-4 years and in South Asia, 5 years –even higher in polluted hotspots; for example, Delhi, India, where residents suffer a 9-year loss of life from air pollution. So, while ensuring clean air is a global priority, it is a crucial topic in South and Southeast Asia, where populations disproportionally experience unhealthy air. This is particularly true in the Least Developed Countries (LDCs) throughout both sub-regions due to societal, geographic, and economic disparities.

Neither sub-region experienced improved air quality through the COVID-19 Pandemic lockdowns as hoped for and instead experienced increased emissions and exposure rates. For example, in Thailand, where air pollution is often blamed solely on traffic, their air pollution levels grew by 25.8 per cent, while travel rates were historically low. This indicates that there are other important factors driving air pollution emissions.

South Asia

Bangladesh, Bhutan, India, Pakistan, Nepal, Sri Lanka
The South Asian Sub-Region consists of the Indo-Gangetic Plain and peninsular India. The region is defined by high and rugged mountains and a diverse and extensive coastline. While only consuming 3.5 per cent of the world's surface, it is home to about one-fourth of the entire population, making it the most populous and densely populated region on earth. And since 2010, 700 million individuals, about half of the South Asian population, have been affected by at least one climate-related disaster, such as earthquakes, mudslides, and wildfires (Abdul Jabbar, 2022).

South Asia is also home to the top four (India, Pakistan, Bangladesh, and Nepal) of the five most polluted countries. According to the World Air Quality Report in 2020, 37 out of 40 of the top-most polluted cities in the world are scattered throughout this diverse region (Abdul Jabbar, 2022). This has made a concentrated issue in the region; while only 25 per cent of the global population lives here, 52 per cent of the life loss from air pollution happens in South Asia (Greenstone, 2022).

Currently, air pollution is the second-highest risk factor for adverse health outcomes and third-highest risk indicator for premature death contributing to 11 per cent of premature deaths and leading to 40 million disability-adjusted life years in South Asia, with the bulk of the disease burden attributed to Particulate Matter (PM) (Abdul Jabbar, 2022). The effects of ambient air pollution on pregnancy losses are an estimated 349,681 annually across Bangladesh, India, and Pakistan alone. By 2050, if changes are not made, air quality is expected to directly dimension the lives of over 800 million people in the sub-region (Abdul Jabbar, 2022).

Vehicles are the core of the issue for the elevated levels of pollution in the region year-round. However, as the monsoon ends each winter, severe spikes, particularly in BC and PM, are experienced throughout the region. This happens as farmers throughout the region set debris from harvest ablaze across thousands of hectares of agricultural land.

Southeast Asia

Brunei, Myanmar, Cambodia, Timor-Leste, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand, Viet Nam

The Southeast Asian sub-region consists of eleven countries between the tropics, stretching from eastern India to China. Geographically the region can be divided into "mainland" and "island" zones. The mainland zone (Myanmar, Thailand, Laos, Cambodia, Viet Nam, Peninsular Malaysia) are an extension of the Asian continent. The island zone (Brunei, East Malaysia, Timor-Leste, Indonesia, Philippines, Singapore) is an archipelago with large islands, like Borneo, and pinpoints, as seen scatted across Indonesia's over 17,000 isles.

And while Southeast Asia only covers about 3 per cent of the earth's total surface, it holds 8.5 per cent of the global population and is responsible for almost 30 per cent of the world's rice harvest.

It is estimated that 99.9 per cent of Southeast Asia's roughly 675 million people now live in areas where particulate pollution exceeds the revised WHO guideline of 5 $\mu g/m^3$, which causes 959.8 million person-years lost annually in the region (Greenstone, 2022). Particularly in their rapidly urbanizing areas, such as Mandalay, Hanoi, Chiang Mai, and Jakarta, where significant peaks of Particulate Matter (PM) pollutants spike during the dry, cool winter months (Greenstone, 2022). In many cases, this pollution becomes so extreme that views are obscured by smog, masks are essential - particularly for vulnerable groups, and schools cancel classes.

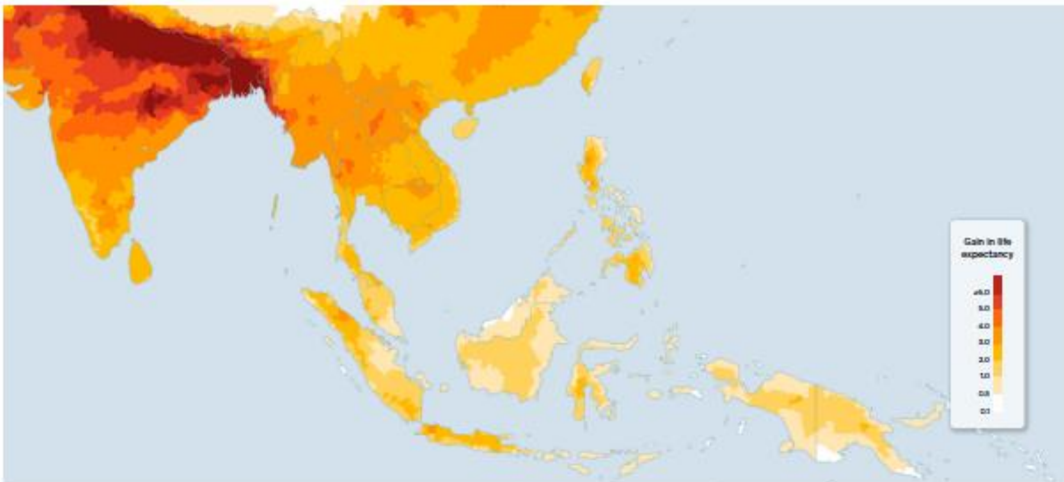
While the underlying sources of air pollution year-round include expanding urban centres, vehicle emissions, and industry, the seasonal spikes come directly from increased fire activity from agricultural burning, which can often spread to uncontrollable peat and forest fires that impact all neighbouring countries during these dry months. Take, for example, the now notorious 2019 fires that spread across Indonesia, consuming about 2.3 million acres of land, and creating a cloud of smoke that made its way to Malaysia, Brunei, and Singapore (Yeung, 2019)

In analyzing the available data for South and Southeast Asia, various sources exist contributing to the unrelenting air pollution issues. In South Asia, industrialization and urbanization bring added air pollution loads through increased populations using vehicles, ongoing construction work, and increased demand for goods. However, the seasonal spikes experienced are often from burning biomass materials (i.e., agricultural by-products) in their dry and cool season (IQAir, 2021). For Southeast Asia, rapid population growth and the accompanying economic development have also been significant contributing factors to increased air pollution, similarly to South Asia. However, open burning is estimated to contribute as much as 5 – 30 per cent of the total human-made emission inventory in the Southeast Sub-Region (IQAir, 2021).

So, while both Regions contribute part of their air pollution issues to growth, another significant burden of air pollutants is from open biomass fires, originating from common burning practices in the agriculture sector. These practices are commonly used to clear land and dispose of 'waste' (i.e., straw residue) during the post-harvest season (Greenstone, 2022). These controlled fires often spread to uncontrollable peat and forest fires. The unsustainable farming practices behind this burning have continued due to a lack of resources, capacity, and awareness.

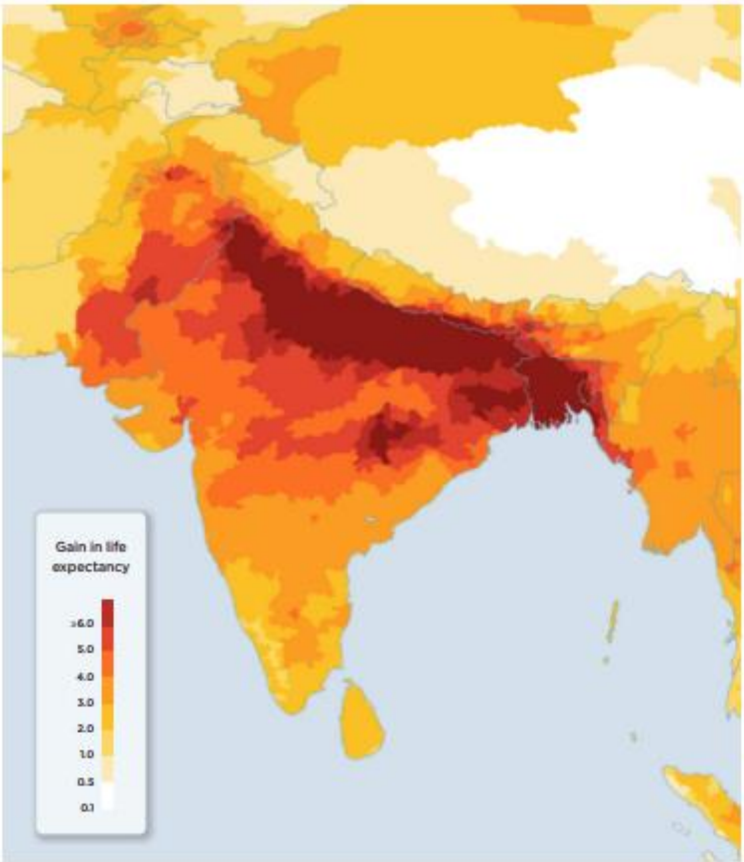
A recommended first step is enhanced monitoring and modeling using advanced data science to pinpoint and understand the patterns of the emissions sources. This needs to be followed with interventions at hotspots, including capacity building and sustainable mechanization of practices. Due to the transboundary nature of air pollution, cooperation – locally, nationally, regionally, and globally, is critical to overcoming this health, economic, and societal burden.
If these Regions can commit to reducing air pollution to the recommended 2021 WHO Guidelines; they can potentially see gains as much as six years of life expectancy on average (See below Figure 1 and Figure 2), increase the productivity of their workforce and agriculture sector; and improve the quality of life across the Regions, particularly for some of the most vulnerable groups. More details on these tools can be found in the Solutions section of this Paper.

Figure 1: Potential gain in years of life expectancy through permanently reducing PM2.5 from 2020 concentrations to the WHO guidelines, Southeast Asia



Source: Greenstone (2022)

Figure 2: Potential gain in years of life expectancy through permanently reducing PM2.5 from 2020 concentrations to the WHO guidelines, Southeast Asia



Source: Greenstone (2022)

3. Greenhouse Gas Emissions and Agriculture

Agriculture is the world's largest industry. Agriculture is the world's largest industry. It employs more than one billion people and generates over $1.3 trillion dollars' worth of food annually. Pasture and cropland occupy around 50 per cent of the earth's habitable land. Keeping the global population fed also causes a vast amount of GHGs, with preventable food waste estimated to be responsible for 7 per cent and livestock cultivation at 18 per cent of total emissions.

Some examples of other unsustainable practices found in food production and the agriculture sector that contribute to climate change are;

- Use of pesticides, fertilizers, and other toxic farm chemicals
- Mismanaged livestock manure
- Inefficient transportation logistics
- Slash-and-burn methods for land and field clearing
- Open burning of agricultural waste (e.g., straw)

In 2018, agriculture and related land use emissions accounted for 17 per cent of global GHG emissions. This input is largely due to controlled agricultural fires spreading to unmanageable wildfires, significantly impacting global warming as carbon-stored pollutants are released when forests and peatlands burn. These fires create a recurrent problem caused and worsened by air pollution. Exacerbating the matter, the world anticipates the intensity and frequency of wildfires to escalate in the coming years - as climate change brings heatwaves and changes rainfall patterns – all afflicting vegetation growth and changing terrains, making them more susceptible to burn. In high-latitude regions, warming is projected to increase disturbance in boreal forests, including drought, wildfire, and pest outbreaks, with near certainty, according to the International Panel on Climate Change (IPCC) (MacGuire, 2021).

A. Biomass Burning

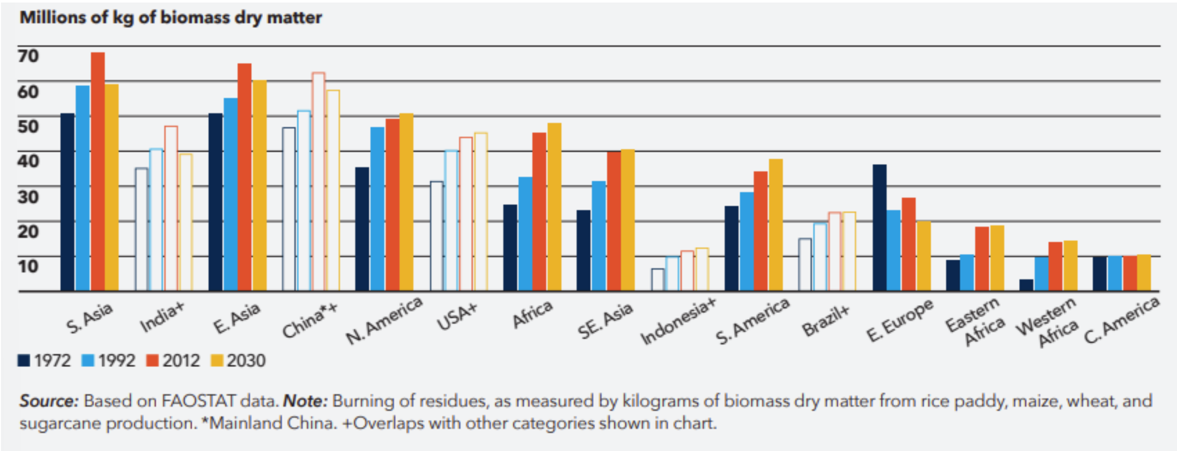
Figure 3: Burning of crop residue

Source: Tribhuvan University, Nepal

Biomass burning refers to the burning of living and dead vegetation. This can be by natural causes, like fires in forests ignited by lightning strikes, or anthropogenic causes, like the mass burning of post-harvest crop residue as means of disposal. These human-made fires release immense amounts of GHG emissions, and if not properly managed, they can quickly spread to uncontrollable wildfires, which create more emissions, damage the ecosystem, and are a great threat to human health.

Anthropogenic biomass burning is a particular issue for South and Southeast Asia, with many countries dramatically more responsible for crop residue burning emissions than anywhere else in the world (see Figure 4). Farmers mostly burn this unwanted crop straw after harvesting or before planting. Preventing agricultural and forest fires in Southeast Asia could avoid 59,000 premature deaths yearly across Mainland Southeast Asia and southern China (C. L. Reddington, 2021), while preventing these fires in Indonesia could avoid 14,000 to 44,000 premature deaths yearly across Equatorial Asia (Kiely, 2020). Preventing agricultural fires in India could avoid 44,000–98,000 premature deaths annually (Lan, 2022).

Figure 4: Geography and evolution of crop residue burning



Source: Cassou (2018) (pg.2)

The three largest staple crops produced in the sub-regions are rice, wheat, and maize (ESCAP, 2020). The cultivation methods of these crops leave an abundance of stalks in the fields. For example, rice, which South and Southeast Asia are responsible for cultivating half of the world's 738.2million annual supply, is estimated to leave behind 1.35 tonnes of straw for every tonne harvested (McLaughlin 2016).

These post-harvest remains must be managed before the next planting season. Since the stalks are viewed as having no tangible value and interfere with planting the subsequent crop, farms are compelled to clear them from the field in the easiest and cheapest way possible. However, when faced with little resources at hand, particularly on smallholder farms, and a tight seeding schedule, residue burning presents itself as the most convenient and cheap option for farmers, and the consequences of the smoke they create are ignored (ESCAP, 2020).

The burning of straw is not a new problem and has only been growing in multiple cropping areas of the sub-regions as populations rise (ESCAP-CSAM 2018). It is estimated that only 20 per cent of the rice straw in the region is used sustainably – with most straw burnt or wasted. For example, 48 per cent of the rice straw in Thailand, 62 per cent in Indonesia, 42-58 per cent in the Philippines, and 54 per cent in Viet Nam are typically burnt (ESCAP-CSAM 2018).

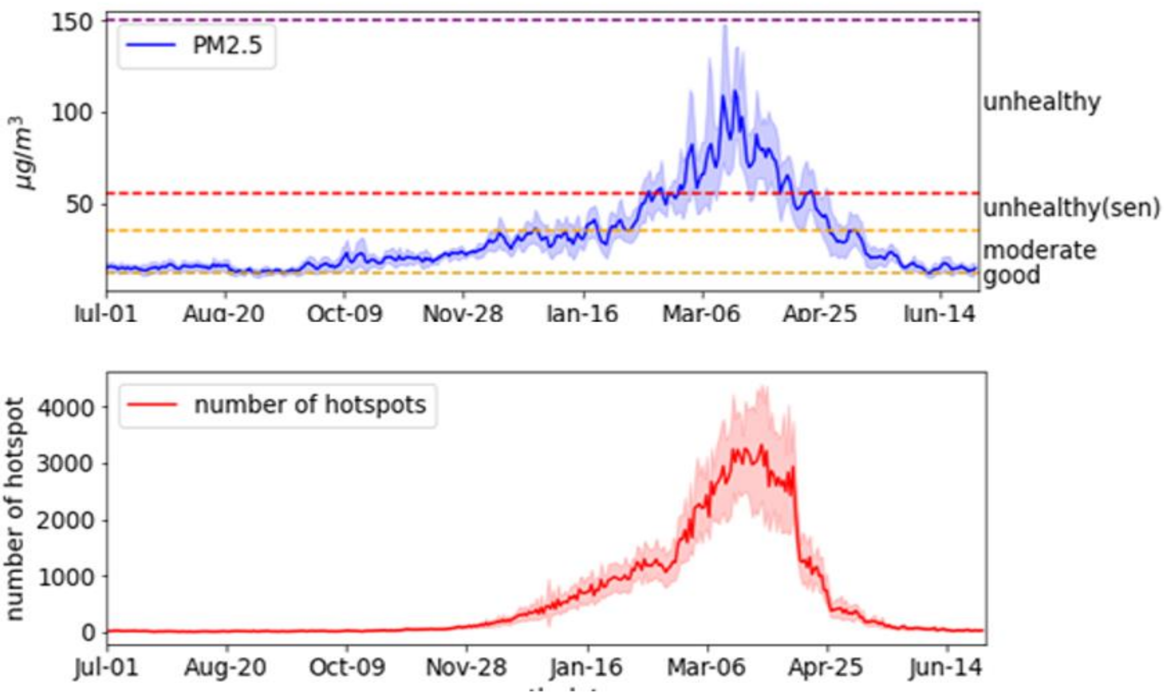
Making the matter more serious is that forest fires can often start due to slash-and-burn clearing methods to convert forests (or other natural ecosystems) to agricultural land on previously deforested or degraded lands that are highly susceptible to burning (Marlier, 2021). These fires spread quickly and uncontrollably in the dry season and contribute to peatland fires, destroying the terrain's ability to sequester carbon, and emitting significant amounts of pollutants (Hu 2018). For many countries in South and Southeast Asia, these land clearing practices are found in the palm oil and pulpwood industries.

B. Patterns of Fire

Further insights on the nature of biomass burning in the region can be found by examining its patterns which show that much of this burning is seasonal and occurs in the same area multiple times – all indicating that this burning is from anthropogenic sources.

Comparing when the sub-regions experience some of their highest peaks of air pollution (in the dry/winter seasons) against when many regional farms are clearing and prepping land for the next cycle of planting (after the end of monsoon, typically starting in November and lasting through April) there is an undeniable correlation. An example of this is illustrated in the Figure below for Chiang Mai, Thailand – where some of the worst seasonal air pollution spikes occur in Southeast Asia.

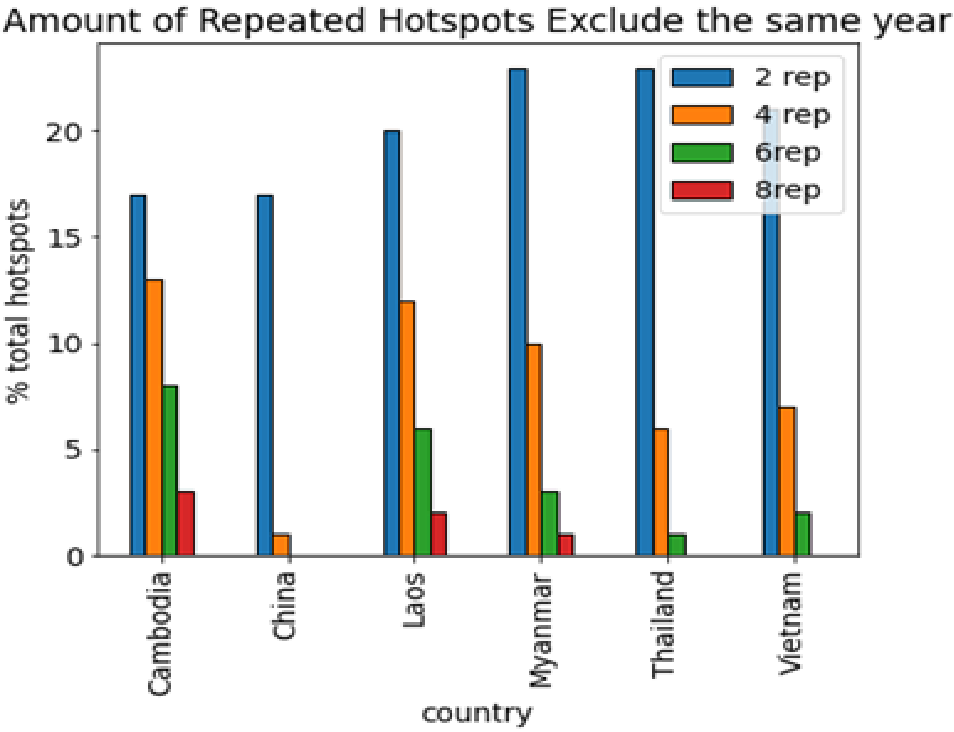
Figure 5: Seasonal air pollution, Chiang Mai



Note:(Top) Seasonal patterns of PM2.5 level, the horizontal lines indicate the values corresponded to AQI 100 (moderate) and 150 (unhealthy for sensitive group) accordingly. (Bottom) The number of hotspots within 900 km from Chiang Mai.

The primary indicator that shows these fires start from human-made sources is that they often occur repeatedly in the same area, which is too predictable to be considered a natural phenomenon. A repetition of over four hotspots is considered human-made, while a two-time repetition of the same location can be wildfires. An analysis by the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) shows that about 20 – 40 per cent of the hotspots repeat locations at least four times over 17 years in the studied countries (Cambodia, China, Laos, Myanmar, Thailand, Viet Nam). These findings can be viewed in the below Figure by country. The repetition suggests that the surrounding areas deliberately burn their fields and point to where interventions are most urgently required.

Figure 6: Number of Repeated hotspots by Country, as seen by MODIS instruments, 2002



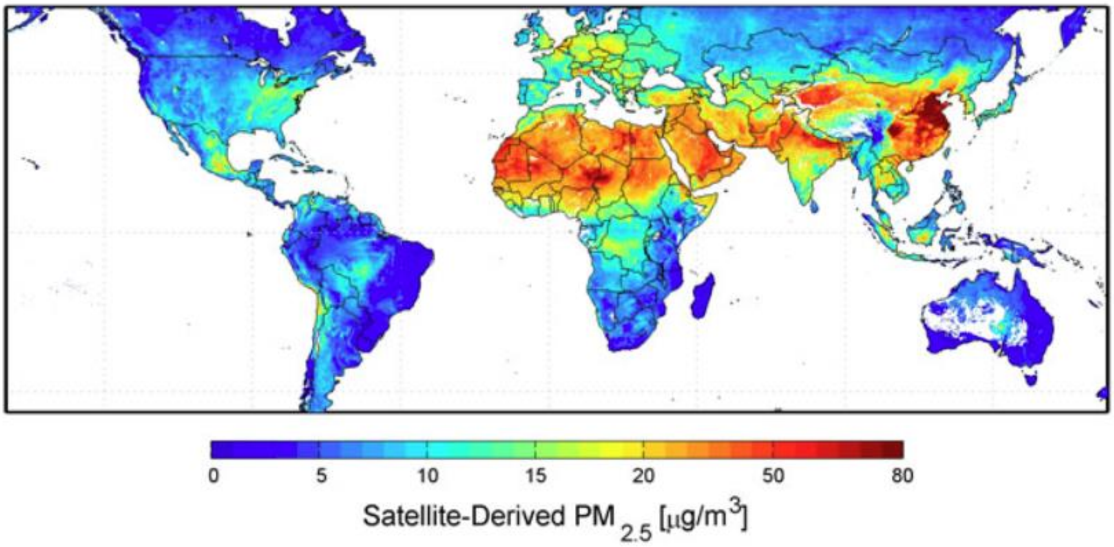
C. Transboundary Effects

Locally, the stakes are high for air pollution, as those near emission sources are often most acutely afflicted, but it does not stop there. The impacts of biomass burning are felt throughout the sub-regions and beyond. Take, for example, a recent study which found that transnational transport of emissions released as a result of burning in Southeast Asia plays a role in determining the air quality levels and patterns of PM2.5 pollution in southern China (Zhang, et al., 2022).

As these emissions move across the earth's surface, they expose more individuals to their adverse health impacts, as experienced in the 2019 fires in Indonesia, where more than 10 million children were exposed to risk, according to UNICEF (2019). A lack of rain created an environment in which around 930,000 hectares (about 2.3 million acres) of land in the Indonesian regions of Sumatra and Kalimantan were affected by agricultural burning that spread to overwhelming wildfires. Indonesia was enveloped in a cloud of smoke that impacted neighbouring countries. The World Bank says that "over 900,000 people reported respiratory illnesses, 12 national airports halted operations, and hundreds of schools in Indonesia, Malaysia and Singapore had to temporarily close due to the fires (Reuters, 2019)."

Regional cooperation, in which data, ideas, and best available techniques (BAT) are exchanged, is crucial to combat air pollution, as emissions know no borders.

Figure 7: Transboundary nature of air pollution



Source: https://www.nasa.gov/topics/earth/features/health-sapping.html

4. Impacts

The impacts of air pollution are innumerable. This Paper concentrates on the burdens associated with air pollution from biomass burning, such as its contributions to climate change; health impacts with particular attention to smoke exposure; how the economy, specifically the agriculture sector, is burdened; and how these impacts on climate, health, economy also accentuate existing societal challenges like geographic disparities and the impacts on women and children.

A. Climate Change

Emissions from agriculture, forestry, and other land use account for 20–22 per cent of global CO_2 equivalent GHG emissions (or about 45 gigatonnes CO_2 eq/year). If emissions for primary production and agricultural value chain operations are included, the emissions from this sector increase by a further 4.3 gigatonnes CO_2 eq/year (Sims 2017).

It has been estimated that open burning of biomass (excluding waste burning) is responsible for as much as 26–73 per cent of global emissions of primary fine organic PM and 33–41 per cent of global emissions of fine black carbon PM. It is further estimated that open burning of biomass produced 51 per cent of global emissions of carbon monoxide (CO) emissions for 2000 (Wiedinmyer 2011).

These high levels of emissions make open biomass burning the world's largest single source of black carbon, which is an important component of PM2.5, and, although a short-lived climate pollutant (SLCP), its impact on global warming is 460–1,500 times stronger than CO_2 (UNEP, 2022). In addition, black carbon can also modify rainfall patterns. These consequences are particularly felt in the Asian monsoon season, disrupting the weather events necessary to support agriculture (UNEP, 2022), which is in addition to the potential increase in the frequency of extreme weather brought on by longer-term climate change in the affected regions.

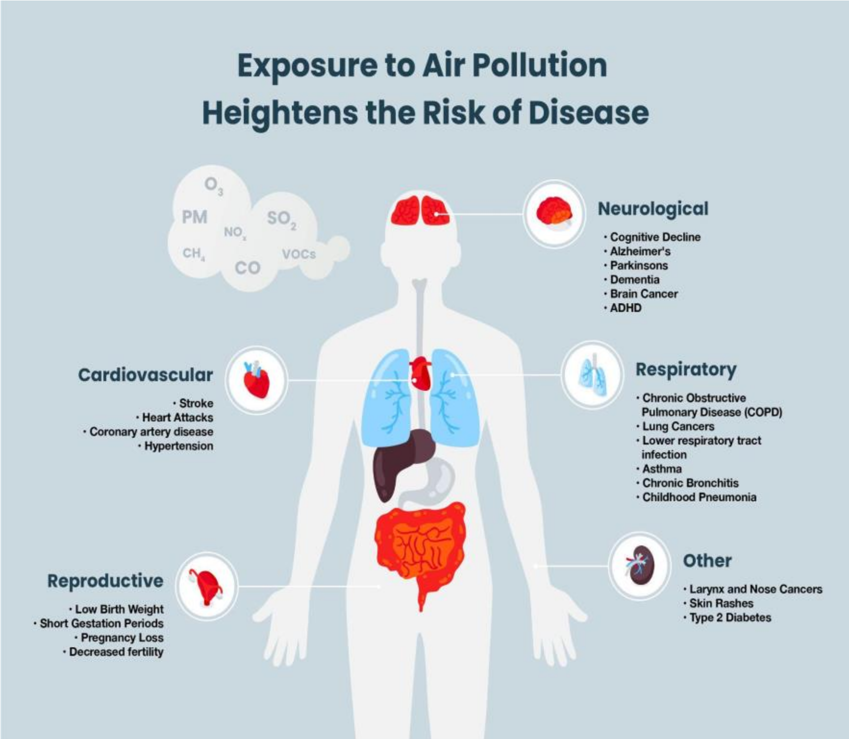
The impacts of black carbon on climate in the near term are directly experienced in the Hindu Kush Himalayan (HKH) region in South Asia today, where black carbon aerosols are a primary contributor to the rapid warming in the Himalayan–Tibetan plateau resulting in accelerated glacial melting (Menon 2010; J.M. Maurer, 2019). This glacial melting is impacting ten large Asian river systems, which provide water, ecosystem services, and the basis of livelihoods to more than 210 million people in the mountains and 1.3 billion people downstream (Nakarmi, 2020).

B. Health

Burning biomass emits large amounts of pollutants, just like burning other solid fuels such as coal. Burning organic material emits PM, nitrogen oxides (NOx), CO, sulfur dioxide (SO_2), lead, mercury, and other hazardous air pollutants (HAPs) (PFPI 2011). The bulk of the health burden associated with exposure to air pollution is believed to be from exposure to PM.

The PM emitted from fires can contain many reactive and irritant chemical compounds that promote inflammation and oxidative stress in the lungs and throughout the body (MacGuire, 2021). Other significant contributors to adverse health effects are ozone (O_3), NO_2, SO_2 and CO (World Health Organization, 2021)– which are all emitted by open burning.

Figure 8: Exposure to air pollution and risk of disease



Exposure to any incremental increase in air pollution can cause adverse effects on human health, especially in babies, children, the elderly, and those with existing chronic medical conditions. As health impacts increase in step with increases in air pollution, so modest rises in air pollutant concentrations can adversely affect a considerable portion of the population's health if enough people are exposed or if the air pollution persists for a long time (MacGuire, 2021). The dramatic spike then experienced in South and Southeast Asia from biomass burning comes with grave consequences. For example, in Singapore, during the 2020 fire season, there was a 30 per cent increase in the demand for medical care for diseases related to smoke exposure (MacGuire, 2021).

A recent time series analysis was done by the Global Climate and Health Alliance (GCHA) to demonstrate the link between health risks and exposure to air pollution from biomass burning. This study found that for every 10 micrograms per cubic meter ($\mu g/m^3$) increment of PM10 from 50 $\mu g/m^3$ to 150 $\mu g/m^3$, there is a 12 per cent increase in hospital visits for diseases of the upper respiratory tract, of which 19 per cent are for asthma and 2 per cent for rhinitis – diseases known to be caused and worsened by exposure to air pollution (MacGuire, 2021). There is recent evidence to suggest that exposure to PM2.5 from biomass burning can negatively impact respiratory health more than exposure PM2.5 from other pollution sources (Aguilera, 2022).

Other studies have revealed compelling evidence that even small amounts and short-term exposure to air pollution can have severe implications. For example, every 5 $\mu g/m^3$ increase in exposure to PM2.5 during pregnancy is associated with a 4 per cent increased likelihood of low birth weight. For adults, exposure to a 5 $\mu g/m^3$ increase in annual average PM2.5 is associated with a 13 per cent increased risk of heart attacks and cardiovascular-related deaths (Cesaroni

2014). Exposure to a 10 μg/m^3 increase in PM2.5 is associated with an increased risk of lung cancer mortality (Huang, 2017) and higher risk for dementia and Alzheimer's disease (Tsai, 2019). For students, exposure to an increase of 10 μg/m^3 of PM10 on the examination day has been associated with a decrease in scores by around 6 points (8 per cent) (Cesaroni 2014).

The global health cost of mortality and morbidity caused by exposure to PM2.5 pollution in 2019 was US $8.1 trillion, equivalent to 6.1 per cent of global Gross Domestic Product (GDP) (World Bank, 2021). Examples of this cost are disability from chronic diseases (US$200 billion), asthma ($17 billion), preterm births ($90 billion), child deaths ($50 billion), and adult deaths ($2,400 billion) (Myllyvirta, 2020). Moreover, these costs undermine a country's economic growth potential. For example, decreasing work hours with sick leave caused by air pollution costs the world $100 billion annually (Myllyvirta, 2020).

C. Economic

It is not just the costs associated with health that cripple economies but also countless indirect costs. Take, for example, the fact that the deterioration of air quality jeopardizes the image of a country. Cities' rankings can fall lower for rankings on top destinations, and liveability as dirty air negatively impacts the quality of life and discourages tourism – a key GDP driver for many South and Southeast Asian countries. This link has been examined in Brunei, where two different methodologies estimated that 1997 and 1998 haze-related air pollution in the country caused a nearly 30 per cent reduction in the number of tourists and that the total direct economic loss suffered by the tourism industry was estimated to be about B$1m to B$8m (respectively, for each methodology) (Eusebio, 2021).

These costs are only increasing as any negative impact on capital accumulation has a permanent effect on economic growth rates (OECD 2016) and a recent report from the World Bank revealed that these global costs are heavily weighted in the low-income regions and be as high as 9.3 per cent in Southeast Asia and 10.3 per cent in South Asia (World Bank, 2021).
The indirect impacts experienced in the agricultural sector are alarming, as poor air quality impacts how much food is produced, which means that air pollution is threatening an already dwindling food supply. With one in three people globally suffering from food shortages today and a constantly growing population, any danger to food production must be taken seriously (FAO, 2021).

Air pollution threatens food production because emissions penetrate plant structures and impair their development ability (Bhandari, 2021). Air pollution can act to impede photosynthesis, reduce the plant's ability to sequester carbon, damage plant cells, and reduce food quality and nutritional value (Climate & Clean Air Coalition n.d.). The short-lived climate pollutant (SLCP), Ozone (O_3), is produced from precursor gases emitted from open burning and is the most damaging air pollutant to plant structures (Bhandari, 2021).

Figure 9: **Damage to plant structures**

Ozone pollution alone was estimated to cause relative global crop losses for soy 6-16 per cent, wheat 7-12 per cent and maize 3-5 per cent. Some crops are more sensitive to ozone exposure, with wheat and soybean being most susceptible and potato, rice and maize being moderately sensitive. Of concern is that these most sensitive crops are all staple foods for most of the world's population (UNECE n.d.), hence the need for a sustainable approach that balances food production/safety, livelihoods, and environmental impacts of agriculture.

Ironically, in South and Southeast Asia, the major source of the air pollution causing these economic and food security issues - burning the by-products of agricultural waste – could potentially produce revenue if managed better. Ideas to move toward an economically productive circular model of rice straw management are discussed in the Solutions section of this Paper.

D. Societal

Air pollution is pervasive and can cause harm to any individual exposed. Still, its impacts are felt heaviest by at-risk groups, such as children and women, the elderly, those with pre-existing medical conditions and the poor.

Many spatial, or geographic factors, make air pollution particularly harmful for those in certain areas due to proximity to sources and high concentrations of pollutants. For example, data suggests that areas near high-volume agricultural production employing unsustainable agricultural practices suffer from high seasonal air pollution from vegetation and forest fires. Furthermore, the local governments in developing countries cannot often monitor air pollutants, provide solutions, or enforce air quality standards. Because of this, PM2.5 pollution from forest and vegetation fires disproportionately impact poorer populations across Southeast Asia, contributing to over a third of their total PM2.5 exposure (C. L. Reddington, 2021).

It is widely reported that indoor air pollution from solid fuel combustion for cooking and/or heating has more drastic impacts on women and children in Asia due to high exposure rates. Gender-specific health impacts of outdoor air pollution have also been studied and quantified. For example, PM2.5 exposure is linked with an 80 per cent increased risk of mortality from breast cancer for women (Wong 2016), and there are indications that gender-differenced duties for childcare when air is unhealthy can adversely impact women and threaten their livelihoods. Furthermore, there is ongoing research that suggests that exposure to air pollution is associated with serious risks during pregnancy and can impact the mother and foetus as early as a few weeks after conception resulting in low birth weight, infant mortality, increased risk of acute lower respiratory infection, reduced lung growth, and increased risk of diseases in childhood and adulthood, like asthma (Johnson, 2021). Therefore, understanding the more nuanced connections between gender and air pollution can help shape policy that has impactful benefits for women and girls in the sub-regions.

5. Root Causes of Agricultural Burning

Open biomass burning contributes to worsening air quality, particularly in South and Southeast Asia. The prevalence and adverse effects are widely demonstrated. However, burning methods are still practised and, in some cases, growing in scale. This phenomenon is driven by socio-economic factors, as many farmers lack the means and know-how to switch to green energy practices.

Some of the root factors which have made transitioning to fire-free practices challenging across the sub-regions are;

- Misconception of benefits and losses from crop burning, along with long-standing established norms.
- Lack of capacity and resources to make needed adjustments to sustainable practice, including tight-harvesting schedules, limited field hands, inappropriate equipment, and lack of training on alternate methods.
- Steady decline in animal husbandry. Crop straw can be used in the raising and feeding of livestock. As the sector moves away from this, farms see no use for post-harvest residue and struggle to find a market for it.

Underlying all these factors are culturally produced mental models, social customs, present bias, procrastination, and other sociopsychological influences that prohibit progress in the farming community. Burning, for example, is supported by the idea that crop residues are a form of 'waste'; ergo, it has zero value (Cassou 2018). This mindset can minimize feelings of loss or connection to these by-products. If this straw was instead viewed as a resource, it could encourage the community to invest in making the best use of it.

These factors are disproportionally experienced in many of South and Southeast Asia's Least Developed Countries (LDCs). The main obstacle faced is that most farms in these countries cannot find or know of any alternatives to burning, and if they do, they face extreme financial barriers in accessing machinery. Furthermore, sometimes the smallholder and family-run farms in the sub-regions do not always fully understand their practices' consequences on health and the environment. Therefore, they do not realize that a change is required.

Many farmers consider agricultural burning the best way to get rid of 'waste' by-products (i.e., crop residue), clear land, fertilize soil, and prepare for the next cycle of cropping. It is even further believed by many in the farming community that burning can enhance soil fertility. However, this is a myth, and agricultural burning only produces a short-lived burst of fertility while actually, in the long run, reducing water retention and soil fertility by 25 to 30 per cent, requiring farmers to invest in expensive fertilizers and irrigation systems to compensate (UNEP, 2022).

While it is true that burning returns some nutrients to the soil, these returns are minimal and do not last, as most of the organic material and nutrient content of straw are lost under the high temperatures of the fires (Cassou 2018). According to some estimations, 1 tonne of rice straw loses 5.5 kilograms (kg) of nitrogen, 2.3 kg of phosphorous, 25 kg of potassium and about 1.2 kg of sulphur when burnt (ESCAP, 2020). In addition, fires agitate soil pH and create moisture and biota (i.e., bacteria, fungi) imbalances, negatively impacting crop production (Cassou 2018). Therefore, farmers seeking to intensify agricultural production through biomass burning end up eliminating essential micro-nutrients from the soil, resulting in infertile land and more costs in the long run (ESCAP, 2020).

Paradoxically, agriculture residues are often a valuable resource worth repurposing. For example, crop stubble can be used as an energy source when converted into pellets, straw can be used in livestock feed or bedding (CCAC, 2015-2022), biogas can be produced with the appropriate equipment, and straw can be used to cultivate mushroom.

Another factor is the view of overall efficiency, as burning is widely seen as a quick way to get rid of crop residues and reduce potential exposure to pests and diseases. This mindset is particularly true for smallholder farms, as they face time and labour constraints to prepare fields for the next planting cycle. In parts of China, for example, there is a short window of typically one to two weeks for the removal of crop residues between harvests, which adds great pressure to dispose of this unwanted straw as rapidly as possible and pushes farms towards biomass burning practices (Cassou 2018).

The high costs associated with the collection, transportation, and storage of straw residue are also a constant barrier to smallholder farms in the two sub-regions. One estimate places the total cost of collection of straw from the field at around $55 USD per acre, far exceeding the cost of simply burning the waste in situ or doing nothing with it (ESCAP, 2020). Switching to practices like producing biogas or compost comes with upfront investments for equipment, land, and chemicals that are required and, therefore, only make sense for operations above a certain scale. However, there are mechanisms available for little to no startup costs. No-till farming, for instance, is greatly facilitated by simple technologies for chopping crop residues into manageable straw lengths, sowing seeds through a thick carpet of straw, and managing weeds (Cassou 2018). However farmers also often lack the awareness, technical knowledge, and know-how to adopt some of these available alternatives.

By addressing these pollution-creating issues, not only will the air become cleaner, but there is also the possibility for payback in the form of cost-saving practices that can improve equality in the industry. Therefore, it is vital that the agriculture sector is supported to transition to these methods and that efforts to reduce biomass burning are concentrated on the identified largest sources of these emissions.

6. Solutions

The need to combat air pollution and protect vulnerable groups was firmly established in October 2021 by the United Nations Human Rights (UNHR) Council when they published a report that recognized that having a clean, healthy and sustainable environment is a human right, recalling the States' commitments to meet the Sustainable Development Goals (SDGs) (OHCHR, 2021). Furthermore, the Report acknowledged that the consequences of pollution are felt most acutely by those segments of the population already in vulnerable situations, including women and girls, indigenous peoples, older persons, and persons with disabilities (OHCHR, 2021).

This resolution empowers governments to act against all factors of environmental degradation that harm human societies. Given the devastating impacts of poor air quality on people's lives, health and human rights, priority needs to be placed on managing air pollution, focusing on ameliorating conditions for the most vulnerable.
In 2019 the UNHR Council helped to provide a framework around air management by providing seven key recommendations (OHCHR, 2021):

- Monitoring air quality and health effects
- Public reporting on air quality
- Establishing air quality legislation, regulations, and standards
- Preparing air quality action plans
- Implementing and enforcing air quality rules
- Evaluating and revising air quality standards and plans
- And protecting environmental human rights defenders

The causes and consequences of air pollution cannot be effectively addressed inside silos due to its transboundary nature. Therefore, to meet these goals, nations need strategies in which intergovernmental cooperation is a cornerstone of their approach. An ongoing example of how regional cooperation can be achieved is the 1979 Convention on Long-Range Transboundary Air Pollution (the Convention), the first multilateral agreement addressing transboundary air pollution. By creating a common framework consisting of eight protocols that can be applied broadly, the regime has helped dramatically reduce air pollution emissions throughout the northern hemisphere, particularly in Europe.

One of the many reasons international cooperation must be a priority area when seeking solutions for air pollution is to share information and data to enhance the understanding of air pollution, particularly to pinpoint pollution hotspots so effective measures can be applied. The advanced technology to capture and use this data and gain an exhaustive overview of emission sources and patterns exists. One such project is the National Aeronautics and Space Agency's (NASA) Pandora Project. The Pandora Project coordinates and facilitates an expanding global network of standardized, calibrated Pandora instruments focused on air quality and atmospheric composition. This information could help policymakers target where interventions are most desperately needed and create advanced alert systems to protect their citizens.

Data alone is not enough; governments will need to regulate polluters. To help guide this, a toolkit has been created to help the Asia-Pacific region meet these goals by the Asia Pacific Clean Air Partnership – Climate and Clean Air Coalition and the United Nations Environment

Programme (UNEP), 25 Clean Air Measures for Asia and the Pacific (UNEP-CCAC, 2018). This report outlines 25 clean air measures that, if applied by governments, would achieve safe air quality levels for one billion people by 2030 – with further benefits for public health, economic development, and the climate (UNEP-CCAC, 2018). There is an emphasis in this Report on the changes required for the agricultural sector, with five of the 25 measures directly related, including explicitly calling for the (21) better management of agricultural crop residues, (22) prevention of peat and forest fires, and (23) promotion of more efficient rice production.

To help the agriculture sector, particularly smallholder farms, meet regulations, they will require support to change their current methods from unsustainable practices (i.e., biomass burning of post-harvest straw) to sustainable ones (i.e., using post-harvest straw to cultivate mushrooms). Meeting their needs will require capacity building and mechanization for farms in identified hotspot emission zones.

This paper, based on the mandate from the UNHR Council, relying on the tools provided by the Climate and Clean Air Coalition and UNEP, taking notes from successful collaborative efforts like the 1979 Convention on Long-Range Transboundary Air Pollution, and using examples from ongoing ESCAP projects, will examine solutions for the reductions in air pollutant and greenhouse gas (GHG) emissions in the agricultural sector from biomass burning, through three main channels (1) cooperation, (2) enhanced monitoring and modeling to pinpoint burning hotspots, and (3) proven approaches to mechanization to reduce emissions from food production.

A. Cooperation

For the region to successfully combat climate change, cooperation is necessary between local governments, countries, and sectors, in which harmonized standards are set, and pacts are made to strive towards global goals, like the Paris Agreement and Sustainable Development Goals (SDGs) (ESCAP, 2020). Political will, government leadership, an intersectoral approach and coordination of nations and partners are critical to ensure the effectiveness and efficiency of any measure.

The need for cooperation is particularly true for air quality management because air pollution can travel vast distances, over national borders, impacting millions of people far downwind of the source. Moreover, polluters affecting any given area might be outside the jurisdictional reach or national boundaries, which hinders those affected by that pollution from being involved in the process of making the needed changes. Furthermore, as many areas in the sub-regions share characteristics (i.e., geography, wind patterns, pollution sources), the exchange of knowledge and best available techniques (BATs) can accelerate the success of projects beyond working independently.

The sharing of data among nations is critical for monitoring air quality and the success of measures in place to mitigate it. Many developing countries face obstacles with data gaps. More robust models can be built across both sub-regions through sharing and exchanging data, ensuring the best quality information for policymakers to understand relevant air pollution issues.

Cooperation is needed among inter-governmental agencies as well. The enforcement of environmental policies can be complicated within governance frameworks, as not all agencies hold the same power, budget, or mandate to control air pollution (UNEP, 2021). Bringing together multiple agencies can better delegate, finance, and manage air quality control.

The 1979 Convention on Long-Range Transboundary Air Pollution, referred to earlier, is one of the most successful global examples of how regional cooperation can be achieved and is still active today. This body of 51 participating nations addresses environmental and health problems caused by industrialization, agricultural modernization, and fossil fuel consumption throughout the Northern Hemisphere (Byrne 2015). The group has mainly focused on acidification, photochemical smog, ground-level ozone, eutrophication, fine PM, black carbon, and contamination by toxic chemicals (Byrne 2015). Their achievements include emission reductions of 80 per cent of 40 harmful substances since 1990 in Europe (UNECE n.d.).

The tools employed by the 1979 Convention on Long-Range Transboundary Air Pollution to realize its goals include using binding and non-binding agreements, finding points of compromise, and ensuring institutional effectiveness. The Convention's ability to make sound institutional agreements and active engagement with the scientific community has provided a model for subsequent international treaties (Byrne 2015). The continued achievements of the UNECE Member States illustrate the need for countries to work together to solve this transboundary crisis.

Several initiatives are available and active in South and Southeast Asian countries. A non-exhaustive list includes:

- **Asia Pacific Clean Air Partnership (APCAP).** Established 2015 established in 2015 to promote coordination and collaboration among various clean air initiatives in the Asia Pacific. (UNEP serves as Secretariat)
- **North East Asia Clean Air Partnership (NEACAP).** Established in 2018 at the 22nd Senior Officials Meeting of the North-East Asian Subregional Programme for Environmental Cooperation (NEASPEC). Transboundary air pollution is one of five thematic areas of NEASPEC. (ESCAP SRO-ENEA serves as the secretariat, coordinates the Workplan and convenes its Science and Policy Committee).
- **Acid Deposition Monitoring Network in East Asia (EANET).** Established in 2001 as an intergovernmental initiative to create a shared understanding of the state of acid deposition problems in East Asia, 13 countries participate (Russian Federation, Mongolia, China, Republic of Korea, Japan, Myanmar, Thailand, Lao PDR, Cambodia, Viet Nam, Philippines, Malaysia and Indonesia. (UNEP serves as the Secretariat, and the Asia Center for Air pollution Research (ACAP) in Japan is the Network Center for EANET).
- **South Asia Co-operative Environment Programme (SACEP).** SACEP member States (Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, Sri Lanka) adopted the Malé Declaration in 1988, calling for regional cooperation on transboundary air pollution. The secretariat is at the Regional Resource Centre for Asia Pacific (RRC.AP) at the Asian Institute of Technology in Thailand, which reports a network of policymakers and stakeholders, monitoring and impact assessments carried out and initiation of policy measures to control air pollutants.
- **ASEAN Agreement on Transboundary Haze Pollution (AATHP).** Signed in 2002 to control haze pollution, the agreement includes measures on monitoring and assessment, prevention, preparedness, national and joint emergency response, procedures for deploying resources across borders, technical cooperation, and scientific research.

- **Malé Convention.** This leading intergovernmental cooperation network in South Asia addresses regional air pollution issues through capacity building on monitoring and analysis, impact assessments, policy formulation and mitigation actions to reduce the transboundary impacts. Even though the network went dormant in recent years for the lack of a stable funding mechanism, member countries recently decided to relaunch the Declaration at the Ministerial Level and extend its scope to climate change by addressing short-lived climate pollutants.

Agreeing to conventions and actively engaging in these types of partnerships are essential to member states' success in combatting air pollution. However, some measures have been ineffective as the approach is fragmented. ESCAP, in its role as a regional entity to promote the exchange of knowledge and good practices amongst member states, recently hosted a series of sub-regional dialogues to unpack the issues surrounding this fragmentation and discuss ways to strengthen regional cooperation.

During these Dialogues, much emphasis was placed on the importance of the Malé Convention and ASEAN Agreement on Transboundary Haze Pollution from senior officials, calling for the need to fully activate and follow through on the goals of these agreements. These dialogues indicate that the political will exists to work together and make the needed changes to improve air quality throughout both sub-regions. However, there is often the lack of capacity in areas like enhanced monitoring, data modelling abilities, and the deployment of sustainable agricultural mechanization.

B. Monitoring and Modeling

Air pollution comes from various sources, and because of that, the first step needs to be identification and source appointment through measuring and monitoring when assessing how to manage poor air quality better. Common solutions for measuring and monitoring air quality are fixed-location air quality monitoring stations, satellite and ground-based remote sensing, specialized in-situ air pollution measurements, and mobile air quality sensors.

Next, innovative data modelling and the deployment of emerging technologies to identify air pollution hotspots are necessary to formulate informed and efficient policies. Emerging solutions to better analyze and use the available data to target policy include chemical fingerprinting, chemical transport models, and machine learning models.

Multiple data-collection approaches should be used to gain an exhaustive overview of air quality and decipher pollutants' sources, as different monitoring technologies have unique advantages and disadvantages and can yield different spatiotemporal resolutions (UNEP-CCAC, 2018). Furthermore, successful source identification solutions plan for the long-term, collect consistently over time with regularly tested equipment, and openly share and exchange data with other air pollution actors and stakeholders.

This monitoring and modelling must be planned long-term to ensure measures' effectiveness and continually seek to improve air quality through innovation. However, developing countries often lack the resources and data to identify the causes of air pollution impacting local conditions. To address the pervasive problems of low data quality and availability, ESCAP has developed a Machine Learning approach using satellite imagery (from the moderate-resolution imaging spectroradiometer or MODIS instrument) and a variety of historical measurement data sets to monitor and model air pollution.

C. Machine Learning

Computer models of the atmosphere use dynamical and chemical equations to represent complex physiochemical processes in the atmosphere. These models are able to simulate atmospheric air pollution and can be used to better understand the processes that drive and influence air pollution concentrations. However, these complex models are computationally expensive to use and often require a large amount of input data for them to run successfully. Machine learning approaches have the advantage of requiring fewer inputs than complex atmospheric models whilst being relatively quick and inexpensive to use. Instead of focusing on physical and chemical processes, machine learning models can be trained on historical data predictions. Machine learning approaches can handle many variables and non-linear relationships between independent and dependent variables.

Machine learning algorithms can be used to predict response variables (e.g., PM2.5 concentration) based on statistical associations with predictor variables (e.g., PM2.5 measurements, meteorological measurements etc.), without explanatory knowledge. A Random Forest (RF) model can be used for this purpose because of its capacity to manage complex relationships. This RF model comprises an ensemble of decision trees that predict the average behaviour for a given set of conditions. After testing the model's accuracy, it can be used to predict future levels of PM2.5 pollution based on inputs of current conditions, including the ability to rank the input features by order of importance. The RF model can be used to simulate the relationship between meteorological data and air pollution with a high level of accuracy.

(i) Case Study – Chiang Mai

To demonstrate the usefulness of machine learning approaches in air pollution prevention, the province of Chiang Mai, Thailand, was used as a pilot city in an ESCAP air pollution project that began in 2019. This project created and trialed a machine learning system to help better understand sources and predict air pollution patterns.

Chiang Mai, Thailand, has been selected because it regularly suffers from seasonal, severe air pollution. One of the primary sources is emissions from open biomass burning. However, with the existing measurements alone, it is difficult to identify locations of the fires that are responsible for the most air quality degradation. The ESCAP project has utilized a machine learning approach to identify these key burning hotspots and understand the degree to which they contribute to air pollution in the city of Chiang Mai. The application of this approach in Chiang Mai can potentially be replicated in areas throughout South and Southeast Asia that suffer from air pollution caused by biomass burning and struggle to address it due to insufficient data.

The development of this machine learning model involved building a system with the following criteria:

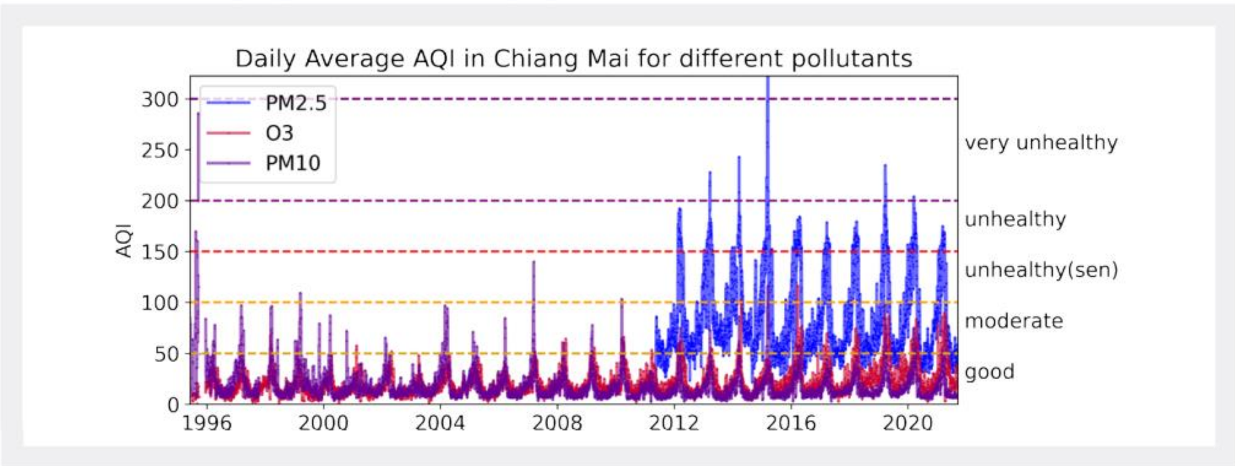
- The ability to identify the primary air pollution sources and determine their influence on air quality.
- Manipulate the data so that air pollution is predicted at an hourly rate. The R2-score (a statistical measure of how close the data are to the fitted regression line) should be in

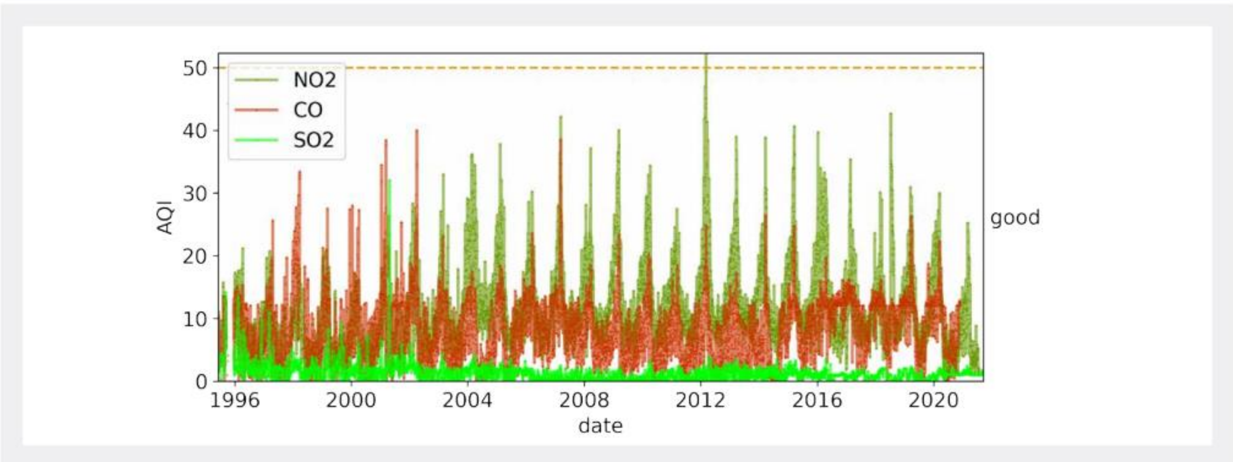
line with state-of-the-art standards to support confidence in the findings. In line with the analysis provided in Annex 1, an R2-score of 0.75 is considered a satisfactory result.

The overarching goal for this specific model is to be able to predict air pollution levels by implementing various scenarios. For instance, demonstrating how seasonal air pollution would change if agricultural burning were decreased at different levels – what would be the difference between a 40 per cent reduction in a 200 km radius and a 20 per cent reduction in a 400 km radius? Understanding this information allows policymakers to identify actions required for the best real-world outcomes.

For this model to function accurately, comprehensive and reliable data is required. The Chiang Mai model used measurement data on chemical pollutant types, burning hotspots, weather, and other variables. Data sources include historical records from the City's existing two air quality monitoring stations, NASA satellite observations, data scraping from websites, and even crowdsourcing. Some data was straightforward to obtain because of proper record-keeping, while others were more complicated to obtain. For example, historical measurements of PM2.5 pollution are not available prior to 2012 (as seen in the Figure below). However, there are measurement data available since 1995 for PM10 and O_3 – two air pollutants known to demonstrate a very close correlation to PM2.5 in certain situations. Therefore, to make improved PM2.5 predictions, the model was enhanced using PM10 and O_3 measurements.

Figure 10: Pollution Level Measures over differential time series, in aggregate (United States AQI Index), Analysis (ESCAP, 2021)

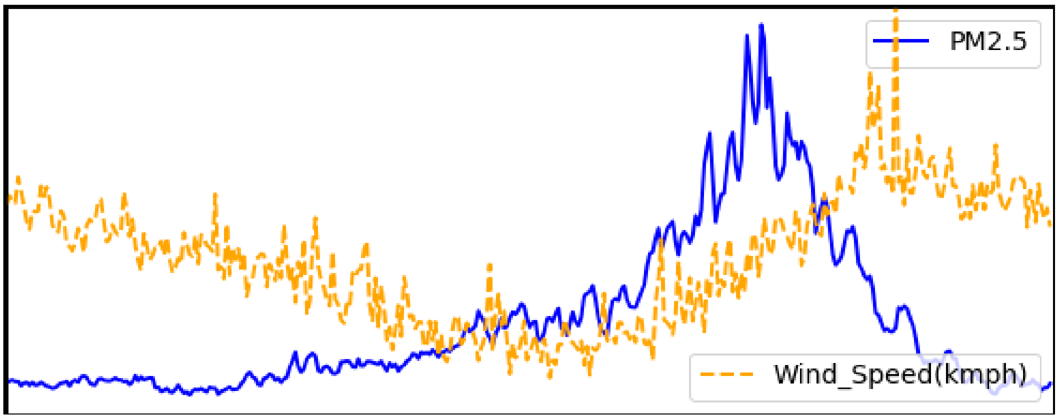




Meteorological conditions also need to be accounted for. For example, wind speed considerably affects air pollution because it changes how air circulates in a region, particularly in mountainous areas like Chiang Mai. High wind speeds can help to disperse air pollutants and reduce concentrations, but winds can also transport air pollutants into the city during the burning season.

For Chiang Mai, wind speed in the winter months is at its lowest level of about a 5 km/hr – it is at its fastest in the monsoon season (April to July). The below Figure compares the annual levels of PM2.5 in Chiang Mai against the wind speed. As seen in this graph, the yearly average pattern of wind speed negatively correlates with the air pollution levels at certain times of the year.

Figure 11: PM2.5 (Solid Blue Line) Hourly Patterns Over 24 hours.

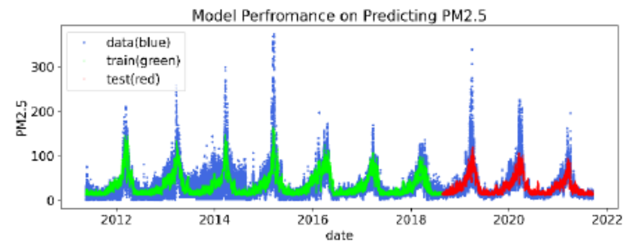
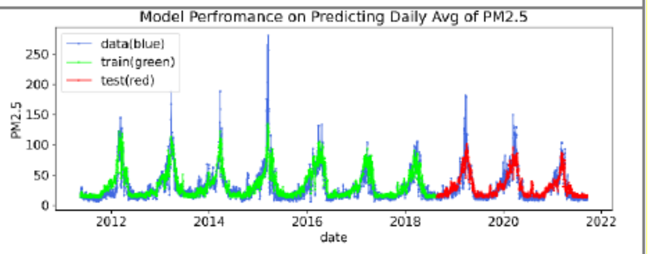


It is important to consider the totality of meteorological effects to make precise predictions. Therefore, other meteorological conditions, such as the average hourly value of wind speed and regular seasonal variation in conditions in the dry and monsoon seasons, were accounted for. It was found in this study that wind speed is a mitigating factor, but not a primary determinant of air pollution levels, particularly the seasonal spikes.

Next, a random forest regressor model was built to predict hourly PM2.5 levels using weather conditions, burning hotspots in a 900 km radius, and date/time information. Measured PM2.5 concentrations were averaged from two monitoring stations in different downtown Chiang Mai areas. The model's performance is evaluated by measuring its objective performance and testing it against previously unseen data. Model training allows a prediction to be made correctly as often as possible.

The validation dataset is then used to optimize the model parameters and later merged with the training dataset for final model training. Then the prediction set is used for model prediction and creating simulated scenarios. Prediction and scenario simulation is undertaken with daily average values to provide higher model accuracy. The Figure below shows the model hourly and daily prediction accuracy for Chiang Mai. The blue lines are the actual data, the green lines are training data, and the red lines are predictions.

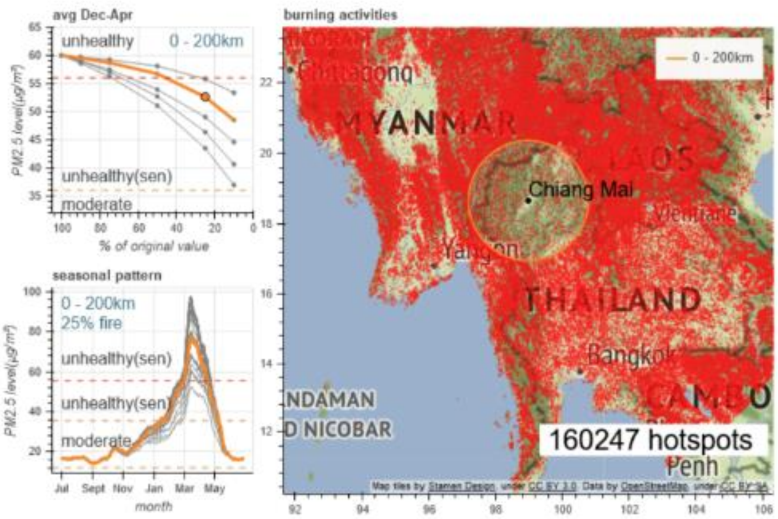
Figure 12: **Model hourly and daily prediction accuracy for Chiang Mai**

Hourly Prediction	*0.71*	*±15*	
Daily Prediction	*0.78*	*±12*	

When the model could not see specific data sets, it still had a reliable prediction score (R2 = 0.66). The prediction error is +/- 16 pm3, which is absorbed in the confidence band's error. This outcome gives the model confidence to begin making and analyzing predictions that can guide the region towards cleaner air.

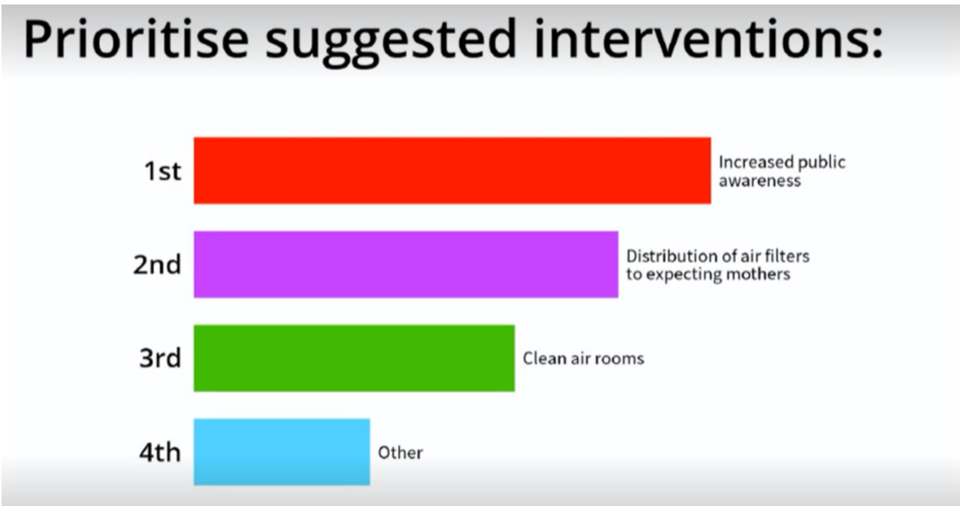
Finally, all of this was applied to generate the desired information (see example below) and provide Chiang Mai with the insights they need to target biomass burning effectively. Knowing where to apply and enforce regulations to reduce this hazard is a critical first step; it is equally important that those who use unsustainable practices due to a lack of resources are provided with suitable mechanisms and training to comply with regulations.

Figure 13: **Effect of reduced fire activities on PM2.5 level in Chiang Mai**



Based on the outcomes of this Study by ESCAP, a group of experts and local government officials created a city-level Action Plan with long and short-term goals. The cohort flagged that their immediate priority to mitigate exposure to emissions was increasing public awareness (see Figure below) and specified that they need a more advanced air quality warning system.

Figure 14: Action Planning Workshop Chiang Mai, Mentimeter Results



Source: ESCAP (2022)

To improve the city's capacity to measure air pollution concentrations, they are expanding their monitoring network to include a third, multi-spectral, ground-based sensor provided by the Geostationary Environment Monitoring Spectrometer (GEMS) at Chiang Mai University in 2022. This enhanced data will link to a public advanced air quality warning system.

They also indicated that a vulnerable group they are most concerned about are pregnant women, as the risks of the types of pollution found in Chiang Mai have grave consequences for both mother and fetus. As a result, the city will now implement a project through ESCAP, in which air filters are distributed to pregnant women during the region's 'pollution season' to continue researching what can be done to protect this group.

D. Sustainable Agriculture Mechanization

Machinery plays a critical role in the world's food production, especially as populations are expanding and the pressure to rev up production rates is continually building. The main requirement for mechanization is not only to increase yields while reducing production costs but also to minimize the impact on the environment, as many standard practices in the sector have proven to have detrimental consequences (ESCAP, 2020). According to the Food and Agricultural Organization of the United Nations (FAO), sustainable mechanization must adopt principles and paradigms that enable agriculture to be both productive and profitable for farmers while contributing to conserving resources and ecosystem services (FAO, 2022).

Therefore, sustainable agricultural mechanization is a critical step to increasing food security, protecting livelihoods, and combating climate change. Sustainable agricultural mechanization technologies range from hand tools and techniques such as no-till farming to more sophisticated means, such as equipment which converts bio-waste (i.e., straw or manure) to bio-gas or bio-char, and to advanced technologies in which power sources are diversified (i.e., moving from diesel engines to electric for ploughing) (Sims 2017).

It is also equally important that the methods follow climate-smart agricultural principles, which focus on three pillars, (1) productivity to provide food security, (2) adaptation both for extreme events and slower, long-term climate change manifestations affecting both agriculture and the consequent food security implications, and (3) mitigating the effects of climate change through reduced GHG emissions (primarily through carbon sequestration and reduced fuel consumption) (Sims 2017). If applied appropriately, sustainable agricultural mechanization can:

- Increase land productivity by facilitating timeliness and quality of cultivation.
- Support opportunities that relieve the burden of labour shortages and enable households to better withstand shocks (eg. pandemics).
- Decrease the environmental footprint of agriculture when combined with good conservation agriculture practices.
- Reduce poverty and achieve food security while improving people's livelihoods.

(FAO, 2022)

Sustainable agricultural mechanization should be further promoted throughout the agricultural sector, from large commercial production farms to smallholder farms that are often family-run. However, the 500 million smallholder farms across the globe will need the most support in this transition, as they face the most economic and societal barriers. It is further essential to support these smallholder farms because they produce 80 per cent of the world's food and occupy 70-80 per cent of all agricultural land, and growing food demands indicate the sector needs to increase production by 100 per cent by 2050 to feed the world's growing population (Sims 2017). To meet this need without causing more damage to air quality, support to smallholder farms must be focused on technology that grows in scale with production demands.

One of the farmers' main and consistent constraints is the lack of reliable agricultural machinery and equipment. The Least Developed Countries (LDCs) face especially difficult limitations. Apart from weaknesses in rural infrastructure and agricultural research and extension services, they have limited capacity to manufacture machinery and equipment and rely predominantly on imports to meet their domestic needs, which are often not well adapted to local conditions.

Therefore, there is a need to test and promote integrated models of utilizing straw, focusing on enhancing the performance of relevant machinery in the specific contexts of different elements. For instance, landholding sizes throughout and South and Southeast are significantly smaller, at an estimated size between 1-6 hectares per farm, than those in the more industrialized parts of the world, like Europe and North America, which average 100 hectares per farm (OECD/FAO, 2022). Where the large industrial farms require a large work force, a farm of 1–2 hectares (ha) can be managed efficiently by family labour consisting of a few workers (Yamauchi, 2021). Therefore, specific studies are needed to address the different needs of these farm sizes and their workforce to match them with the right types of agricultural machinery. Farms must select the most appropriate upgrades and changes depending on the type of work, the size of their operation, and who is performing the work.

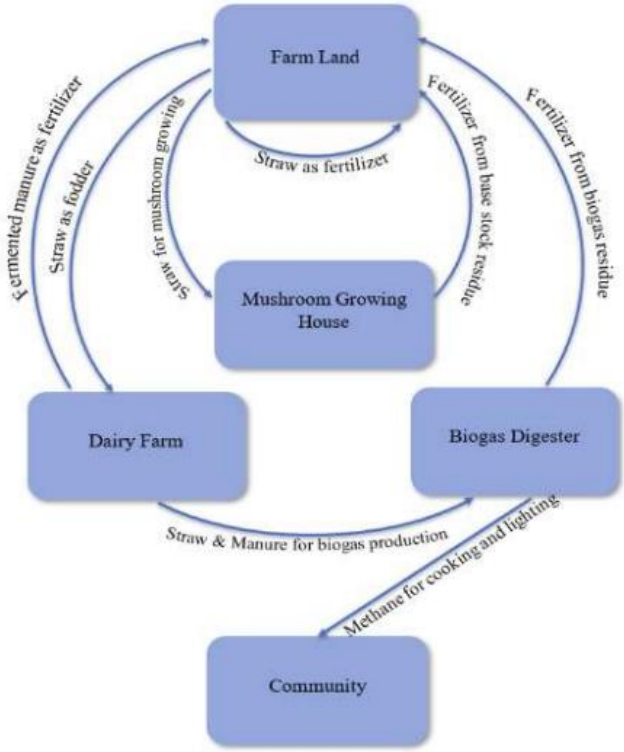
The level of mechanization selected must be understandable and approachable to all in the community employing the advanced techniques. For instance, women play an essential role in many farming-based communities. For developing countries, this can be as high as 80 per cent of total farm labour being contributes by women. In other words, two out of every three women in many developing countries work in agriculture (Debucquet, 2020). Therefore, equipment needs to be adapted to meet their needs from an ergonomic, social, cultural, and economic point of view. In addition, taking a gendered perspective on mechanization can help reduce the drudgery of farming from women's already overburdened workloads worsened by air pollution.

(i) Integrated Straw Management

Sustainable agricultural mechanization can be implemented to prevent biomass burning from post-harvest straw residue that can contribute significantly to the development of value chains and food systems as these more sustainable practices have the potential to render post-harvest, processing and marketing activities and functions more efficient, effective, and environmentally friendly. Furthermore, mechanization reduces the amount of manual labour needed, which can help improve the quality of life for many smallholder farms.

Appropriate agricultural machinery can take post-harvest straw, typically viewed as waste, and transform it into a meaningful product such as fertilizer, cattle feed, bioenergy, substrate for growing mushrooms, and industrial material. Using this by-product in these ways fosters the creation of a circular model of straw utilization. The Figure below illustrates how this model functions and various sustainable pathways to integrate straw residue.

Figure 15: Circular model of straw utilization



Source: ESCAP (2020)

The most common post-harvest uses of straw in South and Southeast Asia are as fertilizer or fodder. As fertilizer, straw can balance soil nutrients, increase soil organic matter content, and consequently help reduce the input of chemical fertilizers into the ecosystem and save farmers money. Creating fertilizer from straw can be done by simply returning the straw to the field and utilizing it with the help of relevant machinery such as choppers, straw chopping harvesters and no-till planters. Straw is also commonly used as animal feed, reducing overhead costs to farmers. The quality of fodder can also be improved by fermenting green straw with anaerobic lactic acid bacteria under confined hypoxia conditions. A machinery called baler can also make straw into compact bales for better storage (ESCAP, 2020).

An emerging practice is to use straw as substrate for mushroom growing. Straw can create an ideal environment for cultivating mushrooms, creating a new market for the farm. This processing involves machinery such as choppers and sterilizers, which can soften the raw paddy straw and then the straw can be used to incubate with spawn that grows mycelium (ESCAP, 2020).

Other methods to be considered for further development is the conversion of rice straw to bioenergy or biomaterials. Small-scale biogas plants produce a clean gas suitable for cooking from a mixture of straw and manure. This use helps discourage straw burning, manage manure, decrease demand for woodfuel, and prevent indoor pollution due to wood – and charcoal-based cooking (McLaughlin 2016). It is further being discovered that rice straw can produce polymeric biomaterials, including paper, biodegradable composites, composite panels, waste tire insulation boards, adhesives, sound-absorbing wooden construction materials, and packaging (McLaughlin, 2016).

And while these methods are employed (i.e., fodder) and being developed (i.e., biomaterials) in some cases, they are not practiced ubiquitously and consistently enough throughout South and Southeast Asia, as it is estimated that only 20 per cent of post-harvest straw enters the circular model, and the rest is wasted or burnt. The bottleneck to get farms to transition to the circular model in many developing countries is that they cannot afford to buy or even rent machinery needed (i.e., choppers, straw chopping harvesters, no-till planters, balers and sterilizers). Sometimes, the equipment is not even available locally, particularly in remote or mountainous areas. Hence, to support changes in the practice of straw burning and move towards a sustainable and integrated approach to straw management, ESCAP recommends three main areas of action, as listed below.

1) **Awareness raising should be prioritized.** Stakeholders, including government officials, policymakers, farmers, and change-makers, should be further sensitized about the adverse effects of residue burning on human health and the environment, including land degradation and air pollution. In addition, emphasis should be placed on the economic benefits that accrue to farmers when they adopt sustainable and integrated solutions for managing straw residue.

2) **Initial investments for the adoption of equipment should be facilitated**. Several measures could be adopted to allow farmers to gain access to machinery. Governments could provide direct financial support through incentives, loans, and other financial schemes to encourage farmers to use sustainable agricultural mechanization by making machinery affordable. Financial support could also include tax exemptions on the import of agricultural machinery and preferential interest rates for loans for the machinery. However, these financial schemes are only effective if bureaucratic barriers are35equissed and eligibility criteria are conducive, allowing 35equire35derrs at all levels to access them. In addition to direct support or incentives to individual farmers, establishing an organization specializing in custom hiring or renting of equipment could also ease issues related to maintenance and make machinery more widely available.

3) **The relevance of agricultural machinery should be taken into consideration**. This implies that machines and equipment used for straw utilization should correspond to the local land conditions, climate, and other circumstances. This also requires that research and development be strongly encouraged and linked with all market segments.

4) **Capacity Building Among Farmers**. Farmers will not only need support in purchasing and accessing suitable types of machinery and equipment, but they also need technical training and education on applying the sustainable solutions appropriately. This support must include consistently following up with farmers as they put the methods to use to help assess progress and tweak approaches as needed.

Several governments throughout both sub-regions have developed national programmes to combat straw burning. For instance, in the national project titled "Promotion of Agricultural Mechanization for in-situ Management of Crop Residue in the States of Punjab, Haryana, Uttar Pradesh and the National Capital Territory of Delhi" developed by the Department of Agriculture, Cooperation & Farmers Welfare under the Ministry of Agriculture & Farmers Welfare of the Government of India, the main focus is to achieve zero burning through the promotion of appropriate strategies for in-situ crop residue management, provision of financial assistance for procurement of the needed machinery and equipment and offering on-field / off-field training to farmers and farmers' societies. As another example, Indonesia initiated a project on 'Carbon Efficient Farming', which assessed biomass in terms of carbon and undertook modeling to reduce CO_2 emissions. Thailand and Viet Nam are among the other countries that have announced and undertaken measures to reduce open burning. (ESCAP, 2020)

(ii) Case Study – Viet Nam

To help move countries toward mechanization, CSAM has implemented a Project to enable sustainable and climate-smart agriculture through integrated straw management in South and Southeast Asia to establish the socio-economic benefits that can accrue to farmers through fertilizer production and fodder.

The Centre for Sustainable Agricultural Mechanization (CSAM) of ESCAP implemented a regional initiative on Integrated Straw Management which aims to identify, test, and promote a circular model for managing straw residue using agricultural machinery in various pilot countries (ESCAP, 2020). This project was operational in Southeast Asia's Viet Nam from January 2018 through March 2019 with national partner, the Sub-Institute of Agricultural Engineering and Post-Harvest Technology (SIAEP).

Viet Nam was selected as a pilot country for the programme based on its high yield of remaining straw after harvest, with grain at 44.0 Mt/yr and straw at 49.59 Mt/yr – far exceeding some mainland neighbours like Myanmar and Thailand. Can Tho, a city in southern Viet Nam's Mekong Delta region, was selected as the study area. Here a survey revealed that burning was a regular practice in the area, despite farmers indicating they would prefer to use residue for different useful purposes in agriculture, such as substrate for mushroom growing, mulching, and cattle feed. The obstacles the farmers in the Mekong Delta region faced was the absence of training courses on techniques; the absence of adequate machinery and facilities to perform different operations from collection to sterilization of straw; the low investment capacity of farmers; and the absence of financial support from the government.

After initial assessments, upscaling the use of straw to cultivate mushrooms was identified as a potential meaningful use of their straw residue. Traditionally in the region, mushroom growing is done outdoors; while these practices have very low investments, they produce low yield and low quality mushrooms. If farmers had access to indoor growing methods that used straw as the base, farms could produce high-yield and high quality mushrooms at significant profits, making the practice more attractive and ultimately reducing the amount of straw burning in the area. Unfortunately, this has been hindered by high initial investments in upgrades, like greenhouses.

To find solutions forward from this obstacle, this Study researched and tested types of greenhouses for gowning of mushrooms indoors. As a result, metal Roofing Simple Sheds were identified as the best type of greenhouse suitable for the area. Furthermore, since the building and operating costs of a Metal Roofing Simple Shed are much lower than those of a Modern Mushroom Greenhouse, the Metal Roofing Simple Shed can partly control growing conditions and considerably improve the yield and quality of mushrooms compared to Simple Thatched Shed.

Two Metal Roofing Simple Sheds were built, used, and outputs analyzed to show the effectiveness of rice straw residue as substrate for mushroom growing in these greenhouses when applying a steam sterilizer. If sterilization is not involved at the material preparation stage, rice straw use-efficiency is between 9.85- 16.15 per cent. Instead, in this Study, which used a steam sterilizer, efficiency was at 26 per, as adding this mechanization can improve the growing conditions by inhibiting pathogenic bacteria and hence increase yield.

The study also revealed that although the indoor mushroom growing 37equirees a higher initial investment cost for building a greenhouse, it also gives a higher yield of mushrooms and much higher annual profit to mushroom growers (see Table below). This is mainly because the mushrooms were more protected from insects, pests, and diseases.

Table 2: Comparative analysis of outdoor and indoor mushroom growing methods

Comparison Criteria	Out-door Method	In-door Method
Investment in growing house (mln. VND)	0	150
Growing cycles (no. of mushroom cycles/year)	1-2	8-9
Mushroom yield (kg of mushroom/meter of bed per cycle)	0.7-0.9	1.67
Mushroom production cost (thousand VND/kg of mushroom)	17.71-22.06	29.99
Selling price of mushroom (thousand VND/kg of mushroom)	24.00-32.05	44.12
Specific profit (thousand VND/kg of mushroom)	6.29-11.11	14.13
Annual profit (mln. VND/1,000 meters of bed per year)	19.99	211.96

Source: Annual Project Progress Report 2019, Sub-Institute of Agricultural Engineering and Post-Harvest Technology, Viet Nam

In line with the integrated approach of straw management, the substrate already used for mushroom growing was further used as a natural fertilizer for fruit trees and vegetables. This considerably reduced the application of chemical fertilizers and lowered the production cost. It also improved the porosity and fertility of the soil and reduced the negative impact on the environment induced by straw burning. The combined approach involved the application of machinery such as choppers and sterilizers, while other equipment such as water pumps, sensors, hygrometers, and thermometers helped to monitor mushroom growing conditions in the two greenhouses (ESCAP, 2020).

7. Country Profiles

This Paper examines how the agriculture sector, particularly the burning of post-harvest straw residue, directly impacts air quality in three countries in two sub-regions, South and Southeast Asia. It exposes some underlying factors that lead farmers to burn and explores possible measures and interventions that could improve air quality for millions.

Nepal, Cambodia, and Indonesia have been selected based on the following criteria:

1) Prevalence of straw residue burning as a key agricultural and air pollution concern
2) Predominance of smallholder farmers in crop production
3) Specific country request for supporting ongoing government programmes for straw residue management and other related areas, which can promote replication and sustainability
4) Priority was placed on countries on the UN's Least Developed Countries (LDCs) list.

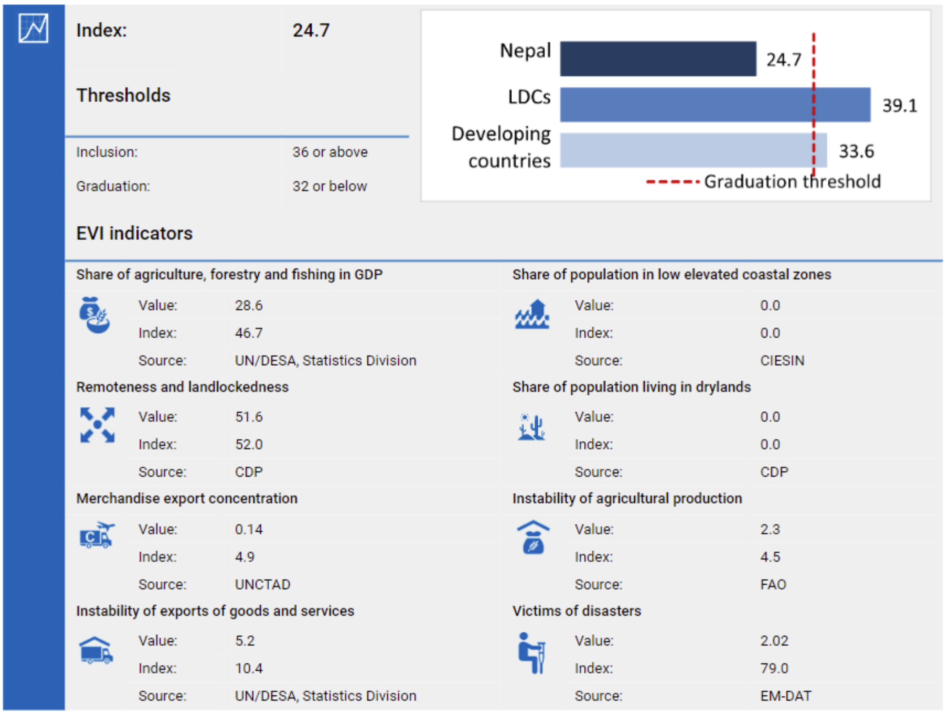
A. Nepal

Nepal is a landlocked trapezoid in South Asia of 143,350 km2 (UNCTAD STAT, 2020), surrounded by India to the east, south, and west and the Tibet Autonomous Region of China to the north. The region is known for its natural beauty; however, this small country is confronting several challenges environmentally and economically, including air pollution, which has historically impeded its efforts towards accelerating sustainable development and the related internationally agreed goals.

Since 1971 Nepal has been on the list of LDCs. It is scheduled to graduate from LDC status by 2026. However, in the face of increasing natural disasters worsened by climate change, geographic disparities, and traditional practice (i.e., discrimination, and the social and economic exclusion of women and vulnerable people) (UN Country Team Nepal 2017), progress has been hindered, and setbacks have occurred such as downward trends in the GDP, shrinking by -8.5 per cent in 2020 (34.19 to 33.66 billion USD) (UNCTAD STAT, 2020).

The results of this are visible when examining the country's economic and environmental vulnerability index (EVI) score, in which it lags behind other LCDs and developing countries. Some indicators for this index include the share of agriculture, forestry, and fishing in GDP (index 46.7) and instability of agricultural production (index 4.5) (see figure below) (UN Department of Economic and Social Affairs, 2021). As nearly one-quarter of the country's GDP depends on the farming community, this sector must be given the tools to grow sustainably and help Nepal graduate from LDC status.

Figure 16: Economic and Environmental Vulnerability Index (EVI)



Source: United Nations Department of Economic and Social Affairs (2021)

Over the last 20 years, Nepal has been in a period of transition and managing the outcomes of a decade-long conflict. Furthermore, it has weathered natural hazards such as earthquakes, drought, heatwave, river flooding, and glacial lake outburst flooding – which are all projected to intensify in the 21st century due to climate change. The most vulnerable communities to these disasters are those living in poverty, remote areas, and/or working in the agricultural sector (Climate Action Network South Asia (CANSA), 2022).

Despite these obstacles, Nepal has demonstrated its will to make the needed changes to become a Middle-Income Country (MIC) by 2030. This commitment is visible in its efforts to meet the SDGs. Not only was Nepal the first country to produce a national SDG report, but it also ratified its intent by including a plan under the 2015 Constitution. The Plan (Fourteenth Plan (2073/74-2075/2076 [2017-2020]) identifies five priority development strategies, each of which are closely linked to specific SDGs:

1. Increase growth and employment through tourism, small and medium businesses (SDG 8) and transformation of agriculture (SDG 1-2).
2. Infrastructure development: energy (SDG 7), road, air transport and information/ communication, rural-urban and trilateral linkages (SDG 9).
3. Sustainable improvement of human development through social development and social security/protection (SDG 1-6).
4. Promotion of good governance and human rights through effective and accountable public finance and clean, transparent and people-friendly public service (SDG 16).
5. Gender equality (SDG 5), social inclusion (SDG 1-6, 7, 8, 9, 10, 16), environmental protection (SDG 11-15) and maximum use of science and technology.

   (United Nations Country Team Nepal, 2017)

The Plan prioritizes an inclusive, multistakeholder partnership and the timely collection and analysis of data to inform policy and programme development to meet the 2030 Agenda for Sustainable Development. The federal model under the 2015 Constitution devolves various executive and legislative powers to provincial governments, which allows local governments the warewithal to truly localize their approaches to meeting the SDGs (UN Country Team Nepal 2017).

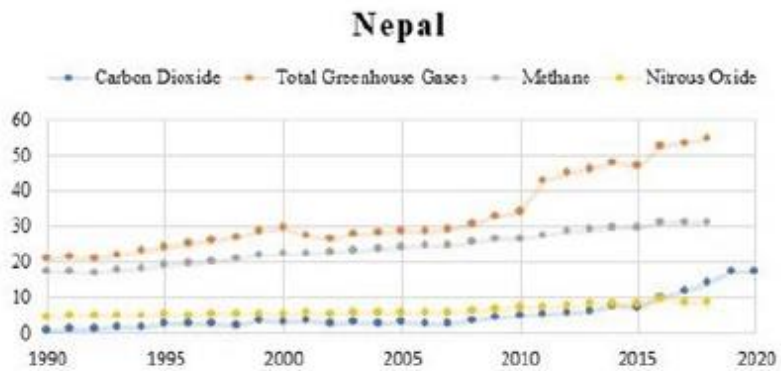
By addressing air pollution, progress can be made in all five of Nepal's priority areas to meet the 2030 Agenda and reach the goal of becoming a Middle Income Country.

(i) Air Quality

Over recent years, Nepal has often been topping lists for worst air quality and experiences some of the highest PM2.5 concentrations globally. According to the 2016 Environment Performance Index (EPI), Nepal ranked 177 out of 180 for air quality issues, just above its heavily industrialized neighbours, India, China, and Bangladesh (Kurmi 2016).

The country faces many issues in tackling this looming problem, including a rugged terrain of mountains and valleys that can trap air pollution, a lack of regulations on industry and agriculture, and expanding cities that demand construction and vehicles for their growth. Despite the country's commitment to reduce pollution, the issue is only growing. From 1990 to 2020, all major air pollution emissions rose (see below figure), with CO_2 emissions alone showing a 24-times rise from 0.72 million tons in 1990 to 16.97 million tons in 2020 (Abdul Jabbar, 2022). This is the highest rise in CO_2 emissions globally by a substantial amount, followed only by Bhutan (15-fold rise) and Bangladesh (6.6-fold rise) (Abdul Jabbar, 2022).

Figure 17: Nepal air quality data between 1990-2020



Note: CO2 is expressed in million tons. Total greenhouse gases, methane, and NO2 are all expressed in million tons of CO2-equivalents

Source: Abdul Jabbar (2022) (pg. 5)

Nepal also faces a troubling problem with PM2.5 pollution. According to the 2021 IQAir Index, it has the 10th worst concentrations of this air pollutant, with an average of 61.2 µg/m^3 – this over 12 times more than the air quality guideline limit of 5 µg/m^3 set by the World Health Organization (WHO). This is not a desirable state keeping in view the wellbeing of citizens and the dependence of the country on tourism, as exposure to PM2.5 pollution is associated with some of the most significant consequences for human health.

The impacts are not going unnoticed. For example, a 2014 study showed that respiratory diseases are the most common reason for outpatient consultations and chronic obstructive pulmonary disease (COPD) is the most common cause of mortality for inpatients (Kurmi 2016). These health issues are linked to exposure, long- or short-term, to PM2.5 pollution. In Nepal, as air pollutant emissions rise, so do deaths from COPD, with a 24 per cent increase in recent years (2000-2013), according to the country's Department of Health (Kurmi 2016).

While more research is needed to properly link Nepal's growing prevalence of cardiovascular diseases with worsening air quality, a pattern is starting to emerge. One study suggests that emissions from all sources in 2010 and 2015 resulted in an estimated annual air pollution health burden of 23,000 and 30,000 premature deaths (respectively, 1 in 1,000 persons) (Nakarmi, 2020). This study posits that if Nepal continues with its projected growth in emissions, air pollution-associated health burdens will increase to 50,000 premature deaths in 2030 and 109,000 premature deaths in 2050, with nearly 88 per cent of premature deaths due to PM2.5 exposure (Nakarmi, 2020).

Nepal's sources of air pollution are varied, but it is believed that 80 per cent of emissions are generated in the dry season, February to May, and predominately arise from the open burning of crop residue known to cause intense spikes in PM2.5 emissions (Das, 2020). Therefore, changing agricultural practices that rely on biomass burning will dramatically improve the air quality and quality of life for the Nepalese people and those throughout the sub-region exposed to these transboundary air pollutants.

(ii) Agricultural Burning

Nepal occupies a small, landlocked area of 147,181 sq. km. Of this, 28 per cent of the land is designated as agricultural, yet, the agriculture sector is where 64 per cent of the population works, and it contributes to about one-third of the national GDP (Das, 2020). This extremely valuable sector of Nepal's economy has upscaled agro-based activities, particularly in the Indo-Gangetic plain (IGP), to meet rising food demand over the last decades. This growth has forced the region to move away from traditional practices and instead employ commercial agricultural practices, which has brought the mechanization of farming to Nepal (Bajracharya, 2021).

While this mechanization is good for crop production, it has had unintended consequences as well. For example, in traditional manual practices, straw left in the field after harvesting had short stalks and was easily collected and used for livestock and household purposes such as roofing and cooking. However, modern machinery (i.e., combine harvesters) leaves longer, unmanageable stalks that are challenging to collect and re-integrate as a resource (Bajracharya, 2021). Furthermore, the need for post-harvest straw in farming communities has changed with modernization, as it is rarely needed for livestock management (i.e., fodder) or household uses (i.e., cooking), demotivating farmers to bother to collect this more cumbersome straw residue left by modern machinery.

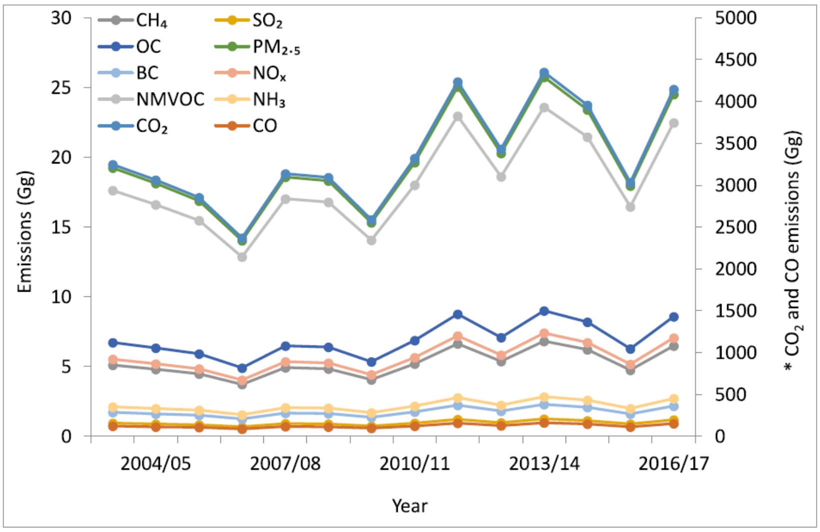
Another pressure that farms face is increased food demands, which has led to shortened planting and cropping cycles to produce higher annual yields. This demand has also significantly cut the time between planting cycles to prepare the fields between harvest and planting, meaning they seek the quickest and cheapest way to get rid of unwanted straw residue, which is often believed to be handled with controlled open fires in the fields of the straw (Bajracharya, 2021).

A study of Nepalese farmers found the following factors significant in a farmer's decision to burn crop straw openly or re-integrate it into their model:

- Farms, where combine harvesters are used, are 54 per cent more likely to burn crop straw than farms using manual labour.
- Farmers owning livestock were 26 per cent less likely to use combine harvesters. These farmers were more likely to harvest the crop manually and less inclined to burn the crop residue, as the residue was used for livestock feeding and bedding purposes.
- Farmers whose primary source of income was through non-farm employment were 8 per cent more likely to burn crop residue than farmers whose primary source of income was agriculture.
- Farmers aware of the adverse effects of burning the residue were 7 per cent less likely to burn.
- A larger household size meant the farmer was 1.3 per cent less likely to burn the crop residue.
  (Bajracharya, 2021)

Some of this straw residue is used for traditional methods and has even increased at pace with the amount of dry matter generated (29 per cent), but it is not enough to keep up with the production growth (Das, 2020). Demonstrating this, a 2003-2017 study shows that trends in crop residue burning emissions have steadily increased, noting the extreme dip in 2015 is likely due to the devastating earthquake in April of that year (see Figure below) (Das, 2020).

Figure 18: National trends in emissions from crop residue open burning (2003-2017)



Source Das et al. (2020)

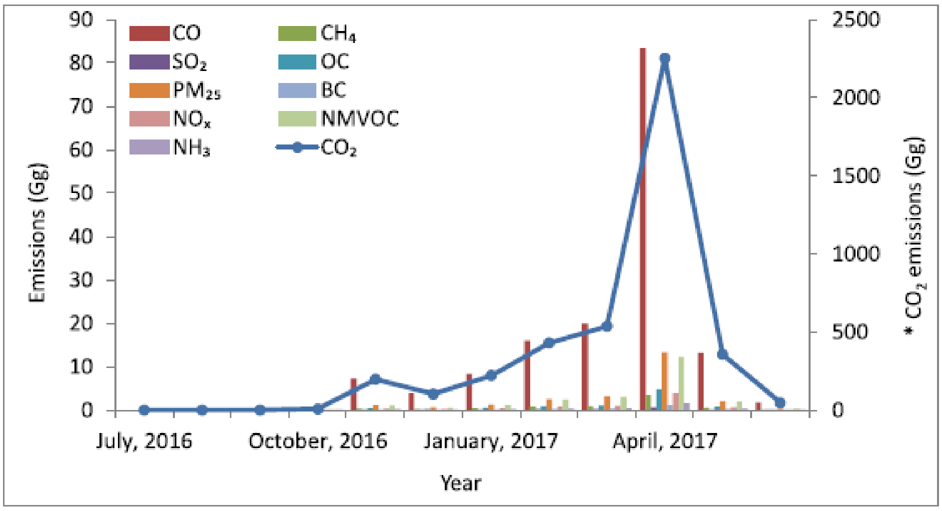
Table 3: **National emissions trend from crop residue burning (in Gg)**

Year	CO_2	CO	CH_4	SO_2	OC	$PM_{2.5}$	BC	NO_x	NMVOC	NH_3
2003/04	3250	120	5.1	0.9	6.7	19.2	1.7	5.5	17.6	2.1
2004/05	3060	114	4.8	0.9	6.3	18.1	1.6	5.2	16.6	2.0
2005/06	2850	106	4.5	0.8	5.9	16.9	1.5	4.9	15.5	1.9
2006/07	2370	88	3.7	0.7	4.9	14.0	1.2	4.0	12.9	1.5
2007/08	3140	116	4.9	0.9	6.5	18.6	1.6	5.3	17.0	2.0
2008/09	3090	115	4.9	0.9	6.4	18.3	1.6	5.3	16.8	2.0
2009/10	2590	96	4.1	0.7	5.4	15.3	1.4	4.4	14.0	1.7
2010/11	3320	123	5.2	1.0	6.9	19.6	1.7	5.6	18.0	2.2
2011/12	4240	157	6.6	1.2	8.8	25.1	2.2	7.2	23.0	2.8
2012/13	3430	127	5.4	1.0	7.1	20.3	1.8	5.8	18.6	2.2
2013/14	4350	161	6.8	1.3	9.0	25.7	2.3	7.4	23.6	2.8
2014/15	3960	147	6.2	1.1	8.2	23.4	2.1	6.7	21.5	2.6
2015/16	3030	112	4.8	0.9	6.3	18.0	1.6	5.2	16.5	2.0
2016/17	4140	154	6.5	1.2	8.6	24.5	2.2	7.0	22.5	2.7
Avg.	3340	124	5.2	1.0	6.9	19.8	1.8	5.7	18.1	2.2

Source Das et al. (2020)

Furthermore, large agricultural fires detected by the MODIS instrument onboard NASA satellites show an increase in open crop residue burning and indicate that this is the greatest source of air pollution in the rice harvesting season (October–November) and the wheat harvesting season (April–May) (Bajracharya, 2021). The figure below shows that 86 per cent of the total air pollutant emissions occurs from February to May, with the peak occurring in April. These peaks correlate with active fire counts in the country (Das, 2020).

Figure 19: **Monthly variations of emissions (2016/2017)**



Source Das et al. (2020)

All of this points to the need for alternate solutions to burning. The above list of factors indicates that mechanization and capacity building are critical places of development to help the Nepalese agricultural community transition to sustainable practices while continuing to grow their production.

(iii) Solutions

The work for Nepal to establish emission control policies began after the Earth Summit 1992 with the introduction of "Vehicle Emission Control in Kathmandu Valley 1993". Furthermore, the 2015 Constitution of Nepal has guaranteed people's right to live in a clean and healthy environment [Article 35: 1 and 2] and reinforced this with the Nepal Health Research Council and National Health Policy of Nepal (2014) placing 'air pollution as a priority on the research/public health agenda. However, past experiences in the country suggest that implementation is a major concern (Kurmi, 2016).

Based on an analysis of studies and ongoing ESCAP projects to understand the needs of Nepalese farmers and the determinants of the farmer's behaviour that leads to open crop burning, the following priority areas have been identified to help the country move away from burning:

1. **Raising livestock and using straw as fodder**
   There is a positive influence from raising livestock in curbing open crop burning towards its utilization as livestock feed among Nepalese farmers. Encouraging raising of livestock and employing machinery like straw choppers that make using straw as feed accessible will help farmers move away from burning practices. (Bajracharya, 2021).

2. **Modifying the use of combine harvesters **
   The use of combine harvester is directly linked to the incidences of burning. One of the drawbacks of the combine harvesters that leads to the burning of the residue is the spread-out residue. It is difficult and time-consuming to manage this and then sow seeds for the next crop. This can be addressed by making collecting the residues and sowing for the next crop convenient for the farmers through modified combine harvesters equipped with residue collectors. Discussions with the farmers revealed that they are willing to use the technology so long as it is economically viable (Bajracharya, 2021) (Das, 2020).

3. **Raising awareness and changing perceptions of farmers**
   If the negative impacts of burning were understood, farmers are 7 per cent less likely to burn. However, a study in Nepal showed that two out of five farmers were unaware of the harmful effects of open burning on the environment, and 36 per cent were unaware of the health effects. Hence, programs that inform the community about these hazards will discourage burning. (Bajracharya, 2021).

4. **Promoting alternate uses of crop residue**
   Promoting alternate ways of disposing of the crop residues like in-situ utilization as mulch, using it as raw materials for industries like brick kilns, paper production, and mushroom cultivation have proven effective, as many farmers do not know all of the benefits of using this resource to its fullest potential.

Interestingly, Nepal has a unique opportunity to work with women in farming. The country has been undergoing ‘feminization of agriculture’ because 95 per cent of Nepalis out-migrating in 2016/17 were men. This has radically changed rural socio-cultural dynamics. Women in agricultural communities have taken the responsibilities of the missing menfolk and are making major decisions related to farming practices, including making investments to improve farming practices (ICIMOD, 2020).

This phenomenon of the feminization of agriculture may very well be a good thing for air quality as research indicates that women understand more so than men that crop residue burning harms the health of their families, the environment, and soil productivity in the long run. Furthermore, they are acutely aware of how fires impact their families as they deal with the health consequences as caretakers and experience the air pollution that remains and affects their homes for up to two weeks after the fires (ICIMOD, 2020). This implies that women may be more receptive to changes like sustainable agricultural mechanizations as they understand it would protect the health of their loved ones and reduce the amount of manual labour required in the fields.

B. Cambodia

The Kingdom of Cambodia occupies an area of 176,520 km2 area in Southeast Asia's southern portion of the Indochina peninsula, and has a population of 16.719 million. It shares land borders with Vietnam, Thailand, and Laos and has a coastline on the Gulf of Thailand. It is one of the most biodiverse countries in Southeast Asia, with over 8,000 plant species (10 per cent of which may be endemic) and over 16,000 amphibian, reptile, fish, and bird species (Fauna & Flora International, 2022). However, due to many unsustainable aspects of its rapid development, Cambodia’s unique environment is at risk with nearly 300 species listed as threatened (IUCN, 2022). The loss of biodiversity is primarily because of the loss of forest cover, which has fallen 20 per cent since 1990 (Fauna & Flora International, 2022) and pollution of water and air from industry, agriculture, and crowded cities.

Yet, Cambodia has demonstrated committed to protecting its environment, with the Constitution including the States’ responsibility to protect the environment and establish a precise plan for the management of land, water, air, wind, geology, ecological system, mines, energy, petrol and gas, rocks and sand, gems, forests and forestry products, wildlife, fish, and aquatic resources (Kingdom of Cambodia 1993). Based on this, The Royal Government of Cambodia (RGC) implemented a Climate Change Strategic Plan 2014 – 2023 (CCSP). The vision of the CCSP was to develop a green, low-carbon, climate-resilient, equitable, sustainable, and knowledge-based society. The plan was designed around a national framework engaging the public and private sectors, civil society organizations, and development partners in a participatory process to respond to climate change to support sustainable development.

To achieve the vision and goals of the CCSP, the Royal Government of Cambodia identified and has been working with eight strategic objectives:

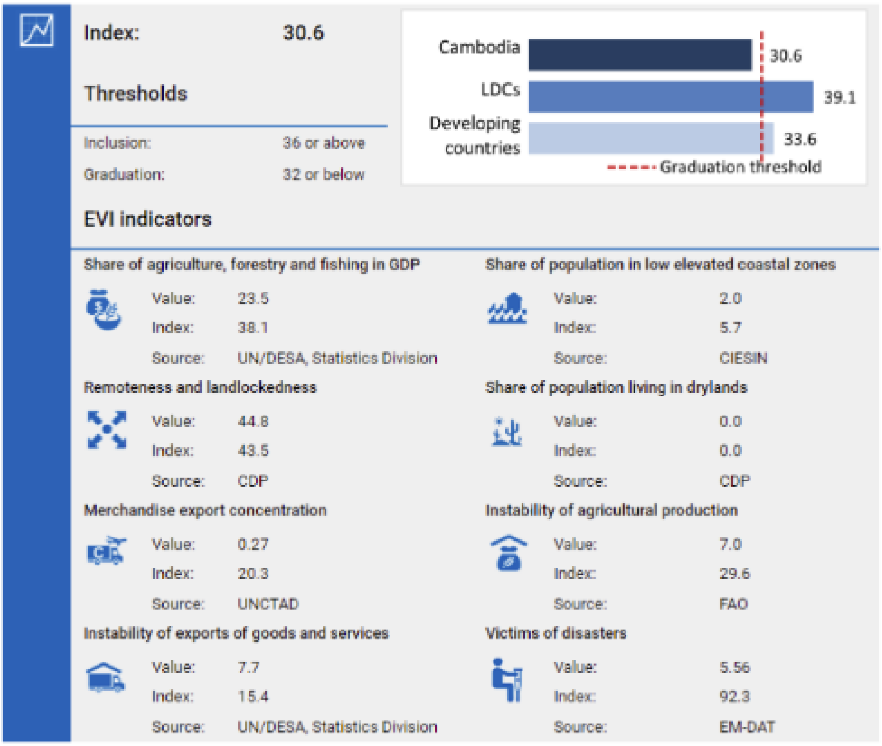
1. Promote climate resilience through improving food, water, and energy security.
2. Reduce sectoral, regional, gender vulnerability, and health risks to climate change impacts.
3. Ensure climate resilience of critical ecosystems, biodiversity, protected areas, and cultural heritage sites.
4. Promote low-carbon planning and technologies to support sustainable development

5. Improve capacities, knowledge, and awareness for climate change responses.
6. Promote adaptive social protection and participatory approaches in reducing loss and damage due to climate change.
7. Strengthen institutions and coordination frameworks for national climate change responses.
8. Strengthen collaboration and active participation in regional and global climate change processes.

(Royal Government of Cambodia, 2013)

These measures have all aided Cambodia in meeting the criteria to graduate from the LDC list, which was achieved in 2021. However, as a requirement, the country must prove in 2024 that it has maintained sustainable growth. This may be challenging as the country is lagging on its economic and environmental vulnerability index (EVI) (30.6) behind other LDCs (see below), with indicators including share of agriculture, forestry, and fishing in GDP (index 23.5) and instability of agricultural production (index 7.0).

Figure 20: Economic and Environmental Vulnerability Index (EVI)



Source: United Nations Department of Economic and Social Affair (2021)

Progress on ensuring environmental and economic sustainability needs to be made rapidly in the country. Nearly 61 per cent of Cambodians live in rural areas where 77 per cent of rural households rely on agriculture, fisheries, and forestry for their livelihoods (USAID, 2022); protecting this population and the agricultural sector should be a priority area for improvement. However, according to FAO, despite the country being a large producer of food, 45 per cent of Cambodians live in moderate or severe food insecurity (UNDAF, 2019).

The agricultural sector is further threatened by climate change as Cambodia is recognized as highly vulnerable to climate change impacts, ranking 140th out of 181 countries in recent reports on climate vulnerability and is projected to experience warming of up to 3.6°C by the 2090s (World Bank Group, 2021). The projected rising temperatures, heat waves, and changing rainfall patterns will all impact growing seasons, creating consequences in crop quality and labour productivity (UNDAF, 2019). It is estimated that if changes are not made, Cambodia will experience an overall 10 per cent drop in GDP by 2050 due to climate change (World Bank Group, 2021).

The Royal Government of Cambodia needs to continue prioritising agriculture as a sector to generate jobs, ensure food security, reduce poverty, and develop the rural economy. The current thrust of commercial development in agriculture creates opportunities for the transformation of agricultural systems, which can result in productivity and efficiency gains (UNDAF, 2019). Furthermore, supporting this sector can help ensure Cambodia graduates from LDC status and can achieve other global goals, such as the SDGs and its Nationally Determined Contributions (NDCs).

(i) Air Quality

Since 2010 Cambodia has experienced tremendous growth, almost doubling its GDP per capita. However, many economic activities that supported this growth are coupled with some key air pollution sources (i.e., increased vehicles, fuel consumption in industries and businesses, agricultural production, waste generation) (Malley, 2022). Currently, Cambodia ranks 125th out of 180 countries for air quality according to the Environmental Performance Index (EPI).

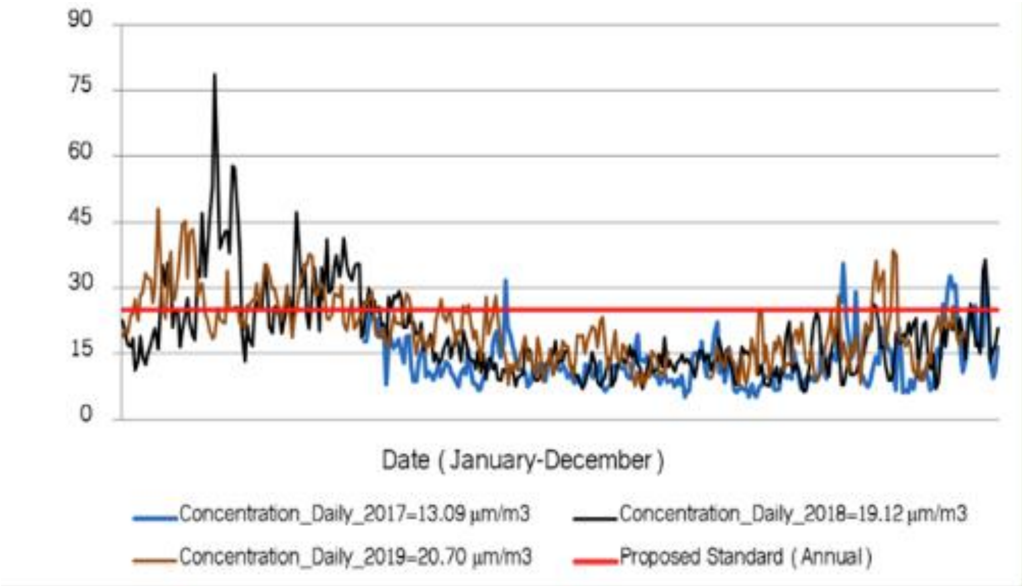
In 2019 population-weighted exposure to PM2.5 was four times the WHO guideline, at 22.1 µg m-3 (Malley, 2022). This level of exposure is associated with a substantial health burden, with 17,000 premature deaths attributed to ambient and household PM2.5 exposure (Malley, 2022). In 2020, when air pollution was anticipated to decrease due to the pandemic, Cambodia saw the greatest rise (26 per cent) in PM2.5 emissions over any other country in Southeast Asia (Greenstone, 2022). Based on current air pollution levels, Cambodians will gain 1.6 years of life if the country can meet the WHO guidelines (Greenstone, 2022).

Cambodia has many sources of air pollution. For instance, due to its arid climate, most of the land is flat with sparse vegetation and dust is easily picked up by the winds, getting into the air and deteriorating air quality. However, most of Cambodia's air quality issues come from anthropogenic sources. Take, for example, the country's rapidly growing cities whose construction calls for the demolition of the old to make way for the new, bringing vast amounts of construction dust (IQAir, 2022). Moreover, while Cambodia is not a largely industrialized country, many factories use old equipment that does not meet standards or regulations. The garment industry, brick kiln, rice milling, and rubber processing industries have all been identified as contributing factors to Cambodia's air pollution (IQAir, 2022).

The transport sector also has a significant impact on air quality in Cambodia. As the country's middle-class grows, so does the number of vehicles and motorcycles on the road; in 2016, there was a 14 per cent increase in registered vehicles (IQAir, 2022). These increased fuel emissions are most noticeable in the metropolitan areas of Phnom Penh and Siam Reap. These emissions have even been blamed for some of the rapid deterioration of the ancient sites (i.e., Angkor Wat) that Cambodia is renowned for (IQAir, 2022).

Dust, industry, increased road traffic and fuel consumption, and growing cities are significant sources of the year-round elevated air pollution levels in the country. However, Cambodia experiences major air pollution spikes, particularly in PM2.5 pollution, during their dry/winter post-harvest months (see figure below). Cambodia is believed to experience this high PM2.5 pollution spike annually, predominately from agricultural fires set to clear land and manage the by-products of food production (Greenstone, 2022).

Figure 21: PM2.5 concentration in Phnom Penh (2017-2019)



Source: Department of Air Quality and Noise Management, Cambodia (2020)

(ii) Agricultural Burning

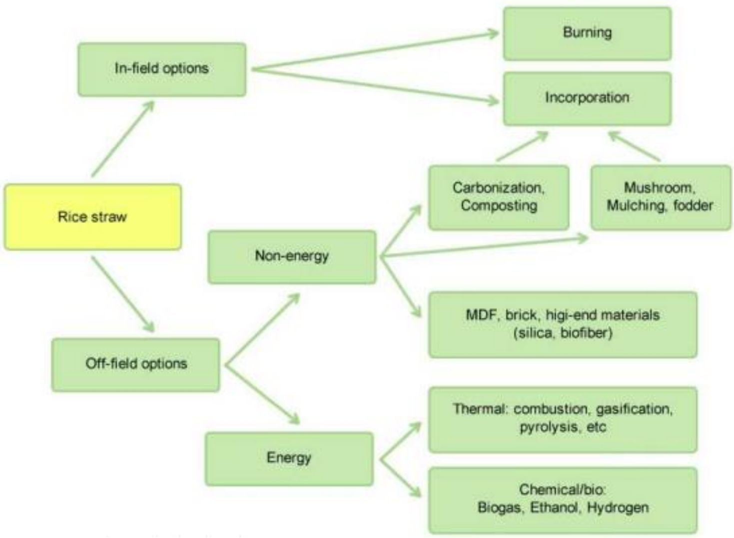
The agriculture sector in Cambodia is valued at nearly a quarter of its total GDP and accounts for around 40 per cent of its labour force. This already large production area for the country has pressure on it to grow to meet rising food demands. To create overall sustainability for the sector, it will need to modernize many of its practices while using models that mitigate environmental impacts—for example, moving away from using burning methods to clear land and manage agricultural waste.

The open burning of post-harvest straw residue is a common practice due to the traditional practices based on the viewpoint that burning is the best way to clear land, rid themselves of waste, and increase soil fertility for the least amount of money. However, these fires have consequences, and as farming production is on the rise, so are the fires. Moreover, with the temperature increases anticipated by climate change, these fires will more quickly get out of control, become more pervasive and consume more of Cambodia's precious forest lands.

A study using Visible Infrared Imaging Radiometer Suite (VIIRS) active fire and land use products to classify biomass burning data for South Asia and Southeast Asia found that Cambodia (2012-2016) had the third highest fire counts among the sub-regions at nearly 200,000 in only 4 years (Vadrevu, 2019). 62.65 per cent of the fires in Cambodia are forest fires, mainly due to slash and burn methods and timber harvesting. When analyzing the data, 78.7 per cent of all of Cambodia's hotspots were proven to stem from anthropogenic burning based on the repetition of hotspots (Vadrevu, 2019).

Cambodia has a total arable land mass of 4,505,267 hectares, of which over half (2,818,323 ha) is used for rice cultivation, making it by far the most important crop for the agricultural sector, followed by sugarcane, cassava, and maize. Rice production comes with large amounts of straw residue; in Cambodia, it equates to about 10 million tonnes annually. While some of this is used as silage for cattle or mushroom and vegetable production, much of it is left decaying in the field without proper treatment and annually, it is believed that 3 million tonnes of straw residue from rice harvesting alone is openly burnt in Cambodia.
Cambodia's unique ecosystem that has a rippling effect on the entire sub-region and its dependence on the vulnerable agricultural sector indicates that effort is needed to mitigate air pollution and support the modernization and development of the farming community to stay on track in relation to global goals and agreements. on track in relation to global goals and agreements.

Figure 22: Options for rice straw management in Cambodia



Source: www.knowledgebank.irri.org

Cambodia's unique ecosystem that has a rippling effect on the entire region and their dependence on their vulnerable agricultural sector indicate that effort is needed to mitigate air pollution and support the modernization and development of the farming community to stay on track with global goals and agreements.

(iii) Solutions

Cambodia's 2014-2023 Climate Change Strategic Plan (CCSP) includes mitigation measures to tackle the country's sources of air pollution and reduce the risk of exposure to citizens. This cross-sectoral plan addresses the specific barriers and vulnerabilities the country faces when combatting air pollution, and its framework is dependent upon enhancing climate resilience, building capacity, and enhancing collaborations and partnerships across government ministries.

The Nation has demonstrated its commitment to reducing air pollution by practising monitoring and giving the Ministry of Environment of Cambodia the power to regulate emissions (The Royal Government of Cambodia, 2000). Ambient air quality standards for the protection of human health for CO, NO_2, SO_2, O_3, lead (Pb), and Total Suspended Particulates (TSP) have all been set. However, these standards have not been updated since their inception in 2000 and no longer align with the recommended levels set by the WHO in the air quality guidelines, nor do they cover all pollutants which negatively impact health and the environment, notably, PM2.5. Therefore, Cambodia must tighten its quality air regulations to stay on track with global standards (Malley, 2022).

These regulations must further be enforced, requiring more efficient measuring and monitoring. This data will not only pinpoint air pollution hotspots so that interventions can be made but also be used to keep residents in danger of exposure aware of the risks and what they can do to protect themselves from the potential harm. According to the Cambodia real-time Air Quality Monitoring project, the best solution for providing real-time Air Quality information is for the Ministry of Environment of Cambodia to provide official hourly AQI readings. This requires investing in more air monitoring stations and the capacity to manage and distribute the data they provide.

Once hotspots are identified, appropriate interventions can be put in place. To identify the most effective types of interventions, Cambodia joined the Climate and Clean Air Coalition in 2014 and has received funding and technical support from the Coalition's partners for activities that align with the Coalition and UNEP's 25 Clean Air measures for Asia and the Pacific. Furthermore, Cambodia's updated Nationally Determined Contributions have identified detailed mitigation action plans, including one focused on the agricultural sector.
In terms of managing leftover straw residue, Cambodia's Department of Agriculture and Engineering has identified the following priority areas to reduce agricultural biomass burning;

- Designing and developing prototype machinery to collect rice straw.
- Improving mushroom and ruminant production technology to increase rice straw's quality, value, and markets.
- Improving technology for bioenergy.
- Researching and educating the farmer using rice straw on sustainable rice production.
- Database and Geographic Information System (GIS) map of rice straw.
- Mechanized collection solutions and supply chain models.

C. Indonesia

The Republic of Indonesia is the largest country in Southeast Asia and the largest archipelago in the world, stretching 5,100 km from east to west of about 1,800 km. It is composed of some 17,500 islands, of which more than 7,000 are uninhabited. It shares borders with Malaysia and Papua New Guinea (Leinbach, T.R., 2022). The major islands are characterized by volcanic mountains in lush forests that sweep toward coastal planes and swamps that dissolve into the Indian and Pacific Oceans (Leinbach, T.R., 2022).

Indonesia contains 34 provinces, 1,300 ethnic groups, and 270 million residents, making it the fourth most populous country in the world. Indonesia's capital and largest city, Jakarta, is the world's second-largest urban cluster, with a population density of 13,000 people per km2. This primate city is known for its traffic and currently boasts 20 million vehicles on the road daily in its 4,384 km2 area (Matinez R., 2020). With an urbanization rate of 57.29 per cent and a growing middle class, the number of people living and driving in the already congested city will only rise.

This growth has provided tremendous economic development with an income gain of 5 per cent annually and significantly reduced poverty rates. Currently, the country is the world's 16th largest economy, and by 2050, it is believed that the Republic will be one of the world's leading economies (UNSDCF, 2020).

However, in terms of risk exposure, Indonesia is exceptionally vulnerable to natural disasters. The archipelago and volcanic history that makes Indonesia's landscape so remarkable is also the cause of its exposure, as it sits in the 'ring of fire' – a notorious centre of earthquakes, tsunamis, and volcanic eruptions. The country is also enormously susceptible to the disasters brought on by climate change, such as floods, mudslides, droughts, wildfires, and storms (UNSDCF, 2020). The greater consequences of these disasters include a decrease in food production, disruption of water availability, the spread of pests and plant diseases, human diseases, rising sea levels, the sinking of small islands, and the loss of biodiversity (Ma'ruf, 2021).

Therefore, protecting and maintaining the natural environment is of utmost importance to Indonesia. In legislation passed in 2009, the Environmental Protection and Management Law Number 32, the government put its responsibility to create a sustainable environment in writing, with focus on development through means of an environmental planning policy and the rational exploitation, development, maintenance, restoration, supervision, and control of the environment.

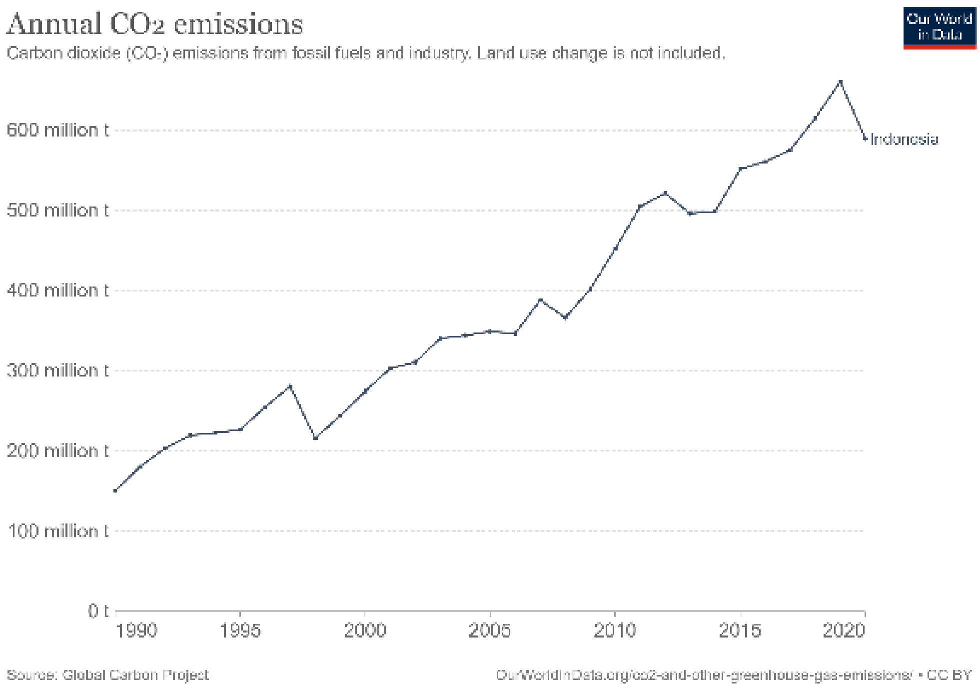
In Article 3 of Law no. 32 2009, the objectives of the Environmental Protection and Management are prioritized as follows:

- Protect the territory of the Unitary State of the Republic of Indonesia from pollution or environmental damage
- Ensure safety, health, and human life
- Ensure the survival of living things and the preservation of ecosystems
- Maintain the preservation of environmental functions
- Achieve harmony and environmental balance
- Ensure the fulfilment of justice for present and future generations
- Guarantee the fulfilment and protection of the right to the environment as part of human rights
- Controlling the wise use of natural resources
- Realizing sustainable development
- Anticipate global environmental issues.

(Ma'ruf, 2021)

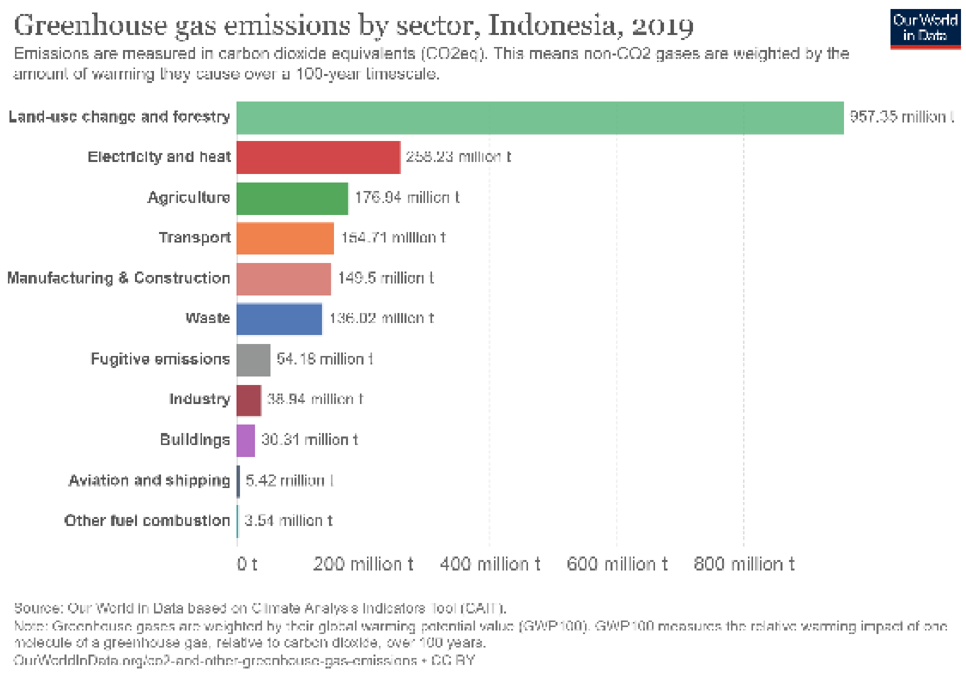
Despite efforts to mitigate climate change, in 2015, Indonesia was ranked as the world's fourth largest emitter of GHGs. In 2018, its GHG levels were at 542 metric tonnes, an increase of 313.47 per cent from the 1990 levels (see figure 23 below). These emissions and huge increases largely stem from deforestation, peatland fires, and, to a lesser extent, the burning of fossil fuels for energy, followed by agricultural production (see figure 24 below).

Figure 23: **Annual CO_2 emissions from fossil fuels and industry (land use change is not included)**



Source: Global Carbon Project

Figure 24: **Greenhouse gas emissions by sector, Indonesia, 2019**



Source: Our World in Data based on Climate Analysis Indicators Tool (CAIT)

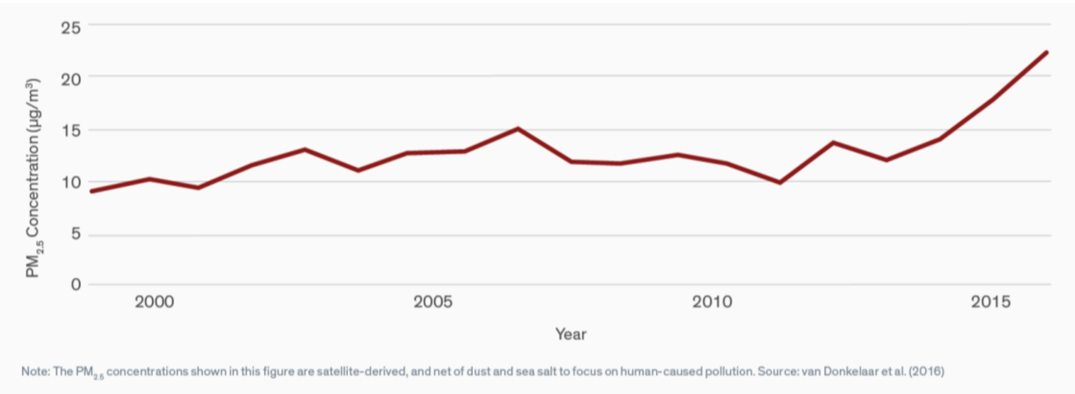
In 2021 Indonesia, with a focus on achieving the SDGs and commitment to reducing its contributions to climate change, submitted a long-term climate strategy, along with the specific aim to cut GHG emissions by 29 per cent. As a result, more extraordinary efforts than ever before are being made to expand and strengthen conservation areas, measures, and regulations to preserve life on land and below water (UNSDCF, 2020).

The agriculture sector of Indonesia is a significant emitter of GHGs, is negatively impacted by climate change, and contributes to 13.8 per cent of GDP - employing almost half their total population (United Nations, 2022). Therefore, by prioritizing sustainable development actions in this sector, significant gains can be made in combatting climate change, protecting vulnerable populations – particularly in rural areas, increasing food security, and reducing air pollution.

(i) Air Quality

Air pollution was not a pressing issue in Indonesia till just two decades ago, but the quality of the air Indonesians breathe has declined dramatically in recent times. From 1998 to 2016, the country went from being one of the cleaner countries in the world to one of the twenty most polluted, as particulate air pollution concentrations increased by 171 per cent (Greeenstone, 2019). PM2.5 more than doubled between 2013 - 2016 alone (see figure below), with some of this burden due to intense fires.

Figure 25: Indonesia's annual average PM2.5 concentration, 1998-2016 (µg/m^3)



Source: Greenstone (2019)

Indonesia has the fifth highest loss of life due to PM2.5 pollution exposure in the world, with the average Indonesian expecting to lose at least 1.2 years due to the air they breathe. These health effects are much more prominent in parts of the country with exceptionally high PM2.5 pollution. For example, residents of Palembang in fire-prone South Sumatra lose almost 5 years, and Jakarta residents can expect to lose 2.3 years if 2016 pollution levels are sustained over their lifetime (Greeenstone, 2019).

In 2021 a Jakarta court ruled in favour of a citizen-led lawsuit regarding safe, clean air to citizens. The court based its decision on leading research that showed that in 2017 alone, there were 123,800 deaths in Indonesia attributable to air pollution exposure, including 52,100 deaths caused by PM2.5 , 68,100 deaths caused by household air pollution from solid fuel combustion, and 4,680 deaths caused by ambient ozone pollution (Greeenstone, 2019).

A variety of sources contribute to particulate air pollution in Indonesia. In Jakarta, motor vehicles accounted for 31.5 per cent of the city's PM2.5 in 2008-2009. There have been sharp increases in electricity generation from coal-fired power plants and gasoline and diesel consumption since 2010, contributing to increased air pollution issues. However, smoke from fires and the effects of deforestation remains a constant and growing hazard. In 2021, Indonesia saw fires burn more than 350,000 hectares of land, a 16 per cent increase over 2020 (United Nations, 2022). These fires often originate from the agriculture sector due to unsustainable practices, such as open biomass burning to manage crop straw.

This biomass burning affects air quality not only in the immediate surrounding area but travels vast distances and can impact millions of people downwind of the fires (Kiely, 2020). For example, these fires are responsible for 31 per cent of Jakarta's PM2.5 concentration, and during the El Nino drought years (1997 and 2015) created a haze of air pollution across Southeast Asia, affecting health and air travel in Indonesia, Singapore, Malaysia, and beyond (Greeenstone, 2019).

(ii) Agricultural Burning

Over 40 per cent of Indonesians live in rural areas (World Bank 2023a) where agriculture is their main source of income. Around 14 per cent of those in the farming community are classified as poor compared to those in urban areas, where only 8.2 per cent live below that line (International Fund for Agricultural Development (IFAD) n.d.). The Ministry of Environment and Forestry data from 2017 suggests that of 9.2 million village households in or at the forest fringe, 1.7 million are low-income households (United Nations, 2022).

However, the agricultural sector, together with forestry and fishing, contributes over 13 per cent of the nation's GDP (World Bank, 2023b) and has an essential role in supporting economic growth, food security, employment, and community empowerment. As an agrarian country with abundant fertile soil and a growing middle class demanding more diverse products, the sector has the opportunity to grow. Rice production, a vital crop for the country, has been on the rise since the 1960s, with an average increase of 2.4 per cent per year (Rifin, 2022), Indonesia produced 49.37 million tonnes of paddy (equivalent to 28.45 million tonnes of rice) across 10.41 million hectares (Statistics Indonesia, 2022).

This growth of Indonesia's agriculture sector must be planned for sustainability to stay on track with environmental targets to mitigate climate change. However, the sector is struggling to modernize and manage increased crop yields. A particular problem is fires started in open fields to dispose of by-products from food production. For example, an estimated 10.0 to 12.2 million tonnes of crop residues have been burnt yearly between 2017 and 2020 (FAOSTAT, 2023) negatively impacting the lives of millions and adding to greenhouse gas emissions.

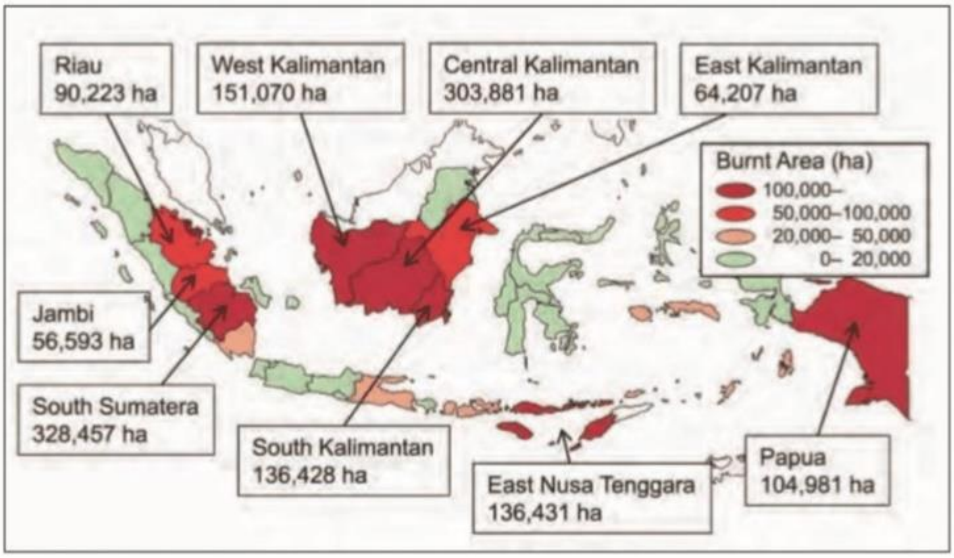
Despite the consequences, farms frequently opt to continue to burn based on the following factors:

- Lack of labour
- High labour cost
- Farmer awareness
- Lack of appropriate machine for straw management
    - Collecting straw in the field
    - Transporting straw from the field
    - Processing straw into (i.e., compost, fodder, silage)

- Poor farm infrastructure

While the smoke from the burning of straw is key as an emissions issue, a more troubling factor is how easily these open fires spread to become uncontrollable forest and peatland fires, particularly in Sumatra and Kalimantan, where forest and peatland fires associated with these burning methods are significant contributors to particulate pollution. This is because much of Indonesia's forests lie atop peatlands consisting of thick layers of decomposed carbon-rich plant matter. Fires on peatlands can burn deep into these layers, even after the surface fire has been extinguished, smouldering for an extended amount of time (days to weeks), thus leading to substantial emissions of PM2.5 and GHGs (Kiely, 2019). Furthermore, these fires have devastated Indonesia's unique ecosystem. The figure below reviews hectares lost in 2019 from burning activities.

Figure 26: Hectares lost in 2019 from burning activities, Indonesia



Source: Tropical Peatland Society Project, 2019

(iii) Solutions

While the issues of air pollution are relatively new to Indonesia, there have been several steps taken to try to reduce emissions. For example, Indonesia's Environmental Protection and Management Law Number 32 (2009) prohibits the burning of straw. Unfortunately, this ban has not been adequately communicated or enforced, as illegal open burnings persist throughout the Republic. However, a court ruling in 2021 underscored the need for the State to adequately protect citizens from air pollution.

Indonesia is working rapidly to respond to the need for transformation in relevant systems to promote clean air, as demonstrated by its 2021 re-submission in relation to the 2030 climate goals, with aggressive GHG reductions also targeting some major air pollutants. Furthermore, the will of the Government to improve food systems and meet the SDGs was reaffirmed at the Food Systems Summit convened by the United Nations in September 2021 by the Minister of National Development Planning, who outlined the Government's main objectives in the agricultural sector, namely to 1) create a sustainable agricultural sector that is inclusive, resilient, and sustainable, 2) provide special support for small-scale farmers, and 3) boost international cooperation and multi-stakeholder partnerships.

The court ruling - which was brought upon the State as a civil suit, new GHG emissions targets, and commitments made during the Food Systems Summit all provide leverage for the Indonesian government to invest in building capacity, strengthening regulations, and enforcing them on polluters, as ensuring clean air is the will of the court, the people of Indonesia and their Government, and the global community.

The evidence of the case brought to light two immediate areas for improvement. First, emissions standards must be immediately updated to meet global standards. While standards exist, they vary for Jakarta and the rest of the country and are weaker than the World Health Organization recommendation for the maximum average annual concentration of PM2.5. Secondly, the geographic coverage of air quality monitoring stations is limited, predominately in Jakarta, and, until only recently, did not monitor PM2.5 pollution. Therefore, Indonesia urgently needs to increase their capacity to monitor to enforce tighter regulations.

Furthermore, interventions at hotspot sites to prevent burning are excellent mechanisms to meet the Government's goals of creating a sustainable agricultural sector and supporting small-scale farmers. As rice straw is typically burnt (before 2009, this was estimated at 85- 90 per cent), left to decompose in the field, and less frequently used for fodder or rudimentary till-in fertilizer, there is room to develop innovative uses for straw that could manage this by-product without environmental damage and provide a resource for the farming community.
A study estimated that if the wasted rice, straw, and husk produced annually in Indonesia were converted to electricity, nearly one-fifth of national energy production could be supplied from crop residue (Rhofita, 2022). This could be achieved through physical, biochemical, or thermochemical processes (Rhofita, 2022). If Indonesia explores and develops new technologies like this, it has the two-fold potential of dramatically reducing air pollution and dependency on fossil fuels.

Lastly, Indonesia must work cooperatively on this issue within its borders, with its neighbours, and with the global community. As the country covers a large and diverse terrain, population and culture, its internal government offices are often fragmented, demonstrated by the different air quality standards for Jakarta and rural Indonesia, hindering the ability to monitor air pollution and enforce standards. These offices must work together and harmonize their goals and approaches for successful results. These goals and approaches, furthermore, must align with other regional and global standards. For instance, working with initiatives like the Climate and Clean Air Coalition to find the appropriate mechanisms can help Indonesia meet regional pacts, such as the ASEAN Agreement on Transboundary Haze Pollution.

8. Conclusion

In recent decades, high air pollutant concentrations in South and Southeast Asian countries have meant that they consistently dominate top positions in world rankings of the poorest air quality. The sources of these air pollutants vary from country to country, province to province, and city to city. However, a constant underlying source, particularly in agrarian communities during the dry/post-harvest season, is the burning of biomass waste such as straw left behind in fields from the cultivation of rice crops. While quick and efficient, burning can negatively impact climate, human health, soil health, and economies while further stratifying societies. Furthermore, these fires can easily spread to become uncontrollable wildfires, which both ravage the landscape and add immense amounts of GHGs and air pollutants to the atmosphere.

The practice of biomass burning of post-harvest straw residue is a particular phenomenon occurring in these sub-regions, rooted in traditional practices, and continued due to a lack of awareness or the resources to make changes needed to protect their communities from the harmful effects of air pollution.

Recommended solutions to provide the appropriate interventions to prevent open biomass burning are as follows:

1. **Cooperation**
   For the two sub-regions to successfully combat climate change, cooperation is necessary between countries, local governments and sectors, in which harmonized standards are set, and pacts are made to strive towards global goals, like the Paris Agreement and the SDGs (ESCAP, 2020). Political will, government leadership, an intersectoral approach and coordination among nations and partners are critical to ensure the effectiveness and efficiency of the measures.

2. **Monitoring and Modelling**
   Air pollution comes from various sources, and because of that, the first step in air quality management needs to be source identification and appointment through measuring and monitoring. Next, innovative data modelling and the deployment of emerging technologies to identify air pollution hotspots are necessary to formulate informed and efficient policies.

3. **Sustainable Agriculture Mechanization**
   Sustainable agricultural mechanization is a critical step to increasing food security, protecting livelihoods, and combating climate change. Sustainable agricultural mechanization technologies range from hand tools and techniques such as no-till farming to more sophisticated means, such as equipment which converts bio-waste to bio-gas or bio-char, and to advanced technologies in which power sources are diversified (Sims 2017). Further promotion of mechanization is needed throughout the agricultural sector, from large commercial production farms to smallholder farms that are often family-run. However, smallholder farms will need the maximum support in this transition, as they face the most economic and societal barriers.

If countries can find ways to avoid open biomass burning and reduce the amount of air pollutants and GHGs emitted from unsustainable agricultural practices they will save lives, protect the environment, and improve the overall productivity of their agriculture sectors.

Works Cited

Abdul Jabbar, S., Tul Qadar, L., Ghafoor, S., Rasheed, L., Sarfraz, Z., Sarfraz, A., Sarfraz, M., Felix, M. and Cherrez-Ojeda, I. 2022. "Air Quality, Pollution and Sustainability Trends in South Asia: A Population-Based Study." *International journal of environmental research and public health* 19 (12): 7534.

Aguilera, R., Corringham, T., Gershunov, A. et al. 2022. "Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California." *Nat Commun 12* 1493.

Bajracharya, S.B., Mishra, A., Maharjan, A. 2021. "Determinants of crop residue burning practice in the Terai region of Nepal." *PLOS ONE.* doi:https://doi.org/10.1371/journal.pone.0253939.

Bhandari, N. 2021. *Farmers unaware of ozone's impact on crop loss.* Accessed July 02, 2022. https://www.scidev.net/asia-pacific/news/farmers-unaware-of-ozones-impact-on-crop-loss/.

Byrne, A. 2015. "The 1979 Convention on Long-Range Transboundary Air Pollution: Assessing its Effectiveness as a Multilateral Environmental Regime after 35 Years." *Transnational Environmental Law* 4 (1): 37-67.

Cassou, E. 2018. *Field Burning. Agricultural Pollution.* Washington DC: World Bank Group. https://openknowledge.worldbank.org/handle/10986/29504.

CCAC. 2015-2022. *Open agricultural burning.* Accessed Jul 01, 2022. https://www.ccacoalition.org/en/activity/open-agricultural-burning.

Cesaroni, G., et al. 2014. *Long term exposure to ambient air pollution and incidence of acute coronary events: prospective cohort study and meta-analysis in 11 European cohorts from the ESCAPE Project.* the bmj. doi:https://doi.org/10.1136/bmj.f7412.

Climate & Clean Air Coalition. n.d. *Short-Live Climate Pollutants (SLCPs).* Accessed Jul 02, 2022. https://www.ccacoalition.org/en/content/short-lived-climate-pollutants-slcps.

Climate Action Network South Asia (CANSA). 2022. *Regional Collaboration of Health Professionals for Resolving South Asia's Air Pollution Climate Crisis.* Climate Action Network South Asia (CANSA), Doctors For Clean Air & Climate Action, Health Care Without Harm (HCWH), Lung Care Foundation, Air Quality Life Index (AQLI) & Fossil Fuel Treaty.

Das, B., Bhave, Prakash V., PS. Praveen, Shaky, K., Maharjan, B., Byanju, RM. 2020. "A model-ready emission inventory for crop residue open burning in the Context of nepal." *Environmental Pollution.*

Debucquet, D.L., Murphy, S., Parent, M., Porciello, J., Smaller, C. 2020. *Sustainable Solutions to End Hunger.* International Institute for Sustainable Development (IISD). https://www.jstor.org/stable/resrep29168.10.

Department of Air Quality and Noise Managment, Cambodia. 2020. "Air Quality Managemnt in Cambodia." ESCAP. https://www.unescap.org/sites/default/files/12.%20Air%20Quality%20Management%20in%20Cambodia_MoE.pdf.

ESCAP. 2020. *Accelerating the implementation of the 2030 Agenda for Sustainable Development in Asia and the Pacific through environmental solutions—Realizing environmental benefits through policy convergence and enhanced regional cooperation.* Sixth Session, ESCAP. ESCAP/CED/2020/2. https://www.unescap.org/sites/default/files/CED6_2E.pdf.

ESCAP. 2020. *Reducing straw residue burning and air pollution through sustainable agricultural mechanization.* Bangkok: ESCAP.

ESCAP-CSAM. 2018. *Status of Straw Management in Asia-Pacific and Options for Integrated Straw Management.* ESCAP-CSAM. https://un-csam.org/sites/default/files/2021-06/StatusOfStrawMgr.pdf.

Eusebio, C., et al. 2021. "The impact of air quality on tourism: a systematic literature review." *Journal of Tourism Futures* 7 (1).

FAO. 2022. *Sustainable Agricultural Mechanization.* Accessed Jul 8, 2022. https://www.fao.org/sustainable-agricultural-mechanization/overview/what-is-sustainable-mechanization/en/.

FAO. 2021. *The State of Food Security and Nutrition in the World 2021: The world is at a critical juncture.* Rome: FAO.

FAOSTAT. 2023. "Amount of biomass dry matter burned by crop type data for 2020 by FAO." License: CC BY-4.0.

Fauna & Flora International. 2022. *Cambodia.* Accessed July 10, 2022. https://www.fauna-flora.org/countries/cambodia/.

Gautam, S., Yadav, A., Tsai, C. J., & Kumar, P. 2016. " A review on recent progress in observations, sources, classification and regulations of PM 2.5 in Asian environments." *Environmental Science and Pollution Research* 23 (21): 21165-21175.

GBD. 2020. "GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019." *Lancet, 396* 1135–59.

Greeenstone, M., Fan, Q. 2019. *Indonesia's Worsening Air Quality and its Impact on Life Expectancy.* Chicago: Air Quality Life Index.

Greenstone, M., Hasenkopf, C., Lee, K. et al. 2022. *Air Quality Life Index (AQLI).* Chicago: University of Chicago.

Hasnat, G.N.T., Kabir, M.A., Hossain, M.A. 2018. "Major Environmental Issues and Problems of South Asia, Particularly Bangladesh." In *Handbbok of Environmental Materials Managment* , edited by C. Hussain. Springer, Cham.

Ho, R. C., Zhang, M. W., Ho, C. S., Pan, F., Lu, Y., & Sharma, V. K. 2014. "Impact of 2013 south Asian haze crisis: study of physical and psychological symptoms and perceived dangerousness of pollution level." *BMC psychiatry* 14 (1): 1-8.

Hu, Y., Fernandez-Anez, N., Smith, T. E., & Rein, G. 2018. "Review of emissions from smouldering peat fires and their contribution to regional haze episodes." *International Journal of Wildland Fire* 27 (5): 293-312.

Huang, F., Pan, B., Wu, J., Chen, E., & Chen, L. 2017. "Relationship between exposure to PM2. 5 and lung cancer incidence and mortality: a meta-analysis." *Oncotarget* 8 (26): 433 - 522.

ICIMOD. 2020. *Women and crop residue burning in Nepal.* International Centre for Integrated Mountain Development.

Indonesia, Statistics. 2022. "Executive Summary of Paddy Harvested Area and Production in Indonesia 2021."

International Fund for Agricultural Development (IFAD). n.d. *Indonesia Country Operations.* Accessed Aug 2022, 2022. https://www.ifad.org/en/web/operations/w/country/indonesia.

IQAir. 2022. *Air quality in Cambodia.* Accessed July 15, 2022. https://www.iqair.com/us/cambodia.

—. 2022. *Air quality in Nepal.* Accessed June 18, 2022. https://www.iqair.com/nepal.

IQAir. 2021. *World Air Quality Report: Region and City PM2.5 Ranking.* IQAir.

IUCN. 2022. *Summary Statistics.* Accessed July 10, 2022. https://www.iucnredlist.org/resources/summary-statistics.

J.M. Maurer, J.M. Schaefer, S. Rupper, A. Corely. 2019. "Acceleration of ice loss across the Himalayas over the past 40 years, (2019)." *Sci. Adv., 5* p. eaav7266.

Jethva, H., Torres, O., Field, R.D. et al. 2019. "Connecting Crop Productivity, Residue Fires, and Air Quality over Northern India. Sci Rep 9, 16594."

Johnson, N.M., Hoffmann, A.R., Behlen, J.C. et al. 2021. "Air pollution and children's health—a review of adverse effects associated with prenatal exposure from fine to ultrafine particulate matter." *Environ Health Prev Med 26* 72.

Kiely, L. et al. 2020. "Air quality and health impacts of vegetation and peatfires in Equatorial Asia during 2004-2015. Environment Research Letters, 15, 094054."

Kiely, L., Spracklen, D. V., Wiedinmyer, C., Conibear, L., Reddington, C. L., Archer-Nicholls, S., Lowe, D., Arnold, S. R., Knote, C., Khan, M. F., Latif, M. T., Kuwata, M., Budisulistiorini, S. H., and Syaufina, L. 2019. "New estimate of particulate emissions from Indonesian peat fires in 2015." *Atmos. Chem. Phys., 19* 11105–11121.

Kingdom of Cambodia. 1993. "THE CONSTITUTION OF THE KINGDOM OF CAMBODIA." Phnom Penh : Constitutional Assembly of Cambodia.

Kurmi, O., Regmi, P.R., Pant, P.R. 2016. "Implication of Air Pollution on Health Effects in Nepal: Lessons from Global Research." *Nepal Journal Epidemiology* 6 (1): 525-527.

Lan, R., Eastham, S.D., Liu, T. et al. 2022. "Air quality impacts of crop residue burning in India and mitigation alternatives. Nat Commun 13, 6537."

Leinbach, T.R. 2022. *Britannica - Indonesia.* Accessed July 8, 2022. https://www.britannica.com/place/Indonesia.

MacGuire, F., Segeeva, M. 2021. *The Limits of Livability: The emerging threat of smoke impacts on health from forest fires and climate change.* The Global Climate and Health Alliance (GCHA).

Malley, Christopher S., Sokharavuth, P., Thiv, S., Nara, C., Him, C., Sokyimeng, et al. 2022. *AIr Pollutiuon Mitigation Assesment to Inform Cambodia's Forst Clean Air Plan.* Phnom Penh: General Directorate of Environmental Protection.

Marlier, M.E., Madrigano, J., Huttinger, A., Burger, N.E. 2021. *Indonesian Fires and Haze: Measuring the Health Consequences of Smoke Exposure.* Santa Monica: RAND Corporation. doi:https://doi.org/10.7249/RRA1314-1.

Ma'ruf, Arifin. 2021. "Legal Aspects of Environment in Indonesia: an Efforts to Prevent Environmental Damage and Pollution." *Journal of Human Rights, Culture and Legal System* 1 (1).

Matinez R., Masron, I.N. 2020. "Jakarta: A city of cities." *Cities* 106. doi:https://doi.org/10.1016/j.cities.2020.102868.

McLaughlin, O., Mawhood, B., Jamieson, C., Slade, R. 2016. "Rice straw for bioenergy: the effectiveness of policymaking and implementation in Asia." Amsterdamn, Netherlands: 24th European Biomass Conference and Exhibition.

Menon, S., Koch, D., Beig, G., Sahu, S., Fasullo, J., and Orlikowski, D. 2010. "Black carbon aerosols and the third polar ice cap, ." *Atmos. Chem. Phys., 10* 4559–4571.

Myllyvirta, L. 2020. *Quantifying the economic costs of air pollution from fossil fuels.* Centre for Research on Energy and Clean Air.

Nakarmi, A.M., Sharma, B., Rajbhandari, U.S. et al. 2020. "Mitigating the impacts of air pollutants in Nepal and climate co-benefits: a scenario-based approach." *Air Qual Atmos Health* 13: 361-370.

OECD. 2016. *The economic consequences of outdoor air pollution.* Paris: OECD Publishing.

OECD/FAO. 2022. *OECD-FAO Agricultural Outlook 2022-2031.* Paris, France: OECD.

OHCHR. 2021. "Promotion and protection of all human rights, civil, political, economic, social and cultural rights, including the right to development. The human right to a safe, clean, healthy and sustainable environmen." Forty-eighth session.

A/HRC/48/L.23/Rev.1. https://documents-dds-ny.un.org/doc/UNDOC/LTD/G21/270/15/PDF/G2127015.pdf?OpenElement.

PFPI. 2011. *Air pollution from biomass energy.* PFPI. https://www.pfpi.net/air-pollution-2.

Reddington, C. L., Conibear, L., Robinson, S., Knote, C., Arnold, S. R., & Spracklen, D. V. 2021. "Air pollution from forest and vegetation fires in Southeast Asia disproportionately impacts the poor." *GeoHealth* 5 (9).

Reddington, C.L., et al. 2021. "Air pollution from forest and vegetation fires in Southeast Asia disproportionately impacts the poor." *GeoHealth, 5, e2021GH000418.*

Reuters. 2019. "World Bank says Indonesia forest fires cost $5.2 billion in economic losses." *Reuters*, Dec 11.

Rhofita, e. i., et al. 2022. "An Energy Potential Estimation of Rice Residue in Indonesia: A Case Study in East Java." *IOP Conf. Ser.: Earth Environ. Sci.* 1024.

Rifin, A. 2022. "Marketed surplus of Indonesian rice production." *Cogent Economics & Finance, 10:1.*

Royal Government of Cambodia. 2013. "Cambodia Climate Change Strategic Plan 2014 - 2023." National Climate Change Committee.

SEI. n.d. *SEI in Cambodia.* Accessed Jul 12, 2022. https://www.sei.org/centres/asia/research-areas/sei-in-cambodia/.

Sims, B., Kienzle, J. 2017. "Sustainable Agricultural Mechanization for Smallholders: What Is It and How Can We Implement It?" *Agriculture* 7 (50). doi:doi:10.3390/agriculture7060050.

Tsai, T. L., Lin, Y. T., Hwang, B. F., Nakayama, S. F., Tsai, C. H., Sun, X. L., ... & Jung, C. R. 2019. "Fine particulate matter is a potential determinant of Alzheimer's disease: A systemic review and meta-analysis." *Environmental research* 177.

UN Country Team Nepal. 2017. *United Nations Development Assistance Framework for Nepal.* United Nations Country Team Nepal.

UN Department of Economic and Social Affairs. 2021. *Least Developed Country Category: Cambodia Profile.* Accessed Jul 14, 2022. https://www.un.org/development/desa/dpad/least-developed-country-category-cambodia.html.

—. 2021. *Least Developed Country Category: Nepal Profile.* Accessed Jul 14, 2022. https://www.un.org/development/desa/dpad/least-developed-country-category-nepal.html.

UNCTAD STAT. 2020. *General profile: Nepal.* United nations Conference on Trade and Development.

UNDAF. 2019. *United Nations Development Assitance Framework: Cambodia 2019-2023.* United Nations Development Assitance Framework.

UNECE. n.d. *Air pollution and food production.* Accessed Jul 02, 2022. https://unece.org/air-pollution-and-food-production.

—. n.d. *Environmental Policy - Air.* Accessed 12 Jul, 2022. https://unece.org/environment-policy/air.

UNEP. 2021. *Actions on Air Quality: A Global Summary of Policies and Programmes to Reduce Air Pollution.* Nairobi: UNEP.

—. 2022. *Toxic blaze: the true cost of crop burning.* Accessed Jul 01, 2022. https://www.unep.org/news-and-stories/story/toxic-blaze-true-cost-crop-burning.

UNEP-CCAC. 2018. *Air Pollution in Asia and the Pacific: Science-based Solutions - Summary.* United Nations Environment Programme and Climate & Clean Air Coalition. https://wedocs.unep.org/handle/20.500.11822/26861;jsessionid=0379F40BE300EF0EF0F95C9BE312584E.

United Nations. 2022. *United Nation in Indonesia: Countrt Results Report 2021.* United Nations in Inodnesia.

UNSDCF. 2020. *United Nations: Sustainable Development Framework: Indonesia 2021 - 2025.* United Nations Indonesia.

USAID. 2022. *Cambodia: AGRICULTURE AND FOOD SECURITY.* Accessed July 15, 2022. https://www.usaid.gov/cambodia/agriculture-and-food-security.

Vadrevu, K.P., Lasko, K., Giglio, L. et al. 2019. "Trends in Vegetation fires in South and Southeast Asian Countries." *Sci Rep* 9 (7422). doi:https://doi.org/10.1038/s41598-019-43940-x.

Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., and Soja, A. J. 2011. "The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning." *Geosci. Model Dev., 4* 625–641.

Wong, et al. 2016. "Cancer Mortality Risks from Long-term Exposure to Ambient Fine Particle." *Cancer Epidemiol Biomarkers Prev. 25 (5)* 839–845.

World Bank Group. 2021. *Climate Risk Country Profile: Cambodia.* Washington DC: World Bank Group.

World Bank. 2023a. "Rural population – Indonesia. World Bank staff estimates based on the United Nations Population Division's World Urbanization Prospects: 2018 Revision."

World Bank. 2021. *The Global Health Cost of PM2.5 Air Pollution : A Case for Action Beyond 2021.* World Bank, Washington, DC: International Development in Focus. https://openknowledge.worldbank.org/handle/10986/36501.

World Health Organization. 2021. *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.* World Health Organization.

Yamauchi, F. 2021. *CHANGING FARM SIZE AND AGRICULTURAL PRODUCTIVITY IN ASIA.* Washington, DC: International Food Policy Research Institute.

Yeung, J. 2019. *Indonesian forests are burning, and Malaysia and Singapore are choking on the fumes.* Accessed Jul 10, 2022. https://www.cnn.com/2019/09/11/asia/malaysia-singapore-pollution-intl-hnk/index.html.

—. 2019. *Indonesian forests are burning, and Malaysia and Singapore are choking on the fumes.* Accessed July 20, 2022. https://www.cnn.com/2019/09/11/asia/malaysia-singapore-pollution-intl-hnk/index.html.

Yin, S. 2020. "Biomass burning spatiotemporal variations over South and Southeast Asia." *Environment International* 145. doi:https://doi.org/10.1016/j.envint.2020.106153.

Zhang, L., S. Ding, W. Qian, A. Zhao, S. Zhao, Y. Yang, G. Weng, et al. 2022. "The Impact of Long-Range Transport of Biomass Burning Emissions in Southeast Asia on Southern China." *atmosphere* 13 (1029): June. https://www.mdpi.com/2073-4433/13/7/1029/pdf?version=1656416004.