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Agricultural Residue Open Burning, Air Pollution, and Health Impact Assessment in the Context of Climate Change in Cambodia

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ការមិនទទួលស្គាល់៖ ការស្រាវជ្រាវនេះ គឺ/ត្រូវបានគាំទ្រដោយរដ្ឋាភិបាលអូស្ត្រាលី តាមរយៈការផ្តល់ជំនួយតូចមួយតាមរយៈកម្មវិធីអាហារូបករណ៏អូស្ត្រាលីប្រចាំនៅកម្ពុជា។មតិដែលបានបង្ហាញក្នុងការ ស្រាវជ្រាវនេះ គឺជាមតិរបស់អ្នកស្រាវជ្រាវ នឹងមិនឆ្លុះបញ្ចាំងពីទស្សនៈរបស់ រដ្ឋាភិបាល អូស្ត្រាលី ឬ កម្មវិធីអាហារូបករណ៏អូស្ត្រាលីប្រចាំនៅកម្ពុជានោះទេ។

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EXECUTIVE SUMMARY

This research study assesses the environmental and health impacts of open burning of agricultural residues particularly rice straw in Cambodia, and proposes sustainable alternatives aligned with the country's climate and public health objectives. Conducted in two high-rice-production provinces, Prey Veng and Battambang, the study integrates air quality monitoring, farmer surveys, and literature review to provide evidence-based recommendations for improved residue management.

Key Findings

1. **Extent of Burning and Air Pollution**:
   - Cambodia produces approximately 10 million tons of rice straw annually, of which an estimated 3 million tons are burned openly in fields.
   - Air quality monitoring in Prey Veng and Battambang provinces revealed PM2.5 concentrations exceeding WHO guidelines by nearly twofold, indicating high health risks, particularly for children, the elderly, and those with pre-existing respiratory conditions.
   - Other pollutants, such as SO_2, CO, and NO_2, remained below WHO and national standards, but their cumulative presence contributes to chronic health burdens.
2. **Health Impact Assessment**:
   - Elevated PM2.5 exposure is strongly linked with respiratory and cardiovascular diseases.
   - Field surveys confirmed that most farmers lack awareness of these health impacts, and that health symptoms such as coughing and shortness of breath are common in burning seasons.
3. **Farmer Practices and Perception**:
   - Open burning remains prevalent due to its low cost, cultural acceptance, and lack of viable alternatives.
   - There is limited access to machinery, market incentives, and extension services that could support sustainable alternatives.
   - Farmers showed interest in residue reuse but cited barriers including cost, technical knowledge, and infrastructure.

4. **Regional Comparisons and Best Practices**:
    - Countries such as Vietnam, India, and Thailand have piloted and promoted residue repurposing for composting, mushroom cultivation, animal feed, biochar, and mechanized in-situ incorporation (e.g., Happy Seeder technology).
    - Lessons from these countries suggest that integrating technical solutions with policy incentives and farmer education can significantly reduce open burning.

Recommendations

To mitigate air pollution and health risks from open burning in Cambodia, the following multi-sectoral actions are recommended:

1. **Enforce Existing Regulatory Frameworks**
    - Ban or gradually phase out open burning of agricultural residues using Circular No. 1 (2020).
    - Establish emission standards for CO.
    - Implement a system of penalties for open burning and incentives for adopting alternatives.
2. **Develop Market-Based Incentives**
    - Support value chains for rice straw products such as biochar, compost, and animal feed.
    - Promote private sector investment in straw processing technologies.
3. **Strengthen Agricultural Extension Services**
    - Train farmers on sustainable residue management techniques.
    - Deploy mobile demonstration units (e.g., composting pits, biochar kilns).
4. **Provide Financial and Technical Support**
    - Subsidize machinery for in-situ straw management and collection.
    - Enable access to low-interest loans or grants for smallholder farmers.
5. **Raise Public Awareness**
    - Conduct health-focused campaigns on the risks of straw burning.
    - Promote climate-smart agriculture via schools, radio, and farmer field schools.
6. **Invest in Research and Data Systems**
    - Expand real-time air quality monitoring networks.
    - Conduct research on the health and economic impacts of open residue burning.

Conclusion

Open burning of rice straw presents a significant threat to air quality and public health in Cambodia. With coordinated policy action, investment in alternatives, and strong community engagement, Cambodia can transition toward sustainable agricultural practices that enhance environmental integrity, public health, and rural livelihoods.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Full Form
AQM	Air Quality Monitoring
AQG	Air Quality Guidelines
AWD	Alternate Wetting and Drying
BB	Biomass Burning
CAS	Chemical Abstracts Service
CH_4	Methane
CO	Carbon MoNOxide
COPD	Chronic Obstructive Pulmonary Disease
CO_2	Carbon Dioxide
DSR	Direct Seeded Rice
ESCAP	Economic and Social Commission for Asia and the Pacific
FAO	Food and Agriculture Organization
GAP	Good Agricultural Practices
GHG	Greenhouse Gas
GIEWS	Global Information and Early Warning System
ICAR	Indian Council of Agricultural Research
INM	Integrated Nutrient Management
IPM	Integrated Pest Management
IRRI	International Rice Research Institute
ME	Ministry of Environment (Cambodia)
NAAS	National Academy of Agricultural Sciences
NGO	Non-Governmental Organization
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
O_3	Ozone
OCEANUS-AQM-09	Model of air quality monitoring equipment
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter

Acronym / Abbreviation	**Full Form**
PM2.5	Particulate Matter ≤ 2.5 micrometers
PM10	Particulate Matter ≤ 10 micrometers
RSD	Relative Standard Deviation
SMS	Super Straw Management System
SO_2	Sulfur Dioxide
SOx	Sulfur Oxides
THS	Turbo Happy Seeder
TIH/PIH	Toxic Inhalation Hazard / Poison Inhalation Hazard
UNEP	United Nations Environment Programme
VOCs	Volatile Organic Compounds
WHO	World Health Organization

CHAPTER 1: INTRODUCTION

1.1 Significance

The agricultural sector faced increasing pressures from economic and population growth which resulted in the implementation of intensive farming practices and technological advancements. The combination of synthetic fertilisers and pesticides with expanded land use has resulted in serious environmental problems such as water contamination, air pollution, greenhouse gas emissions and soil degradation. These environmental problems threaten the long-term health of the ecosystem and present substantial health risks to human communities. Crop waste burning during crop preparation activities has amplified existing environmental issues according to Raza et al. (2022). Burning residues generates air pollutants including primary particulate matter (PM2.5 and PM10) and secondary nitrogen oxides, sulphur dioxide, ammonia which results in respiratory and cardiovascular diseases among humans and leads to transportation difficulties and school closures due to smog-related economic activity disruption. According to the World Health Organization research air pollution indoors and outdoors results in 2.2 million people dying prematurely every year. Pneumonia accounts for 8% of these premature deaths while ischaemic heart disease accounts for 29% with stroke responsible for 27%, chronic obstructive pulmonary disease makes up 22% and lung cancer contributes 14% according to the World Health Organization 2021 report.

Many Asia-Pacific countries engage in regular straw burning practices which farmers perform twice annually. Southeast Asia's agricultural residue open burning represents 43 percent of global open biomass burning *(Oanh et al., 2018, 2011)*. Globally burned biomass consists of 23 percent agricultural residue according to BB category data *(Yadav Devi, 2018)*. Cambodia dedicates more than 80 percent of its cultivated land to rice production which serves as its most important agricultural export product while also being the main source of crop value-added products and the leading force behind agricultural growth. Cambodia's Ministry of Agriculture, Forestry, and Fisheries projected a rice production exceeding 12 million tonnes on 3,497,682 hectares of cultivated land during 2021. The country produces approximately ten million tonnes of rice straw *(Lorn et al., 2022)*. Three million tonnes of the rice straw that is produced in Cambodia after harvest is burned *(Kosal, 2019)*. It is not difficult to find rice straw in Cambodia, and its price is relatively modest. Rice straw is allowed to burn in the field without being subjected to additional treatment. This practice creates a significant risk of raising pollution levels in nearby air spaces *(Lorn et al., 2022)*. Air pollution from straw burning becomes a transnational issue because smog is capable of traveling extensive distances through the wind between countries and regions *(Economic and Social Commission for Asia and the Pacific [ESCAP], 2020).* There was a study that was conducted on the emission of pollutants from agricultural residue open burning in Southeast Asia, which included Cambodia. The study discovered that 117 Tg/year of rice straw was burned, and that rice straw accounted for 85–98% of the total CROB emissions, which was a considerable proportion *(Kim Oanh et al., 2010)*.

The harmful consequences of crop residue burning are now becoming more prevalent across regions. It is not difficult to find rice straw in Cambodia, and its price is relatively modest. Rice straw is allowed to burn in the field without being subjected to additional treatment. Three million tonnes of the rice straw that is produced in Cambodia after harvest is burned [19]. The country produces approximately ten million tons of rice straw. As a consequence, this practice leads to increased emissions of greenhouse gases, contributes to the toxicity of the air, and is detrimental to the health of humans. The harmful impact from burning crop residue has expanded to cover more areas worldwide. Research studies have demonstrated several crop residue management practices which are eco-friendly while also delivering economic advantages through revenue generation and reduced health costs *(Huijbregts et al., 2017)*. Rice straw serves as a mushroom cultivation feed as well as for vegetable production and cattle feeding. Cambodia intends to advance rice straw waste management by creating a prototype collection machine and enhancing mushroom and ruminant farming technology along with bioenergy technology *(Lorn et al., 2022)*. Protecting human health and ecosystem sustainability requires the implementation of residue management strategies that are environmentally friendly and sustainable. However, the uptake of sustainable crop residue management practices remains low even though their benefits have been widely researched and understood for local implementation *(Sheikh, Rehman, Yates, 2003)*. The low adoption rate probably stems from insufficient knowledge about the benefits of these practices concerning environmental impacts and human health *(Raza et al., 2022)*.

1.2 Problem Statement

Cambodia widely practices open burning of agricultural residues like rice straw and stubble because it is both cost-effective and easy to operate with limited accessible alternatives available. This method results in air pollution and the emission of greenhouse gases such as methane (CH_4), sulfur dioxide (SO_2), nitrous oxide (NO_2), particulate matter (PM2.5), carbon moNOxide (CO), and black carbon. The mentioned pollutants play a role in driving global climate change while reducing air quality and causing serious health problems which mainly affect respiratory and cardiovascular systems (UNEP, 2021; WHO, 2021). The dry season between November and April experiences peak air pollution levels due to the combined effects of open agricultural residue burning and forest fires (MOE, 2022).

Despite there are harmful impact to environment and human health, open burning of agricultural residue remains continued because the farmers have less technical knowledge and access to sustainable alternatives. The awareness program from relevant institutions is also limited. Further, there is limited information and adoption of best practices for residue management that are economically viable, environmentally sustainable, and socially acceptable in Cambodia. The effective alternatives including mulching, incorporation of residues into soil, composting, conversion to biochar, utilization for energy, and animal feed have seen as good option in both reducing emissions and enhancing soil fertility (FAO, 2019; Gadde et al., 2009). However, there are challenges such as upfront initial expense, inadequate extension services, and low market development and volume hinder the extensive implementation of these alternatives recently.

Therefore, this report seeks to solve this urgent issue as having assessed the effects of burning agricultural residue on the environment and human health and suggesting workable, situation-specific best practices and alternatives. By doing this, it hopes to support the development of integrated policy and technical solutions that enable sustainable residue management in line with Cambodia's goals for public health, air quality, and climate mitigation efforts.

1.3 Research Objectives

The research titles Agricultural Residue Open Burning, Air Pollution, and Health Impact Assessment in the Context of Climate Change in Cambodia aims to:

- Assess the open burning of agricultural residue on air pollution and public health
- Improve farmers' knowledge of agricultural residue management to reduce air pollution from burning, and
- Formulate policy recommendation aimed at reducing the adverse effects of agricultural residue open burning on air quality and public well-being.

1.4 Scope of the Study

Due to time and budget constraint and with discussion with the officers of Battambang and Prey Veng Provincial Department of Environment, the team has conducted the research study in two villages of Prey Veng and Battambang Provinces. The information related to the cultivation, residue management as well as perception of farmers on burning of agricultural residue and air pollution related health issue have obtained through interview and group discussion with head of villages and farmers, while the data on air quality has retrieved from the air quality monitoring equipment installed in Khsom Tboung Village, Kampong Popil Commune, Pea Reang Disctrict, Prey Veng Province and Hai San Village, Chrey Commune, Thmor Kol District, Battambang Province (see map of Khsom Tboung and Hai San Village in figure 1).

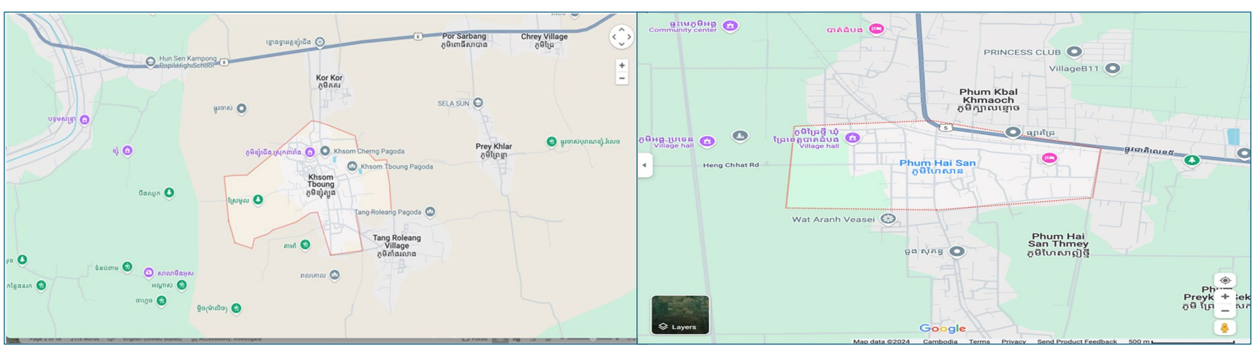

Figure 1: Location for installation of the air quality monitoring equipment

Source: Google Map of Khsom Tboung village, Kampong Popil commune, Pea Reang District, Prey Veng province and Hai San Village, Chrey Commune, Thmor Kol District, Battambang Province.

CHAPTER 2: LITERATURE REVIEW

A literature review is performed to examine the practice of agricultural residue open burning, health issues associated with air pollution and open burning and gap in knowledge of agricultural residue open burning. The lessons learned from successful of agriculture residue management from neighboring countries or countries in the Asian region can be used to recommend to the policy makers for formulating any related regulations to reduce the burning of agriculture residue. The recommendation can also be directly introduced to the farmers to stop/reduce burning of the agriculture leftovers in order to improve air quality and better the human's health, particularly the farmers. Moreover, a literature review can help to establish the foundation for further research.

2.1 Experience of Agricultural Management of Some Asian Countries

Asian countries produce and consume around 90% of the world's rice supply making it a crucial food source in the region. The leading producers of rice include China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, and Japan. China leads in rice production by farming approximately 188.5 million tons annually across 28.7 million hectares which results in average yields of 6.5 tons per hectare. India ranks second with a yield of 3.3 tons per hectare across 42.8 million hectares producing 142.5 million tons (Shifotoka, 2024). Efficient management of rice straw plays a vital role in advancing sustainable agricultural practices throughout Asia. Different nations have developed innovative approaches to utilize rice straw which both diminish environmental damage and enhance economic returns.

2.1.1 Rice Cultivation

Rice is a fundamental food and agricultural systems in Asian countries, serving as a critical source of income for millions of smallholder farmers. The region's diverse agro-ecological zones enable both irrigated and rainfed rice cultivation, with countries varying in productivity, farming practices, and technological adoption (FAO, 2021).

Vietnam

Vietnam ranks among the leading global producers and exporters of rice having produced approximately 43 million metric tons of paddy rice in 2022 according to FAO data from 2023. The Mekong River Delta produces over half of Vietnam's rice yield as it stands as the central hub for rice cultivation. Northern Vietnam has two rice growing seasons while southern Vietnam goes through three growing seasons which are winter-spring, summer-autumn, and autumn-winter (IRRI, 2021). Farmers practice both transplanting and direct seeding while mechanization increasingly supports harvesting and land preparation tasks. Despite strong irrigation systems supporting rice cultivation the productivity of delta regions is reduced by climate-related problems such as drought and salinity intrusion (Gummert & Rickman, 2021). Vietnam promotes sustainable agricultural techniques such as Integrated Pest Management (IPM) and Alternate Wetting and Drying (AWD) to boost environmental sustainability and meet export quality requirements.

Thailand

Thailand is known across the world for its premium export varieties, particularly Jasmine rice (Khao Hom Mali), and produced about 32 million metric tons of paddy rice in 2022 (FAO, 2023). There are normally two rice seasons, in which a dry season depends on irrigated system from November to February and a main rainfed season from May to October. The Central Plains, Northeastern, and Northern areas are the main locations for rice cultivation. Although direct seeding is becoming more popular, transplanting is still frequent, especially in the Northeast where labour shortages and rainfall fluctuations are more severe (IRRI, 2021). Regional differences exist in water management; the Northeast mostly depends on rainfall, whereas irrigated regions in the Central Plains have superior water control. Particularly for premium markets, Thailand has advanced organic rice growing and Good Agricultural Practices (GAP) (Thai Rice Exporters Association, 2022). However, rice growers still face significant risks from drought and climatic variability.

China

The FAO 2023 report identifies China as the leading rice producer globally after harvesting more than 206 million metric tons of paddy rice in 2022. Three primary agro-ecological zones are used for rice cultivation: Northern China has a short growing season while Central China practices single cropping and Southern China engages in double cropping. The development and adoption of hybrid rice by Yuan Longping represents a significant agricultural achievement in China which helped achieve high crop yields and strengthened food security (Yuan, 2014). Mechanised transplanting and harvesting techniques dominate rice production across the majority of Chinese fields while precision agriculture continues to expand its use for better fertiliser application and reduced environmental impact. Alternate Wetting and Drying (AWD) methods for methane reduction receive support in certain regions alongside large irrigation networks that promote water management (USDA, 2022). Despite technological progress China continues to struggle with worker shortages alongside the urbanisation of agricultural land and pollution from heavy agrochemical use.

India

Following China, India is the world second largest paddy rice producer with almost 196 million metric tons in 2022 (FAO, 2023). In eastern, northern, southern, and northeastern states, rice is grown in a variety of agroclimatic zones, where West Bengal, Uttar Pradesh, Punjab, Andhra Pradesh, and Bihar are major producers. Three seasons are used to grow rice: Kharif (monsoon), Rabi (winter), and Summer. Most of the rice is produced during the monsoon season. Despite the widespread use of traditional transplanting techniques, Direct-Seeded Rice (DSR) is becoming more popular, particularly in Punjab and Haryana, because of its potential to save water and adaptability for mechanisation (ICAR, 2022). Interestingly, the government subsidies have led to widespread usage of fertiliser and pesticides, yet initiatives supporting Integrated Nutrient Management (INM) and Integrated Pest Management (IPM) are growing. According to Gadde et al. (2009), open-field burning of rice straw is another issue in India that contributes to seasonal air pollution, particularly in the northern regions. India is the biggest exporter of rice in the world, providing both basmati and non-basmati types to international markets in spite of these obstacles.

2.1.2 Rice Straw Burning

Rice straw burning is a prevalent post-harvest practice among farmers in Asian countries. This practice is economically, effectively, and quickly clear fields for upcoming planting cycles.

Vietnam

In Vietnam farmers burn rice straw as a standard post-harvest practice in regions like the Red River Delta and parts of the Mekong Delta where rice farming occurs extensively and yields multiple harvests annually. Farmers often burn field straw because limited storage options combined with insufficient labour and restricted disposal methods force them to quickly prepare for the next planting season (Yamaji et al., 2022). The burning of straw on fields releases significant amounts of methane, black carbon and PM2.5 which leads to air pollution especially around urban areas near Hanoi and Ho Chi Minh City. Despite existing programs promoting rice straw applications for composting and mushroom cultivation and bioenergy production, its adoption remains low due to insufficient infrastructure support and market incentives along with low awareness levels (Gummert & Rickman, 2021). The government is exploring sustainable rice straw management solutions through international partnerships to aid climate change mitigation and air quality improvement.

Thailand

Burning rice straw is a common practice by farmers in Thailand, significantly in the rainfed season, to quickly clear fields for the following cultivation season. Despite being a cheap and labor-efficient way to dispose of straw, open burning of rice straw contributes to seasonal haze and health issues in both rural and urban regions by releasing large levels of PM2.5, NOX, and VOCs (Gadde et al., 2009). Good Agricultural Practices (GAP) and zero-burn campaigns are two initiatives that the government tries to lessen burning, although enforcement and implementation are still lacking, particularly for smallholder farmers.

India

The practice of burning rice straw remains a significant threat to ecosystems, human health, and climate conditions in Punjab and Haryana where millions of tons of straw get burned after the Kharif rice harvest to clear fields for wheat planting. The burning of rice straw produces PM2.5, black carbon, CO_2, methane, and nitrous oxide which heavily contributes to air pollution across

Northern India, with Delhi experiencing significant seasonal smog as a result (Gadde et al., 2009; IQAir, 2023). Farmers struggle to handle the large quantities of loose straw left after mechanization and combine harvester use since high labour expenses limit their options to alternatives of burning. Government initiatives such as Happy Seeder machines and financial incentives have not successfully increased adoption rates for sustainable farming practices (NAAS, 2017).

Lao DPR

Farmers in Lao DPR commonly burn rice straw following harvest to quickly ready their fields for the next planting season. Farmers opt for this method because it offers a cost-effective and efficient solution for regions where resources and options are scarce. Laos generates roughly 2 million tons of rice straw each year while farmers burn about 70% of it directly in the fields. Local farmers collect the remaining 30% of rice straw and employ it for growing mushrooms as well as using it for soil mulching and feeding livestock. Open-field burning practices create substantial negative effects on both the environment and public health. This activity results in air pollution through GHG and particulate matter emissions which degrade air quality and threaten the health of nearby residents. The practice of burning rice straw leads to soil nutrient depletion and reduces soil fertility as time progresses (UN-CSAM 2024). Laos has launched initiatives to develop sustainable rice straw management techniques in response to recognized challenges. Sustainable rice straw management practices include its utilization for compost production, livestock bedding materials, and mushroom cultivation substrates. The use of these alternative methods reduces harmful burning effects while providing farmers with economic advantages. A shift from rice straw burning depends on overcoming obstacles like limited awareness among stakeholders as well as inadequate infrastructure together with essential supportive policy frameworks. Farmers must learn about alternative agricultural practices and receive essential resource investments to establish sustainable farming methods in Lao PDR.

2.2 Best Practice of Agricultural Residue Management

In the process of decay, burning rice straw from traditional rice cultivation is common in developing countries. Although there are some advantages to burning, these activities emit various types of chemicals or pollutants, which pose significant air pollution, health risks, and contribute to climate change. Based on the experiences of other countries, best practices and recommendations have been suggested. In this section, India, Thailand, and Vietnam have gathered relevant information on alternative techniques to eliminate rice straw burning. The related information is reported in Table 1.

Table 1: Best practices for straw-burning alternatives from experienced countries

Country	**Alternative Technique**	
	Pros	**Cons**
Vietnam	- Cutting rice straw to be made into various products such as animal feed (for cows or buffaloes), mushroom cultivation, bedding, composting, and garden mulching. - Investment in converting rice straw into biochar and fuels like bioethanol or pellets/briquettes (Kim Oanh, 2021).	- Loss of nutrients in soil and low-quality - Labor cost expenditure: Cutting, transporting, and storing require financial expenses. - Transportation and storage issues after harvest, as well as the risk of disease and pests due to improper storage and poor management. - High investment cost and Energy Severe Process - Logistic interest and limitations of technology - Environmental challenges, low energy efficiency and complete use (rice straw is animal food)

India	In situ crop residue management with the super straw management system (SMS) and turbo happy seeder (THS) is one of the most sustainable and effective methods recommended (Naresh et al., 2021).	- High investment cost – - Expertise required - Potential yield reduction in the early years (research suggests that yield might decrease initially but will improve as soil quality improves) - Repair and maintenance costs - Regular maintenance
India	There are a few recommended techniques to eliminate the burning of straw, including composting, conversion to biochar, in-situ management, and mechanical intensification (Bhuvaneshwari et al., 2019)	- Composting (odor problems, labor-intensive, and time-consuming) - Conversion to biochar (high investment cost, high energy consumption, low market demand, and expertise required) - In-situ management (long decomposition time, risk of disease and pests, and specialized equipment needed) - Mechanical intensification (high machinery and fuel costs, and soil compaction)
Thailand	- Incorporating straw residue into the soil - Preparing agricultural land effectively	- Incorporating straw residue into the soil (slow nutrient decomposition and imbalance, pest and disease risk, and special machinery required)

	- Converting rice straw into organic fuel - Using machinery to clear straw residue - Applying controlled burning techniques or prescribed burning - Utilizing agricultural residue through various techniques	- Preparing agricultural land effectively (high cost and time-consuming, soil erosion risk, and increased water usage) - Converting rice straw into organic fuel (logistics issues and marketing challenges, high investment cost, and energy requirements) - Using machinery to clear straw residue (high machinery and fuel costs, and soil compaction) - Applying controlled burning techniques (prescribed burning) (air pollution, health risks, wildfire risk, and loss of soil nutrients)
Lao PDR	- The use of rice straw for composting - Livestock bedding - Substrate for mushroom cultivation - Such alternatives not only mitigate the negative impacts of burning but also offer potential economic benefits to farmers	- Limited awareness - Insufficient infrastructure - The need for supportive policies. - Efforts to educate farmers on the benefits of alternative practices, coupled with investments in necessary resources, are essential steps toward more sustainable agricultural methods in Lao PDR.

2.3 Agricultural Sector in Cambodia

The agricultural sector represents a key economic foundation of Cambodia by producing 22% of national GDP in 2022 and providing jobs to 2.6 million workers. Rice dominates Cambodian agriculture by utilizing 3.5 million hectares of land and producing 11.62 million metric tons of paddy rice each year which supports rural farmers as their primary income source and stands as Cambodia's most significant agricultural export commodity worth USD 1 billion. Currently 67 percent of the rice crop is exported in its paddy form while only 33 percent reaches foreign markets as milled rice (https://www.fao.org/hand-in-hand/hih-IF-2023/cambodia/en). The FAO Global Information and Early Warning System (GIEWS) Country Brief predicts Cambodia's paddy rice production will reach about 14 million tons during the 2024/25 season (https://www.fao.org/giews/countrybrief/country.jsp?code=KHM).

2.3.1 Rice Cultivation

The cultural and economic foundations of Cambodia depend heavily on its traditional rice farming practices. This cultivation method relies on a collection of ancestral practices that families continue to teach each other through generations. Cambodia's rice farming produces two annual harvests with a long-cycle monsoon-season crop followed by a short-cycle dry-season crop. During late May to July farmers plant the main monsoon crop after initial rains saturate the soil making it suitable for cultivation. Farmers move rice shoots into the fields from late June up until September. Six months after farmers plant their main crop they typically harvest in December. The dry-season crop matures more quickly than the monsoon crop because it takes only three months from planting to harvest time. Farmers sow their dry-season crops in November in areas where monsoon rains have accumulated and they gather the crops by January or February. The annual production total has less than 15 percent made up by the dry-season crop. Cambodia's rice farming areas divide into three separate categories. Cambodia's most productive rice-growing zone consists of the Tonle Sap Basin and provinces such as Battambang, Kampong Thom, Kampong Cham, Kandal, Prey Veng, and Svay Rieng which produce over one ton of rice per hectare. The second rice-producing region produces four-fifths of a ton per hectare and encompasses Kampot and Koh Kong provinces beside the Gulf of Thailand together with less fertile central provinces. The highland and mountainous areas of Preah Vihear, Stung Treng, Ratanakiri and Mondulkiri provinces yield less than three-fifths of a ton of rice per hectare.

2.3.2 Rice Straw Burning

The agricultural production of rice generates substantial quantities of rice straw as a waste product which remains plentiful even though its economic value remains minimal. The agricultural industry generates around 10 million tons of rice straw annually of which about 3 million tons undergo open field burning. The prevalent practice of open burning of rice straw among farmers stems from their restricted alternatives for its utilization compounded by financial restrictions. Open burning generates harmful air pollution and greenhouse gases which destroy the environment and pose health threats to local populations. Several factors contribute to the continued practice of open rice straw burning in Cambodia.

a) Economic and practical considerations:

- Low-value by-product: Rice straw represents an agricultural byproduct that holds minimal economic worth. Smallholder farmers find open burning appealing because it enables them to clear fields without cost and with great speed due to their limited ability to invest in other processing techniques.
- Lack of market incentives: Rice straw has not been adequately incorporated into existing market value chains. Burning continues to be the standard practice because processing facilities for bioenergy, fodder, or organic fertilizer have not yet been established.

b) Technological and infrastructure gaps:

- Limited access to alternatives: A substantial number of farmers face barriers in obtaining technologies that match their scale requirements for rice straw collection, processing or repurposing. Farmers require machinery designed for mulching operations and biochar production along with tools that enable efficient residue management.
- Insufficient support systems: The lack of adequate extension services and technical support continues to restrict farmers from implementing sustainable straw management methods.

c) **Cultural and traditional practices:**

   - Historical methods: Cambodian rice farmers widely practice open burning because it is an established tradition in their farming methods. The practice of burning agricultural residue after harvest persists due to its deep-rooted presence in farming routines which resists change despite available alternative methods.

d) **Policy and regulatory environment:**

   Enforcement and incentives: The existing regulations lack effective enforcement tools and adequate incentives to support alternative rice straw management techniques. Regulatory frameworks frequently lack precise instructions and assistance to help farmers move away from open burning techniques.

2.3.3 Pollutants Emitted from Burning of Agricultural Residues

Farmers employ burning agricultural residue including rice straw as a vegetation management practice which uses fire to eliminate agricultural waste from fields after harvest. Farmers choose to burn agricultural residue because it offers cost-effective land clearing and pest monitoring while enhancing nutrient cycling and providing convenience (Akahoshi et al., 2024; Wangwongwatana, 2021).

Burning rice straw poses significant health risks and environmental threats because it releases air pollutants which harm human health and generates greenhouse gases that accelerate climate change. Burning rice straw creates several environmental and social problems including soil degradation along with biodiversity loss and it triggers wildfires and community conflicts. These pollutants are produced when rice straw is burned:

- **Nitrogen Dioxide (NO_2):** Nitrogen dioxide (NO_2) in the atmosphere and indoors, making it more difficult to isolate its precise effects. Nitric oxide is an essential signaling molecule in the human body that affects a number of physiological functions, such as vasodilation and the control of enzyme activity. It has a major impact on immunological responses, metabolism, neurotransmission, and cardiovascular function (Lundberg & Weitzberg, 2022). High quantities of inhaled nitric oxide have been used in medical settings, especially to treat disorders like infant pulmonary hypertension and hypoxic respiratory failure, usually with no negative side effects. Research on nitric oxide's wider effects on immunological responses and lung function is still ongoing, though. Although nitric oxide possesses antibacterial and anti-inflammatory qualities, some research indicates that its function in lung damage and respiratory disorders is complicated and poorly understood (Van Der Vliet et al., 2000).

According to research on animals, nitric oxide may affect lung structure more strongly than nitrogen dioxide, which could result in airway blockage and lung inflammation. Furthermore, cytotoxic effects, DNA damage, and immune function suppression may be caused by nitric oxide's high affinity for heme-bound iron. However, compared to nitrogen dioxide, nitric oxide's toxicity has received less attention, thus further study is required to completely understand its consequences National Center for Biotechnology Information (2025). PubChem Compound Summary for CID 3032552, Nitrogen Dioxide. Retrieved on 2 April 2025 from:

https://pubchem.ncbi.nlm.nih.gov/compound/Nitrogen-Dioxide

Table 2: Chemical properties of nitrogen dioxide

Chmical name	**Nitrogen Dioxide**
Synonyms	• Dioxide, Nitrogen • Nitrogen Dioxide • Nitrogen Peroxide • Peroxide, Nitrogen
Molecular formula	NO_2
CAS number	10102-44-0
Molecular weight	46.006 g/mol
Odor	Irritating odor
Boiling point	70.07 °F at 760 mmHg (EPA, 1998)

Melting Point	15.3 °F (EPA, 1998)
Solubility	Reacts with water NIOSH, 2024)

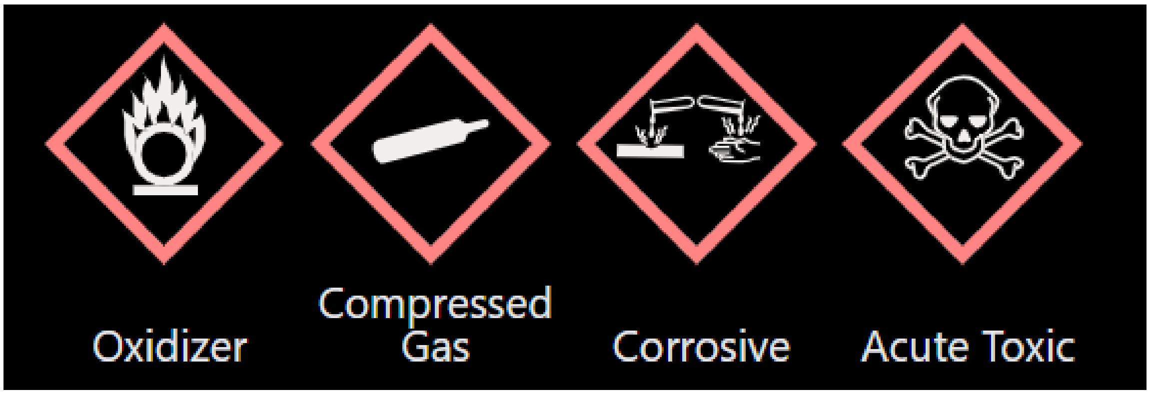

Figure 2: Nitrogen dioxide diagram

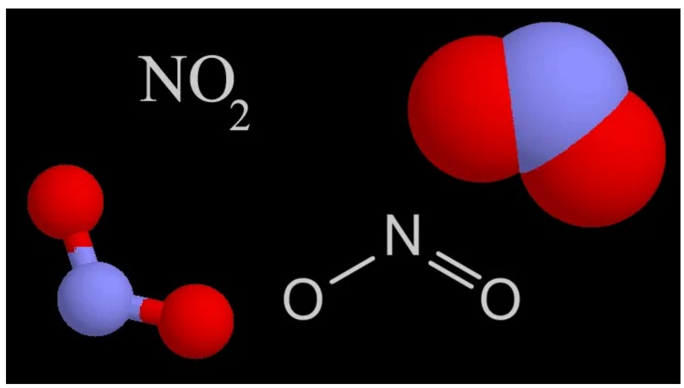

Figure 3: Chemical structure of nitrogen dioxide

- **Sulfur Dioxide (SO_2):** As a colorless gas that emits a strong odor Sulphur dioxide (SO_2) serves as a fungicide and preservative in the metal refining and paper bleaching industries as well as food processing National Center for Biotechnology Information (2025). The PubChem database provides a summary for compound CID 1119 which is Sulfur Dioxide. Retrieved April 2, 2025 from https://pubchem.ncbi.nlm.nih.gov/compound/Sulfur-Dioxide. Human Effects: SO_2 levels exceeding 10 ppm can cause irritation in both nasal passages and the throat. Exposure to 400 ppm of this substance is considered dangerous even for short durations while 50 ppm has been linked to serious health effects. Research reveals that prenatal exposure increases the risk of childhood asthma and wheezing while prolonged exposure exacerbates respiratory issues particularly in individuals with pre-existing asthma (Bai et al., 2022). Ecotoxicity: Research indicates that plants suffer damage from SO_2 at concentrations ranging between 0.3 and 0.5 ppm as demonstrated by harm to wheat and alfalfa crops (Shore et al., 1987).

Table 3: chemical properties of nitrogen dioxide

Chmical name	Sulfur Dioxide
IUPAC name	Sulfur dioxide
Molecular formula	SO_2, O2S
CAS number	7446-09-5
Molecular weight	64.07 g/mol
Odor	Strong suffocating odor
Boiling point	14 °F at 760 mmHg (EPA, 1998)
Melting Point	-98.9 °F (EPA, 1998)
Solubility	10 % (NIOSH, 2024)

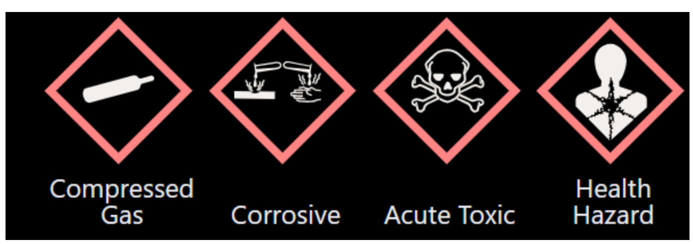

Figure 4: Sulfur dioxide chemical diagram

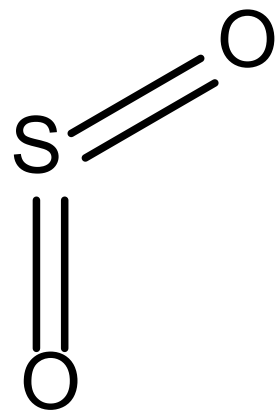

Figure 5: SO_2 Chemical structure and properties

- **Carbon MoNOxide (CO):** Carbon moNOxide (CO) forms by sharing three electrons between each carbon and oxygen atom (Figure 5). The pictogram for carbon moNOxide includes symbols for flammability, compressed gas, acute toxicity, and health hazards (Figure 6). Carbon moNOxide is an odorless and colorless gas (Table 5). Prolonged exposure to carbon moNOxide-rich atmospheres may be fatal. CO is easily ignited. It is slightly lighter than air, and a flame can easily flash back to the source of the leak. Under prolonged exposure to fire or intense heat, containers may violently rupture and rocket National Center for Biotechnology Information (2025). PubChem Compound Summary for CID 281, Carbon MoNOxide. Retrieved on 15 March 2025 from: https://pubchem.ncbi.nlm.nih.gov/compound/Carbon-MoNOxide.

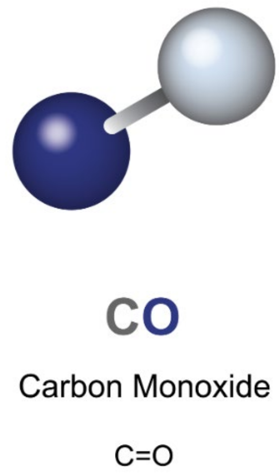

Figure 6: carbon moNOxide chemical structure and formula

Table 4: carbon moNOxide property

Chmical name	**Carbon MoNOxide**
IUPAC name	carbon moNOxide
Synonyms	MoNOxide, Carbon
Molecular formula	CO
CAS number	630-08-0
Molecular weight	28.010 g/mol
Odor/ form	Colorless gas/Odorless
Boiling point	-312.7 °F at 760 mmHg (USCG, 1999)
Melting Point	-326 °F (USCG, 1999)
Flash Point	Flammable gas
Hazards Identification	Toxic/poison by inhalation (TIH/PIH)

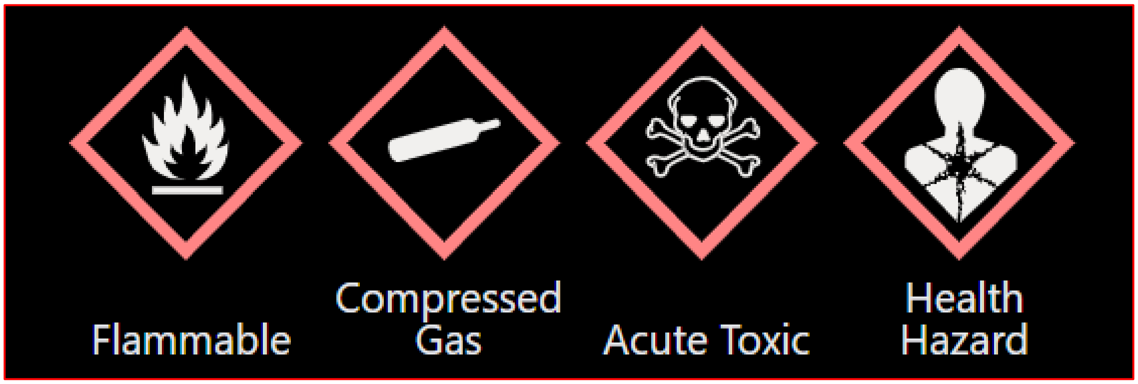

Figure 7: carbon moNOxide pictogram (s)

- **Particulate Matter 2.5 micron (PM2.5 µm):** The atmospheric aerosol particulate matter (PM) serves as a criteria air pollutant. The term "aerosol" describes a system where particles that are solid or liquid exist suspended within a gas like air with PM indicating the particle component of atmospheric aerosols. The composition of these particles contains numerous complexities which determine how they move through and interact in the atmosphere based on their size. There are two main categories of particulates which include "fine" and "coarse" particles. Fine particulates have an aerodynamic diameter of 2.5 micrometers (µm) or smaller compared to coarse particulates which range from larger than 2.5 µm to smaller than 10 µm.

The main constituents of PM are carbon-based materials which include a mixture of both organic and inorganic components. The components of PM become harmful to health after they are inhaled and settle in the respiratory system. The presence of specific chemicals in particulate matter produces reactive oxygen species which result in oxidative stress for lung cells (Tao et al.). 2003). The impact of PM on both the environment and human health depends on its mass concentration and morphology because both particle size and chemical makeup determine health effects. Exposure to PM for short periods results in inflammation in the upper respiratory tract and reduced lung function among the general population. The elderly along with children and people suffering from asthma and heart or lung conditions often experience coughing, phlegm production, wheezing, breathing difficulties and conditions like bronchitis that worsen their existing diseases. High levels of PM exposure in both ambient and occupational settings lead to chronic obstructive pulmonary diseases such as bronchitis and emphysema according to Jyethi (2016).

Rice straw combustion stands out as a significant air pollution source because it produces a large amount of particulate matter (PM). Scientific studies reveal that burning rice straw produces high amounts of PM2.5 and PM10 which stand for fine and coarse particulate matter. The health risk of these particles includes both respiratory and cardiovascular problems according to Kim Oanh et al. (2011). Studies indicate that rice straw burning produces PM2.5 emission factors between 4.2 g/kg and 20.67 g/kg which shows substantial differences based on the burning techniques used (Lasko & Vadrevu, 2018). These findings illustrate both environmental and health risks caused by rice straw burning and emphasize the need for alternative agricultural residue management techniques. Adopting these measures will help decrease air pollution levels and protect public health.

Table 5: Desk review on the burning of agricultural residues related to health risk assessment

Title	**Agricultural burning in Imperial Valley, California and respiratory symptoms in children: A cross-sectional, repeated measures analysis**
Key findings	The respiratory symptoms affect children, with an increased risk, especially for wheezing and bronchitic symptoms. Children with asthma have a 14% higher risk of experiencing wheezing. Low-income Hispanic communities living near burning sites are the most impacted.
Study design	Questionnaire data (parent report) and geocoded burn data were collected from 735 elementary schools from 2017 to 2019. The observation of burning at approximately 3 km indicates exposure for children living in residential areas.
Policy implication	To improve children's respiratory health, alternative policy interventions and farming practices are encouraged.

Reference	(Kamai et al., 2023)
Title	**Assessing people's awareness of environmental and health impacts of straw burning in southeast Vietnam through factor analysis and proposing sustainable solutions**
Health risks	PM10, PM2.5, toxic gases (VOCs, SO_X, CO, and NOx), and carcinogenic compounds of PAH pose health problems such as respiratory and cardiovascular diseases. These gases come from straw burning. Among the volunteers, they observed that children, the elderly, and those with pre-existing conditions are at higher risk.
Keys findings	Students and farmers understand the health risks. However, to control pests and improve soil fertilization, they still burn rice straw.
Policy recommendation	Restrict or limit access to straw burning and promote sustainable management methods. Increase public knowledge and provide commercial incentives for farmers who adopt alternative techniques.
Reference	(Dinh et al., 2024)
Title	**Crop residue burning: Impacts, management techniques and policies**
Health risks	The gases (PM2.5, NOx, SO_X, CO_X, VOCs, PAHs) emitted by the burning of crop residue cause health issues, including acute respiratory symptoms (throat irritation, and eye and nose irritation) and chronic diseases (asthma, lung cancer). The economic burden and premature mortality are extremely considerable, with 28,965 deaths attributed to air pollution in Haryana.

Keys findings	PM2.5 increases by 7 to 78% during the burning season, making the air quality in Delhi unsafe.
Policy recommendation	Reinforce policy implementation for in-situ (e.g., Turbo Happy Seeder) and ex-situ (e.g., biofuel production) residue management. Improve health investigations and public awareness to reduce crop residue burning.
Reference	(Mor et al., 2022)
Title	**Tackling air pollution from agricultural residue burning:** **The Aakash project: Challenge for reduction of rice-stubble burning in the Indian Punjab region**
Health risks	During the burning season, PM2.5 pollution increases in Delhi and the surrounding areas. The concentration of PM2.5 exceeds the WHO's restricted standard. Consequently, schools are closed, and public health is disrupted.
Keys findings	The limited awareness among rural populations poses a health risk, especially in areas where high population density contributes to increased pollution.
Future research	The next research should focus on understanding public attitudes toward the health impacts of air pollution. The limited awareness among rural populations poses a health risk, especially in areas where high population density contributes to increased pollution.
Reference	(Research & 2024, 2023)

2.4 Health Risk Assessment

A health risk assessment for rice straw burning emissions requires evaluation of multiple aspects including gas concentration levels, exposure timeframes, human breathing rates, toxicological properties, and their impact on human health. Health risk assessment studies analyze specific pollutants which include sulfur dioxide along with carbon moNOxide nitrogen oxide and PM2.5 particulate matter.

The World Health Organization (WHO) developed the Air Quality Guidelines (AQGs) to shield the population from air pollution's detrimental health effects. The guidelines specify the recommended concentration limits for various contaminants during their respective averaging periods. Below you will find the AQG values for primary air pollutants.

Table 6: Recommended Air Quality Guidelines (AQG) levels and interim targets

Pollutants	**Average time**	**AQG**
Sulphur Dioxide (SO_2)	24 H	40 µg/m³
Carbon MoNOxide, or CO	24 H	4 mg/m³
Nitrogen Dioxide (NO_2):	24 H	25 µg/m³
Fine Particulate Matter, or PM2.5	24 H	15 µg/m³

Citation: WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon moNOxide. Geneva: World Health Organization; 2021.

The sub-decree on air and noise pollution from the Ministry of Environment, Cambodia, has established air quality regulations as presented in the table 8.

Table 7: Air quality regulations from sub-decree on air and noise pollution from the Ministry of Environment

Pollutants	Average time	AQG
Sulphur Dioxide (SO_2)	24 H	300 µg/m³
Carbon MoNOxide, or CO	24 H	-
Nitrogen Dioxide (NO_2):	24 H	100 µg/m³
Fine Particulate Matter, or PM2.5	24 H	-

CHAPTER 3: RESEARCH METHODOLOGY

This study uses both qualitative and quantitative methods to assess the environmental and public health impacts of open burning of agricultural residues, mainly rice straw in Cambodia. The methodology is conceptualized with 3 components including agricultural residue burning (rice straw burning), air quality monitoring/air pollution assessment, and health impact assessment against national standard and WHO air quality guidelines. The data and information of open burning of agricultural residue, air quality, perception, and health impact from air pollution and burning of agricultural residue can be obtained from primary and secondary sources.

3.1. Data Collection

The information of rice cultivation and burning of agricultural residues, best practices, and alternative option to burning of agricultural residue from Asian countries and Cambodia was reviewed as well. Further, the data on air quality at the selected study sites was gathered through the installation of air quality monitoring equipment (OCEANUS AQM-09) for 24 hours.

3.1.1 Primary Data

To collect data from the survey and group discussion, a set of questionnaires was established to obtain the necessary information from farmers. The formulation of the questionnaire, combined demographic information, farming practices, awareness and attitudes, health impact, perceptions on air pollution, open burning, and climate change, policy support, and open-ended questions, required detailed responses to make the research more practical and reliable. The interview and group discussion have conducted with head of village and farmers. Also, the open burning and air pollution data has received from air quality equipment installed at the selected locations in Prey Veng and Battambang Provinces.

3.1.2 Secondary Data

On the other hand, the secondary data on open burning of agricultural residue, best practices and alternatives to burning of agricultural residue, and air pollution and open burning related issues in Cambodia and Asian countries has received from the existing policies/regulations/publications from the Ministry of Environment and related ministries as well as the publications from various researchers.

3.2 Data Analysis

The data obtained from the analytical instrument and questionnaire form were transformed and interpreted using Microsoft Excel charts (data visualization) to extract meaningful patterns, relationships, and insights relevant to the research objectives. The health risk assessment scientific formula, derived from a literature review, was used to calculate the estimated concentration. A combination of quantitative, qualitative, and statistical methods was employed to ensure a comprehensive understanding of the issues under investigation. Finally, data interpretation and reporting were conducted to produce the final results for decision-making.

3.2.1 Air Quality Monitoring Equipment Used for the Study

Air quality monitoring equipment (OCEANUS-AQM-09) is a real-time and fast measurements of outdoor air pollutants. The measurement parameters can be adjusted to meet the needs of various applications. These include the following gas types: ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon moNOxide (CO), particulate matter PM2.5 and PM10, as well as noise and meteorological parameters (such as temperature, humidity, wind direction, speed, and barometric pressure). This equipment was installed at Khsom Tboung Village, Kampong Popil Commune, Pea Reang Disctrict, Prey Veng Province and Hai San Village, Chrey Commune, Thmor Kol District, Battambang Province.

Table 8: OCEANUS-AQM-09 specifications

Item	Analytes	Specification
Particle Modules	PM2.5	○ Monitoring method: Continuously, automatically and real-time ○ Working principle: Light scattering technique ○ Measuring range: 0~1000ug/m3 (Range can be extended) ○ Response time: ≤60s
Gas	CO	○ Measuring range: 0~200ppm ○ Resolution: 0.1ppm ○ Response time: ＜45s
	NO_2	○ Measuring range: 0~2000ppb ○ Resolution: 1ppb

		○ Response time: ＜45s
	SO_2	○ Measuring range: 0~2000ppb ○ Resolution: 1ppb ○ Response time: ＜45s

Figure 8: OCEANUS-AQM-09 Air Quality Monitoring Equipment

3.3 Air Quality Monitoring Process

OCEANUS-AQM-09 was installed at Khsom Tboung Village, Kampong Popil Commune, Pea Reang Disctrict, Prey Veng Province and Hai San Village, Chrey Commune, Thmor Kol District, Battambang Province for 24-hour monitoring. The installation procedure involved selecting an appropriate area to capture real time atmospheric data continuously and automatically and then a local expert validated the instrument's data before scheduling its operation. Finally, the result of the air quality monitoring was recorded and stored and awaiting interpretation.

Figure 9: OCEANUS-AQM-09 installation processes

Figure 10: Interview and group discussion with farmers

CHAPTER 4: RESULTS AND FINDINGS

4.1 Results

Following a comprehensive description of the literature reviews and research methodology for data and information collection of open burning of agricultural residue, air quality, perception, and health impact from air pollution and burning of agricultural residue, the result of the study can be shown as follows:

4.1.1 Air Quality Monitoring Data

Air quality monitoring equipment known as OCEANUS-AQM-09 was installed by the research team in Khsom Tboung Village within Kampong Popil Commune of Pea Reang District and Hai San Village located in Chrey Commune of Thmor Kol District in Battambang Provinces for 24-hour air quality assessment. Four main air pollutants such as sulfur dioxide (SO_2), carbon moNOxide (CO), nitrogen dioxide (NO_2), and particulate matter (PM), especially PM2.5 have been identified as harmful to humans and the environment. The 24-hour air quality monitoring data showed that Prey Veng province reported average pollutant concentrations of 19.09 (ug/m3) for SO_2, 1.21 ($\mu g/m^3$) for CO, 17.32 ($\mu g/m^3$) for NO_2, and 26.32 ($\mu g/m^3$) for PM2.5 compared to Battambang province which had averages of 18.41 ($\mu g/m^3$) for SO_2, 0.97 ($\mu g/m^3$) for CO, 5.25 ($\mu g/m^3$) for NO_2, and 36.90 ($\mu g/m^3$) for PM2.5.

<u>Prey Veng Province</u>

Table 9: Real-time monitoring of SO_2, CO, NO_2, and PM2.5 within 24 hours in Prey Veng Province.

Time	SO_2($\mu g/m^3$)	CO ($\mu g/m^3$)	NO_2($\mu g/m^3$)	PM2.5($\mu g/m^3$)
09:00	19.12	1.2	15.46	17.85
10:00	19.08	1.11	16.65	17.39
11:00	19.22	0.93	21.28	33.71
12:00	19.11	0.8	20.58	45.54
13:00	18.84	0.9	24.35	51.31
14:00	18.73	1.48	20.53	41.72
15:00	19.4	1.07	19.4	36.42

16:00	19.18	1.52	18.79	37.94
17:00	19.11	1.24	18.72	59.13
18:00	19.37	0.95	13.31	33.55
19:00	19.24	0.96	16.5	26.33
20:00	19.22	1.23	15.8	21.07
21:00	18.99	1.42	16.83	27.91
22:00	18.76	1.43	16.03	28.52
23:00	18.37	1.39	15.43	21.78
24:00	18.89	1.93	17.87	26.13
01:00	19.37	1.44	19.27	18.29
02:00	19.72	0.85	16.29	14.45
03:00	19.65	0.9	15.35	11.37
04:00	18.59	1.06	21.56	9.09
05:00	19.03	1.39	13.88	10.11
06:00	19.18	1.43	13.36	15.31
07:00	19.04	1.22	14.53	16.07
08:00	18.96	1.22	13.83	10.63
Average	**19.09**	**1.21**	**17.32**	**26.32**
Standard Deviation	**0.31**	**0.27**	**2.93**	**13.70**
RSD-Related Standard Deviation	**0.02**	**0.22**	**0.17**	**0.52**
Result +SD	**19.40**	**1.48**	**20.25**	**40.02**
Result -SD	**19.07**	**0.99**	**17.15**	**25.80**

NOTE: The air quality monitoring data was collected within 24 hours.

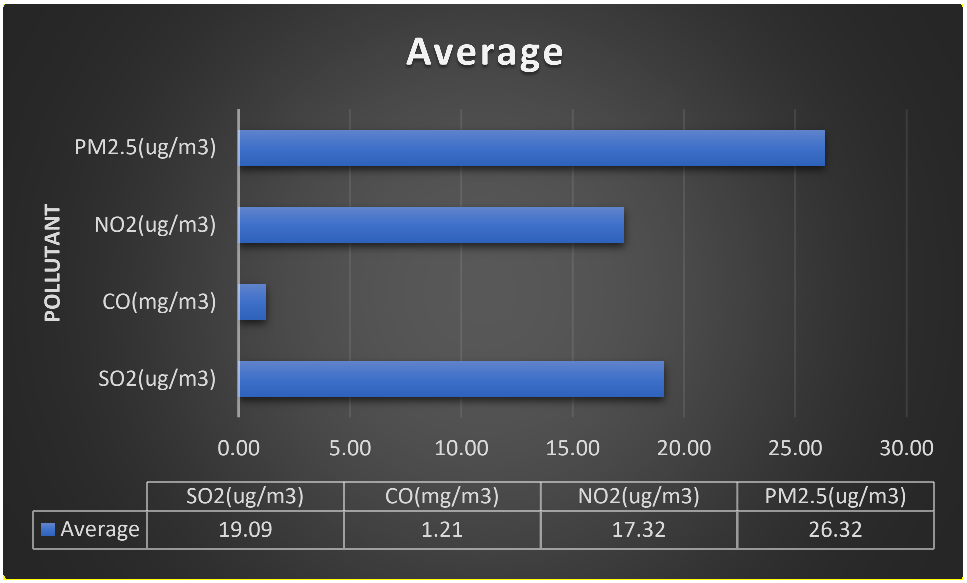

Figure 11: Average pollutants emissions from straw burning in Prey Veng Province.

Battambang Province

Table 10: Real-time monitoring of SO_2, CO, NO_2, and PM2.5 within 24 hours in Battambang Province.

Time	**SO_2**($\mu g/m^3$)	**CO**($\mu g/m^3$))	**NO_2**($\mu g/m^3$)	**PM2.5**($\mu g/m^3$)
09:00	18.15	0.86	6.07	28.78
10:00	18.15	0.94	4.11	28.76
11:00	18.42	0.96	4.6	29.6
12:00	18.37	0.91	6.14	29.36
13:00	17.64	0.96	5.27	29.43
14:00	18.24	1.06	5.29	28.87
15:00	18.23	1.19	5.9	28.45
16:00	18.22	1.38	6.41	34.54
17:00	18.3	1.52	5.31	35.89
18:00	18.56	1.02	7.18	55.32
19:00	17.63	1.05	5.3	56.23
20:00	18.33	0.79	7.44	56.76

21:00	18.48	0.96	7.56	52.57
22:00	18.55	0.91	3.61	52.34
23:00	18.59	0.73	4.73	47.23
24:00	18.51	0.67	4.33	43.88
01:00	18.58	0.84	5.32	36.88
02:00	18.54	0.9	2.98	36.76
03:00	18.65	0.72	4.02	31.74
04:00	18.69	0.87	4.65	28.99
05:00	18.66	0.99	3.65	28.54
06:00	18.69	1.36	7.15	28.45
07:00	18.77	0.91	4.12	28.11
08:00	18.93	0.82	4.88	28.1
Average	18.41	0.97	5.25	36.90
Standard Deviation	**0.31**	**0.21**	**1.27**	**10.58**
RSD-Related Standard deviation	**1.70**	**21.56**	**24.23**	**28.66**
Result +SD	**18.73**	**1.18**	**6.52**	**47.48**
Result -SD	**18.10**	**0.76**	**3.98**	**26.32**

NOTE: The air quality monitoring data was collected within 24 hours.

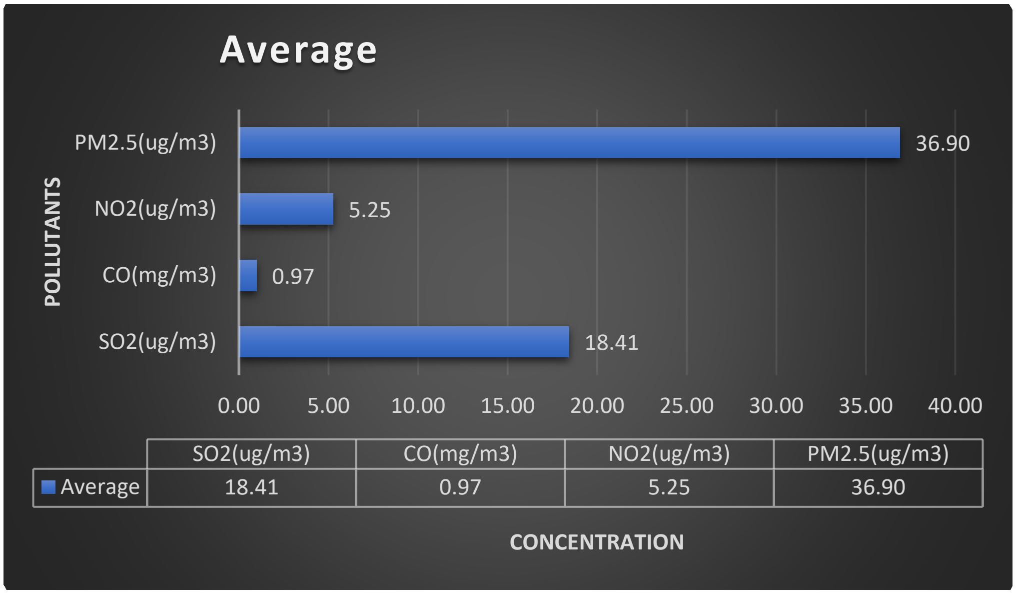

Figure 12: Average pollutant emissions from straw burning in Battambang Province.

4.1.2 Survey Result by Questionnaires

A. Prey Veng Province

Figure 13: Q1-Demographic & Socioeconomic Profile

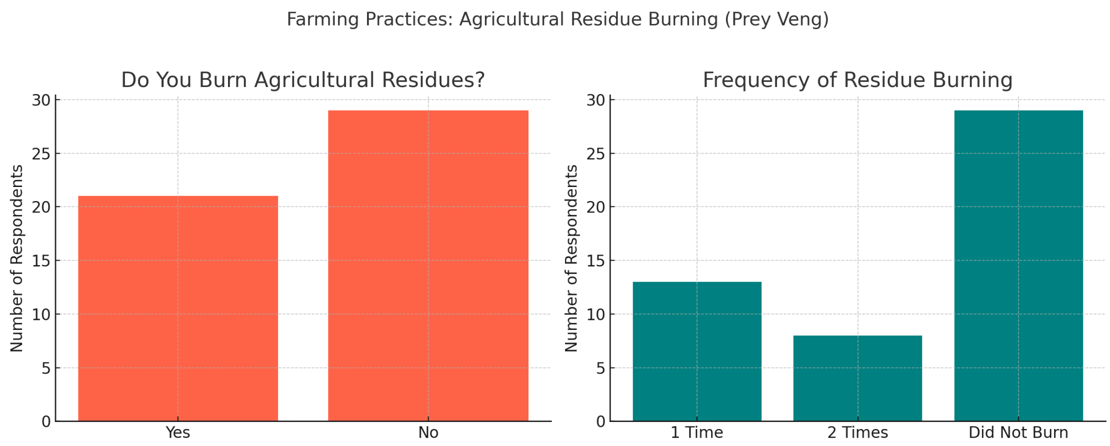

Figure 14: Q2-Farming Practices

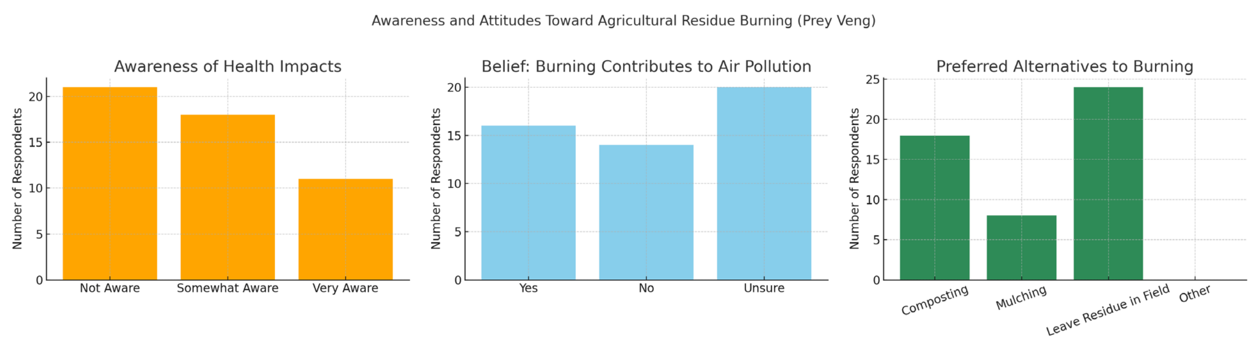

Figure 15: Q3-Awareness & Attitudes Toward Burning

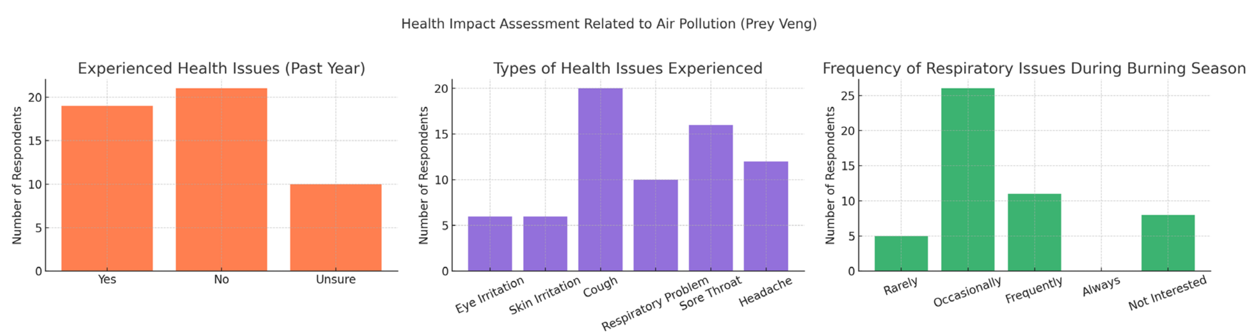

Figure 16: Q4-Health Impact Assessment

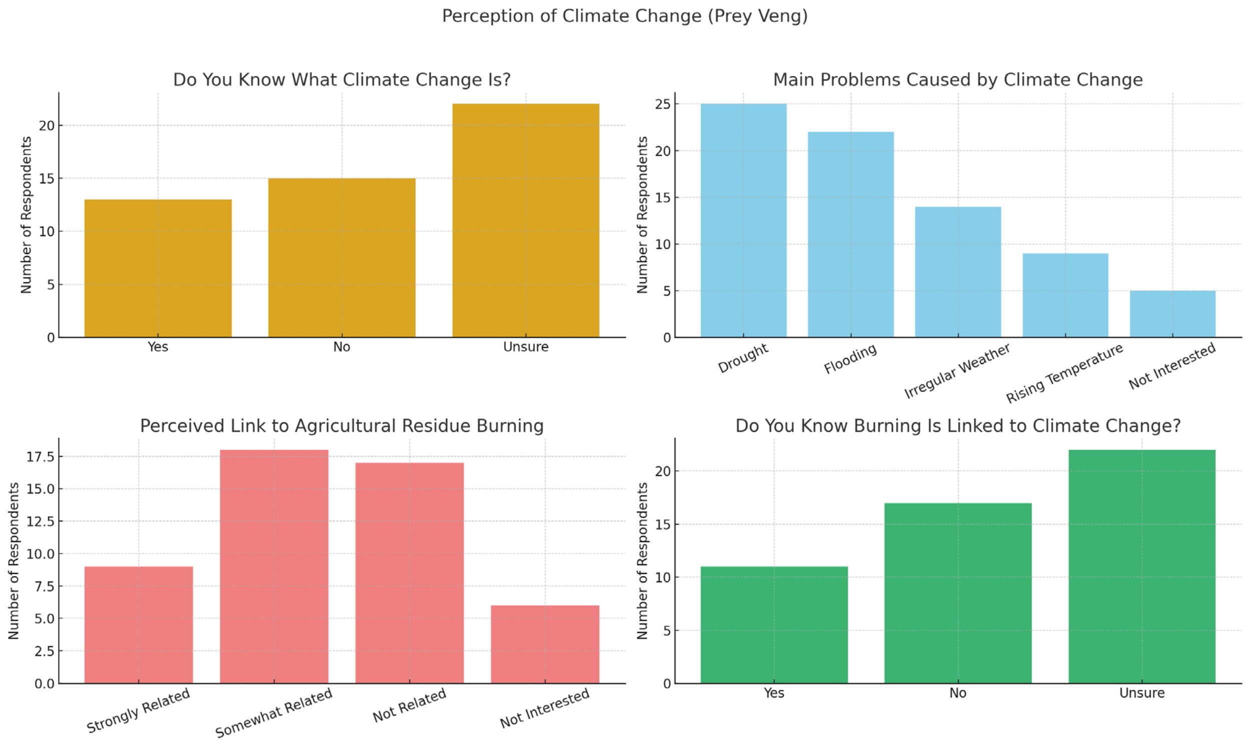

Figure 17: Q5-Perceptions of Climate Change

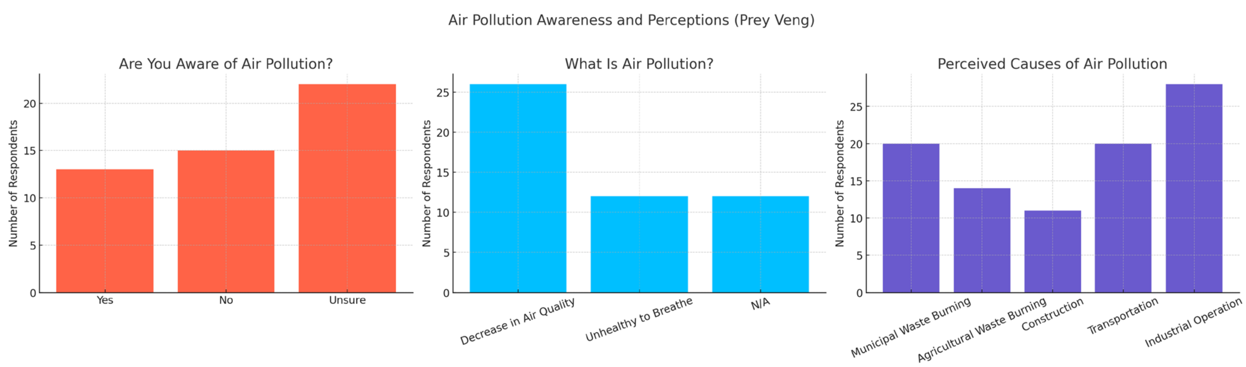

Figure 18: Q6-Air Pollution Awareness

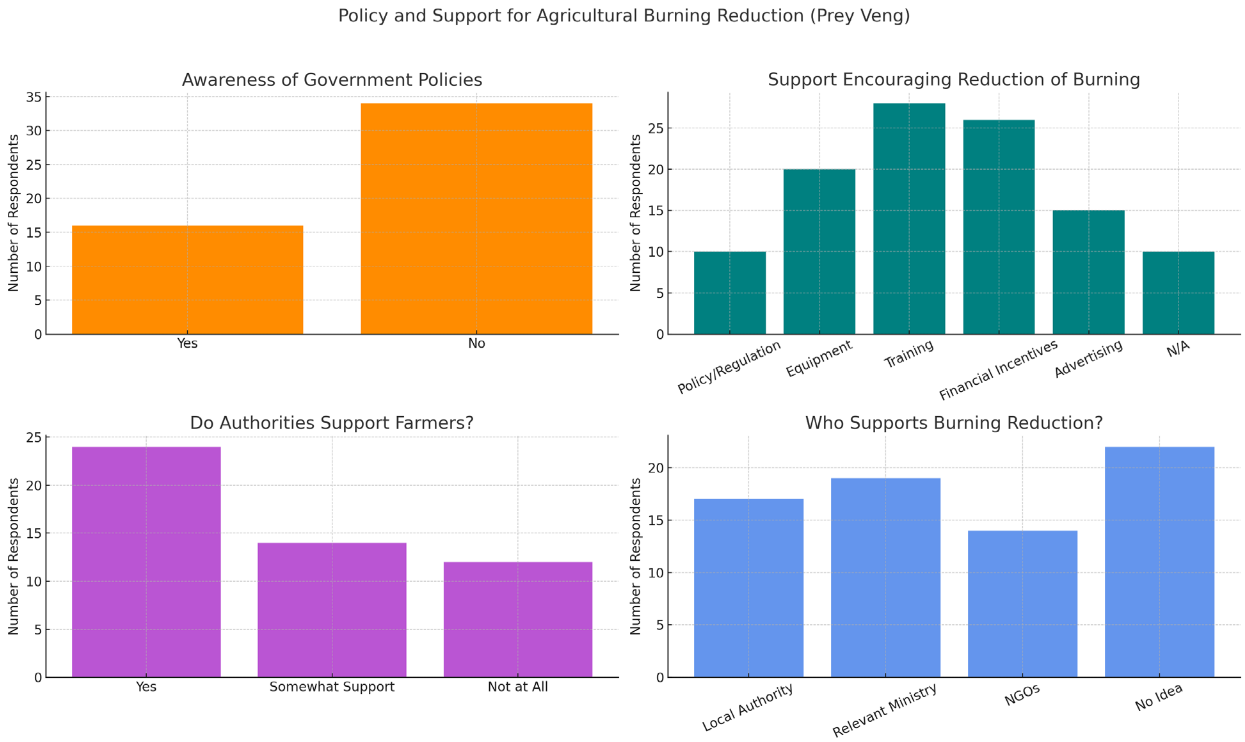

Figure 19: Q7-Policy Awareness & Support

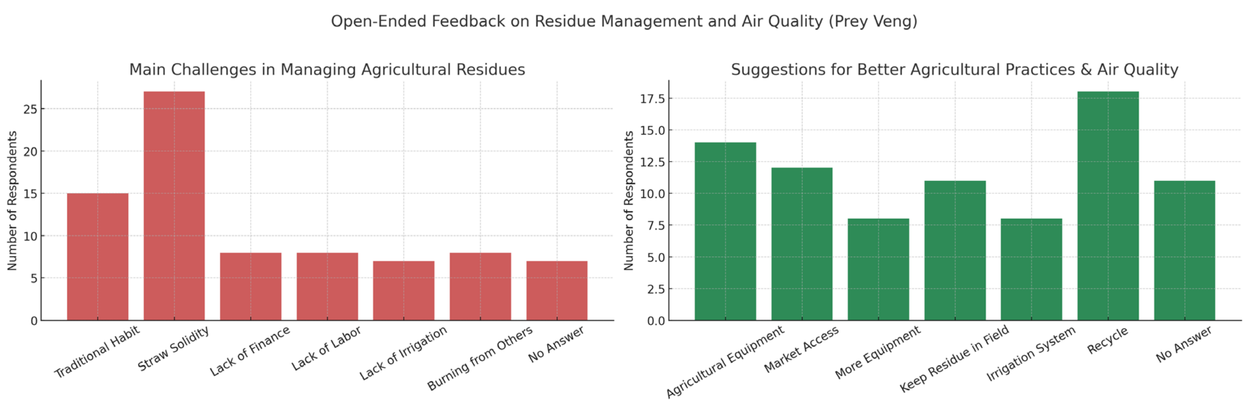

Figure 20: Q8-Challenges & Suggestions

B Battambang Province

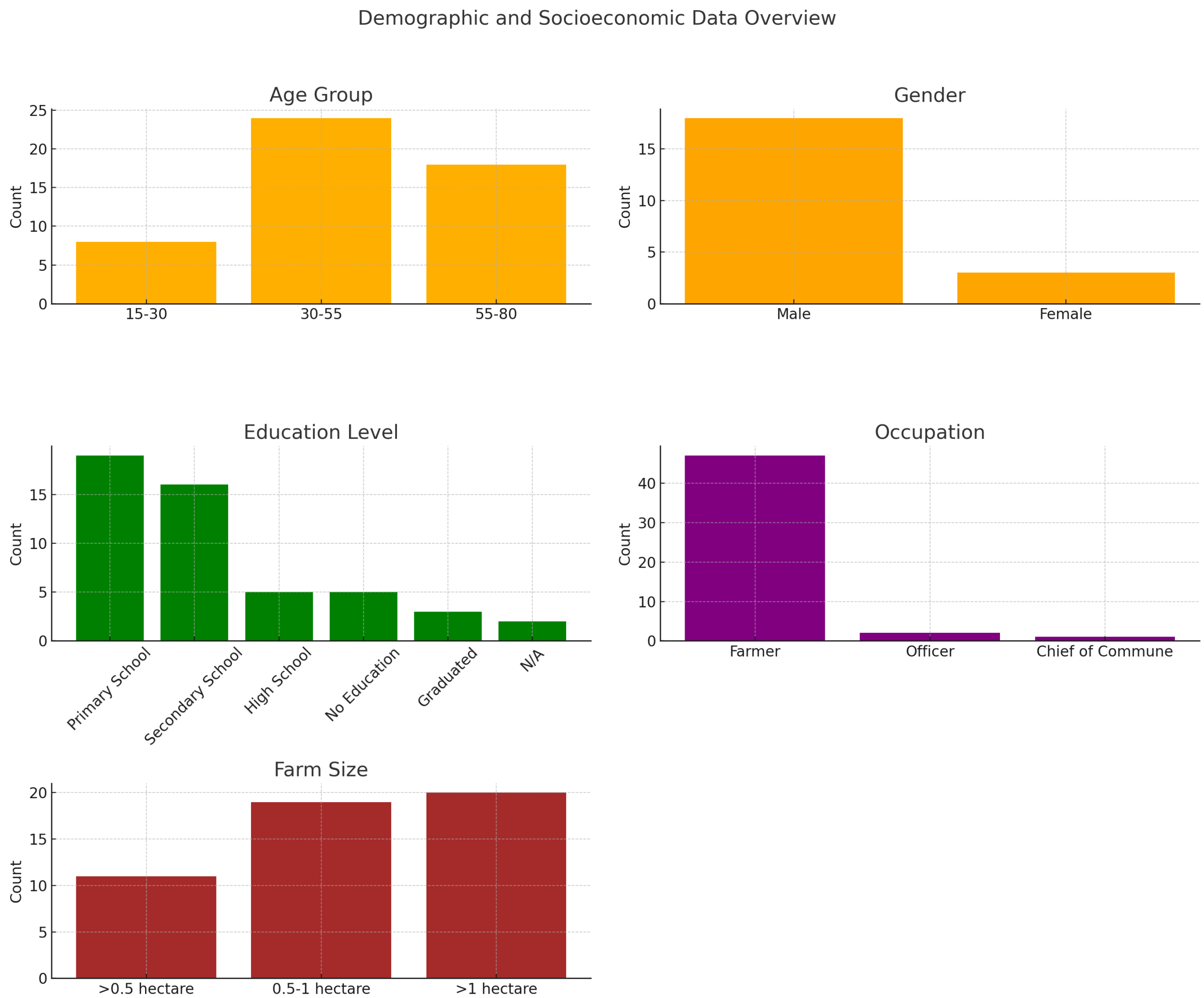

Figure 21: Q1-Demographic & Socioeconomic Profile

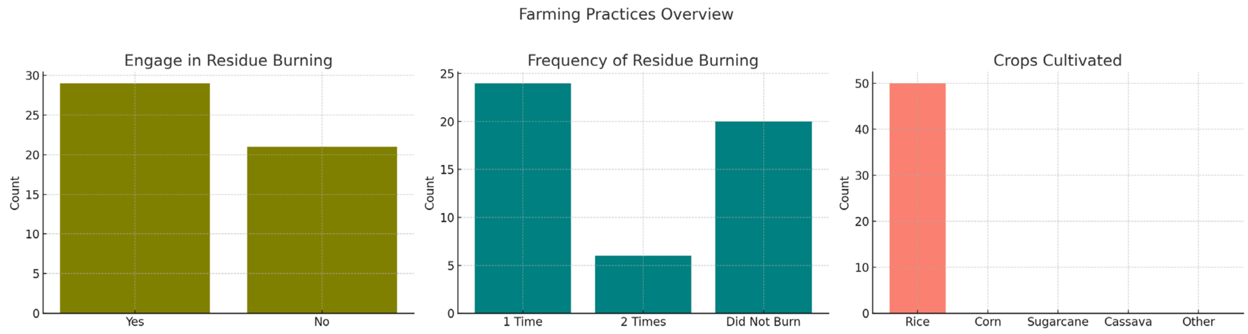

Figure 22: Q2-Farming Practices

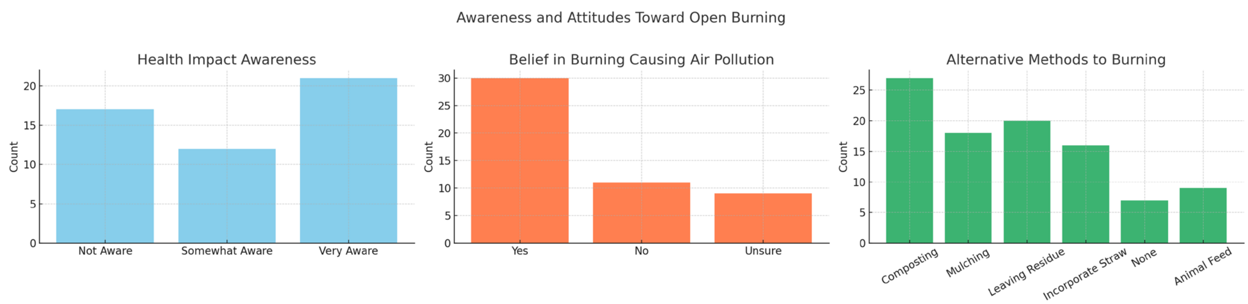

Figure 23: Q3-Awareness & Attitudes Toward Burning

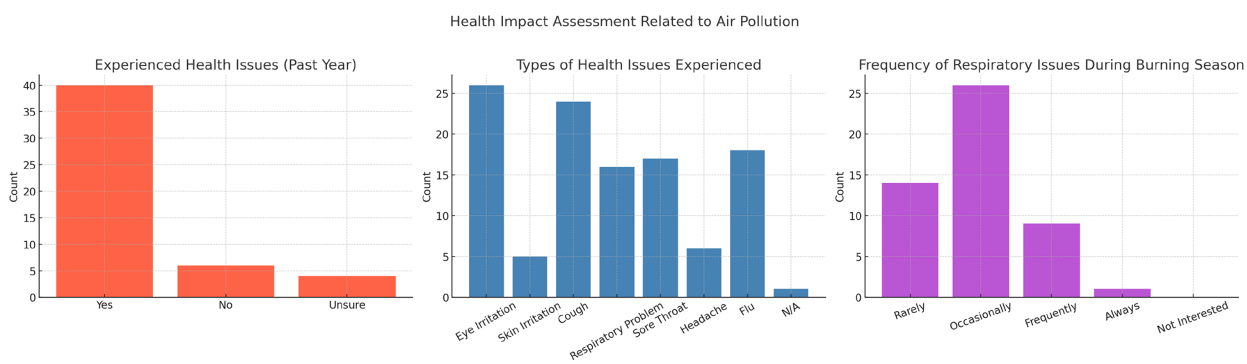

Figure 24: Q4-Health Impact Assessment

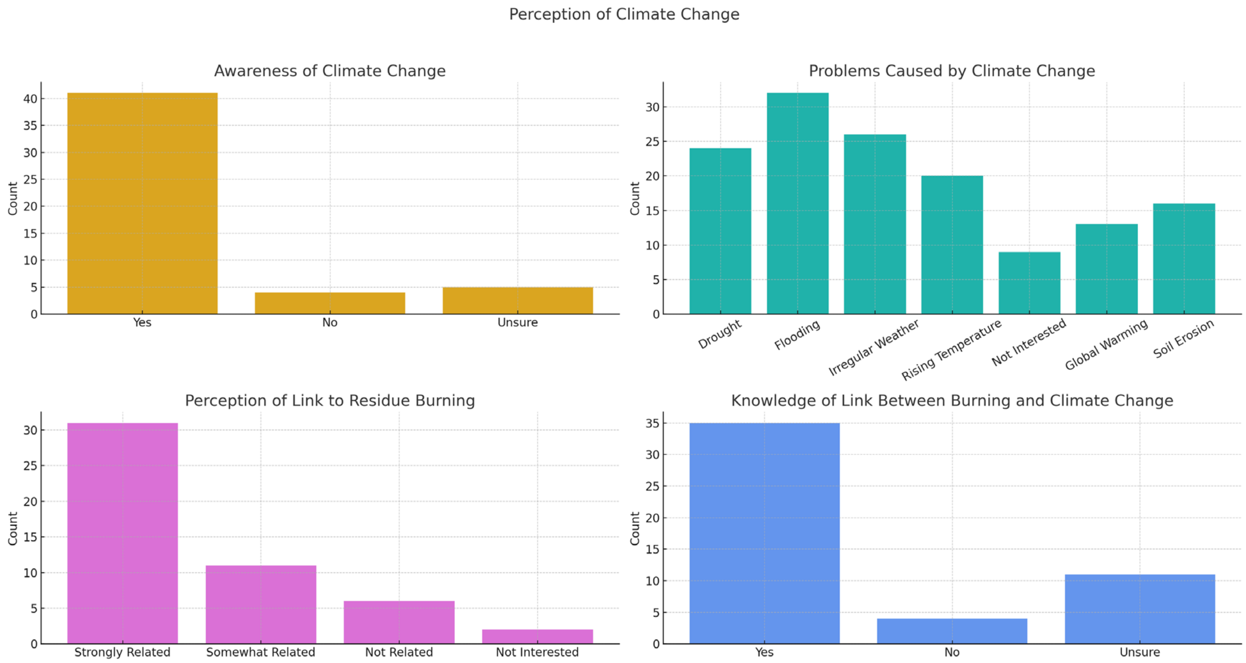

Figure 25: Q5-Perceptions of Climate Change

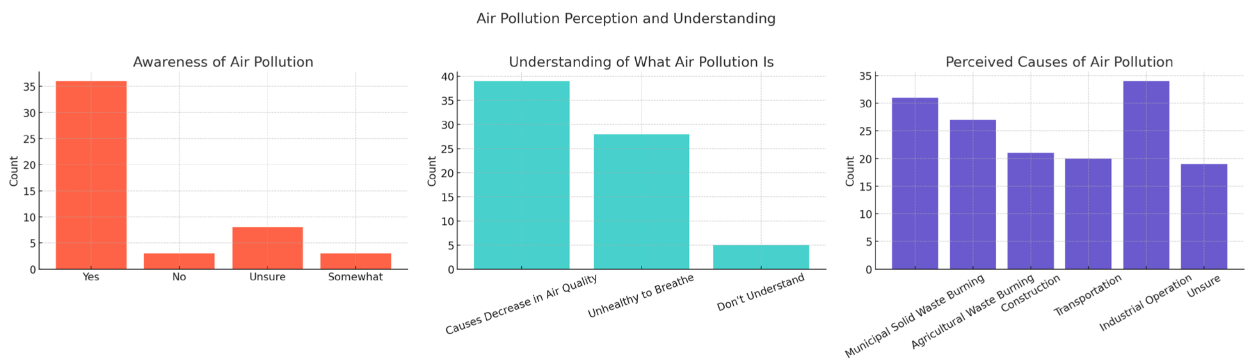

Figure 26: Q6-Air Pollution Awareness

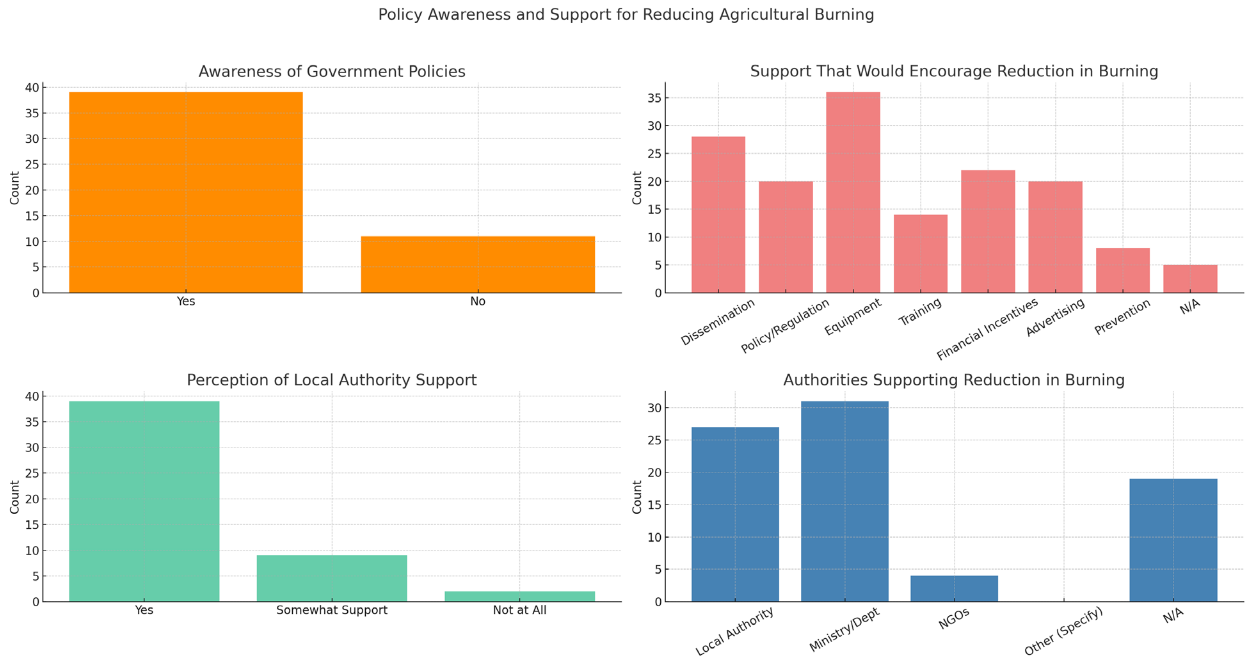

Figure 27: Q7-Policy Awareness & Support

Figure 28: Q8-Challenges & Suggestions

4.2 Findings

4.2.1 Air Quality Analysis

Based on the calculation of the air quality concentration in Table 11: Health risk assessment interpretation (WHO limit) and Table 12: Health risk assessment interpretation (MOE limit) for Prey Veng Province, the air pollutant concentrations against WHO Air Quality Guidelines (AQG) and MOE limit indicate that the average concentration of SO_2 and CO is lower than the AQG limit considering as LOW RISK and VERY LOW RISK to public health respectively at the time of measurement, while the SO_2 and CO concentration is at about 15 times and closer to 6 times respectively comparing to MOE limit. Also, although the average concentration of NO_2 is below WHO guideline limit. It is at the moderate level for public health impact. The NO_2 concentration is also likely within Cambodia's national ambient air quality standards, which are generally more lenient than WHO guidelines. However, PM2.5 concentration exceeds the WHO guideline by almost 2 times, indicating a high-risk level of exposure at the time of measurement. This poses a significant health concern, particularly for vulnerable people such as children, the elderly, and individuals with respiratory or cardiovascular conditions. In addition, PM2.5 value may fall within Cambodia's national standard, which was set around 50 µg/m3 for 24 hours and 25 µg/m3 for annual basis).

Table 11: Health risk assessment interpretation (WHO limit)

	Pollutant (µg/m^3)	Result	WHO's AQG	Interpretation
Prey Veng Province	SO_2	19.09	40	(19.09> 40) Low risk
	CO	1.12	4	(1.12< 4) Very low risk
	NO_2	17.32	25	(17.32<25) Moderate exposure
	PM2.5	26.32	15	(26.32>15) High risk, 2 times higher than WHO's limit

Table 12: Health risk assessment interpretation (MOE limit)

	Pollutant (μg/m³)	Result	MOE Limit	Interpretation
Prey Veng Province	SO_2	19.09	300	(19.09> 300) 15 times lower than MOE limit Very low risk
	CO	1.12	NA	NA
	NO_2	17.32	100	(17.32<100) Close to 6 times lower than MOE limit Low risk
	PM2.5	26.32	50	(26.32<50) Close to 2 times lower than MOE limit Low risk

Legend

Low risk, very low risk

Moderate exposure

High risk

NA

In short, air quality in Prey Veng Province shows unhealthy levels of PM2.5, raising concerns over public health and environmental management. While NO_2, SO_2, and CO are within WHO guidelines and national standard at the time of measurement. Therefore, the concentration of PM2.5 must be taken into account for urgent mitigation actions. Ongoing monitoring and stronger regulatory frameworks, including awareness raising, especially with farmers are needed to address the root causes of pollution (burning of agricultural residues and waste) and protect community well-being and it will ultimately lead to the improvement of living conditions.

In addition, according to the comparison of air quality concentration in Table 13: Health risk assessment interpretation (WHO limit) and Table 14: Health risk assessment interpretation (MOE limit) for Battambang Province, the air pollutant concentrations against WHO Air Quality Guidelines (AQG) and MOE limit indicate that the average concentrations of SO_2 and CO, and NO_2 are both well below the WHO limits, which they are not at the concerned level for human health. The concentrations of SO_2 and CO are more than 2 to 4 times respectively and NO_2 nearly 5 times lower than the AQG limit. It means the health issue is considered at LOW RISK and VERY LOW RISK at the time of measurement. However, the concentration of PM2.5 is the most concerning pollutant in Battambang, with levels more than 2 times higher than WHO's safe limit**,** indicating a HIGH RISK for health at the time of measurement. This can be linked to cardiovascular and respiratory issues, especially for vulnerable populations.

Furthermore, comparing these pollutant concentrations with MOE's limits, PM2.5 recorded higher than other parameters at the time of measurement at 36.90 µg/m3. Although its concentration is below the MOE threshold, it is close enough to the alarming concern for public health, significantly for children and elderly as it can causes cardiovascular and respiratory diseases, and long-term exposure increases risk of premature death. For SO_2 and NO_2 concentration is at about 15 times and closer to 6 times respectively comparing to MOE limit. It means the health issue is considered as VERY LOW RISK and LOW RISK at the time of measurement. It is noted that, MOE has not set the standard for CO, making it difficult to assess health impact at the selected village, however, if CO concentration is at higher level, it can impair oxygen delivery to organs and tissues and chronic exposure can cause cardiovascular health issue. Therefore, establishing CO standard would strengthen national air quality frameworks.

In conclusion, air quality in Battambang Province indicates unhealthy levels of PM2.5, raising concerns over public health and environmental management, while NO_2, SO_2, and CO are within WHO's guidelines and national standard at the time of measurement, excluding CO as it has been missing from MOE limit. Therefore, the concentration of PM2.5 must be taken into account for urgent mitigation actions. Ongoing monitoring and stronger regulatory frameworks, including the formulation of CO standard, awareness raising, especially with farmers are needed to address the root causes of pollution (burning of agricultural residues and waste) and protect community well-being and it will ultimately lead to the improvement of living conditions.

Battambang Province

Table 13: Health risk assessment interpretation (WHO limit)

	Pollutant (µg/m^3)	Result	WHO's AQG	Interpretation
Battambang Province	SO_2	18.41	40	(18.41> 40) 2 times lower than WHO's limit Low risk
	CO	0.97	4	(0.97< 4) 4 times lower than WHO's limit Very low risk
	NO_2	5.25	25	(5.25<25) close to 5 times lower than WHO's limit Very low risk
	PM2.5	36.90	15	(36.90>15) 2 times higher than WHO's limit High risk

Table 14: Health risk assessment interpretation (MOE limit)

	Pollutant (µg/m^3)	Result	MOE Limit	Interpretation
Battambang Province	SO_2	18.41	300	(18.41> 300) 15 times lower than MOE limit Very low risk
	CO	0.97	NA	NA
	NO_2	5.25	100	(5.25<100) Close to 6 times lower than MOE limit Low risk
	PM2.5	36.90	50 for 24 hours	(36.90<50) Close to MOE limit Moderate risk

Legend

(white)	*Low risk, very low risk*
(orange)	*Moderate exposure*
(red)	*High risk*
(light green)	*NA*

4.2.2 Questionnaires

<u>Prey Veng Province</u>

1. Demographic Profile
    - Age: Most respondents are aged 30–55, followed by 55–80. Youth representation (15–30) is minimal.
    - Gender: Slightly more females than males.
    - Education: Primary education is most common. A notable number have no formal education, and few reached high school.
    - Occupation: All respondents are farmers.
    - Farm Size: Most own small to medium-sized farms. Larger farms (>1 hectare) are less common.
2. Farming Practices
    - Residue Burning: More respondents do not burn residues than those who do.
    - Frequency: Among burners, the majority burn once; fewer burn twice.
3. Awareness & Attitudes Toward Burning
    - Health Impact Awareness: A majority are not aware or only somewhat aware of health effects. Few are very aware.
    - Air Pollution Belief: Many are unsure whether burning causes air pollution. Those who believe it does slightly outnumber skeptics.
    - Preferred Alternatives: "Leaving residue in the field" is the top alternative, followed by composting. Mulching is less practiced.
4. Health Impact Assessment
    - Health Issues: Nearly equal split between those who experienced health issues and those who did not.
    - Types: Cough, respiratory issues, and headaches are common.
    - Frequency: Most experience respiratory symptoms occasionally; some report frequent or constant issues.
5. Perception of Climate Change
    - Awareness: A majority are unsure about climate change; awareness is low.
    - Recognized Impacts: Drought and flooding are seen as key problems.

- Link to Burning: Most believe burning is somewhat or not related to climate change.
- Knowledge: Many are unsure whether burning contributes to climate change.

6. Air Pollution Awareness
   - Awareness: Many respondents are unsure about air pollution; fewer are clearly aware.
   - Understanding: Most define it as a decrease in air quality.
   - Perceived Causes: Industrial operations and municipal waste burning are the most cited sources, followed by agriculture and transportation.
7. Policy Awareness & Support
   - Government Policy Awareness: Most respondents are unaware of any policy on burning reduction.
   - Support Needs: Training, financial incentives, and equipment are most desired.
   - Authority Support: Only a minority believe authorities are fully supportive; many see limited or no support.
   - Recognized Supporters: "No idea" ranks highest, indicating uncertainty. Ministries and local authorities are mentioned more than NGOs.
8. Challenges & Suggestions
   - Challenges: Straw solidity and traditional practices are major barriers. Lack of finance, labor, and irrigation are also concerns.
   - Suggestions: Emphasis on irrigation systems, agricultural equipment, and recycling as ways to improve residue management and air quality.

Battambang Province

1. Demographic and Socioeconomic Profile
   - Age & Gender: Most respondents are men aged 30–55.
   - Education: Majority have primary or secondary education.
   - Occupation: Predominantly farmers.
   - Farm Size: Most own farms larger than 0.5 hectare.
2. Farming Practices
   - Residue Burning: Many engage in burning; others do not.
   - Frequency: Mostly burned once; fewer burned twice or not at all.
   - Crops: Rice is the primary crop; other crops are negligible.
3. Awareness & Attitudes Toward Burning

- Health Awareness: Mixed levels; one-third are very aware.
- Air Pollution Belief: Most link burning to air pollution.
- Alternatives: Composting, mulching, and residue retention are practiced, though some do nothing.

4. Health Impacts from Air Pollution
    - Health Issues: Majority experienced problems in the past year.
    - Types: Eye/skin irritation, cough, and respiratory issues are common.
    - Frequency: Respiratory symptoms occur occasionally or rarely, with some frequent cases.
5. Perceptions of Climate Change
    - Awareness: Most are aware of climate change.
    - Impacts: Flooding, drought, and irregular weather are key concerns.
    - Burning Link: Many see residue burning as related to climate change.
    - Knowledge: Most recognize the link; some remain unsure.
6. Perception & Understanding of Air Pollution
    - Awareness: High awareness levels.
    - Understanding: Recognized as harmful and tied to poor air quality.
    - Causes: Agricultural burning and industry are top perceived causes.
7. Policy Awareness & Support
    - Policy Awareness: Most know of relevant policies.
    - Support Needs: Equipment, training, and financial incentives are desired.
    - Authority Role: Local authorities and ministries seen as key supporters.
8. Challenges & Suggestions
    - Challenges: Lack of irrigation, finance, equipment, and straw management.
    - Suggestions: Promote irrigation, residue retention, and better market access.

Overall insights of Battambang and Prey Veng province comparison

Comparison Questionnaire between Battambang and Prey Veng Province

1. Demographic & Socioeconomic Profile

Factor	Prey Veng (N=50)	Battambang (N-50)
Age	Mostly 30–55, followed by 55–80	Mostly 30–55
Gender	Slightly more females	Mostly male
Education	Primary most common; some with no school	Primary and secondary dominant
Occupation	All respondents are farmers	Mostly farmers
Farm Size	Smaller farms (<1 ha) dominate	Majority have farms >0.5 hectare

Insight: Prey Veng respondents tend to be less educated and operate smaller farms, possibly influencing awareness and access to alternatives.

2. Farming Practices

Factor	Prey Veng	Battambang
Residue Burning	Fewer burn; majority do not	More burn residues
Frequency	Mostly burn once or not at all	Mostly once; some twice or none
Crops Cultivated	Not indicated	Predominantly rice

Insight: Prey Veng shows a lower engagement in burning, which could reflect earlier behavior shifts or different crop residue characteristics.

3. Awareness & Attitudes Toward Burning

Factor	Prey Veng	Battambang
Health Awareness	Mostly unaware or unsure	Mixed; one-third very aware
Belief in Pollution Link	Many unsure, few affirm	Most believe in pollution link
Alternatives Used	Leaving residue, composting	More diverse (composting, mulching)

Insight: Battambang respondents are more environmentally informed and open to alternatives. Prey Veng may benefit from targeted awareness campaigns.

4. Health Impact Assessment

Factor	Prey Veng	Battambang
Health Issues	Mixed responses	Majority experienced issues
Common Symptoms	Cough, respiratory, headache	Eye/skin irritation, respiratory
Frequency	Mostly occasional	Ranges from rare to frequent

Insight: Health impacts from air pollution are more pronounced or recognized in Battambang, suggesting differences in exposure or awareness.

5. Perceptions of Climate Change

Factor	Prey Veng	Battambang
Awareness	Many unsure, awareness is low	High awareness
Perceived Impacts	Drought, flooding	Flooding, drought, irregular weather
Burning Link Perception	Mixed or weak link	Stronger belief in link
Knowledge of Link	Many unsure	Most recognize connection

Insight: Prey Veng respondents lack both awareness and conviction on climate-burn relationships, indicating a gap in climate communication.

6. Air Pollution Awareness

Factor	**Prey Veng**	**Battambang**
Awareness	Low; many unsure	High awareness
Understanding	Mainly linked to air quality	Seen as health hazard
Perceived Causes	Industry, municipal waste	Agriculture, industry

Insight: Both regions see industrial activity as a major contributor, but Prey Veng's understanding is less developed.

7. Policy Awareness & Support

Factor	**Prey Veng**	**Battambang**
Awareness of Policy	Most unaware	Most aware
Support Needed	Training, incentives, equipment	Equipment, training, incentives
Perceived Support	Unclear; "No idea" ranks high	Local authorities and ministries favored

Insight: There's a clear need to increase policy visibility and authority engagement in Prey Veng.

8. Challenges & Suggestions

Factor	**Prey Veng**	**Battambang**
Main Challenges	Straw solidity, traditional habits, finance	Irrigation, finance, equipment
Key Suggestions	Irrigation, recycling, agri-equipment	Irrigation, residue retention, market support

Insight: Common themes around resource access and management show up in both, but Prey Veng points to cultural/traditional barriers more.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Rice is a fundamental staple in Asia, accounting for approximately 90% of global rice production and consumption. China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, and Japan are among the top producers. China is a leading country to cultivate about 188.5 million tons, following by India about 142.5 million tons. Among those Asian countries, Cambodia produces rice approximately 11.62 million tons per year and it is considered as the main source of income for rural farmers. Rice production is the Cambodia's largest agriculture export commodity worth about USD 1 billion. Further, based on the FAO Global Information and Early Warning System (GIEWS) Country Brief on Cambodia, the total paddy rice production is estimated to be approximately of 14 million tons for the 2024/25 season (https://www.fao.org/giews/countrybrief/country.jsp?code=KHM).

The production process of rice generates substantial quantities of rice straw as a by-product that persists in abundance because it holds little economic value. Each year farmers generate about 10 million tons of rice straw with over 3 million tons burned openly in fields. Limited application choices for rice straw and financial constraints drive farmers to burn it openly in fields. Open burning practices lead to major environmental harm through the release of air pollution and greenhouse gases while causing health problems and soil degradation and resulting in biodiversity loss, wildfires and community conflicts. Burning rice straw produces these specific pollutants:

- Nitrogen dioxide (NO_2): The presence of this substance both in the atmosphere and indoor environments complicates efforts to identify its exact effects. This substance significantly influences immunological responses while also affecting metabolism and neurotransmission and cardiovascular function as shown by Lundberg & Weitzberg (2022). It possesses antibacterial and anti-inflammatory qualities. The study performed by Van Der Vliet et al. in 2000 suggests it leads to lung damage and respiratory disorders.
- Sulphur dioxide (SO_2): The colorless gas Sulphur dioxide (SO_2) possesses a strong odor and serves as a common fungicide and preservative in metal refining, food processing and paper bleaching industries. Children exposed to SO_2 have higher chances of developing

asthma and wheezing and continuous exposure can intensify respiratory issues in people with existing asthma conditions (Bai et al., 2022). SO_2 damages plants at concentrations between 0.3 to 0.5 ppm which leads to detrimental effects on crops including wheat and alfalfa as shown in Shore et al. (1987).

- Carbon moNOxide (CO) is a poisonous, colorless, odorless, and tasteless gas. It's a dangerous substance because it reduces the blood ability to carry oxygen, potentially leading to serious health problems, and if prolong inhale can lead to death.
- PM2.5: describes airborne fine particles that measure 2.5 micrometers or less in diameter. The tiny particles of PM2.5 pose serious health risks because they reach deep into the lungs and may enter the bloodstream. The general population experiences both upper respiratory tract inflammation and reduced lung function when exposed to PM2.5 for short durations. Children, the elderly, asthmatics and people with heart and lung conditions face higher risks of developing symptoms including coughing, phlegm production, wheezing, breathlessness and bronchitis along with frequent asthma attacks and deteriorating lung or heart diseases (Jyethi, 2016).

In addition, according to the data of air quality monitoring at Khsom Tboung Village, Kampong Popil Commune, Pea Reang Disctrict, Prey Veng and Hai San Village, Chrey Commune, Thmor Kol District, Battambang Provinces, 3 air pollutants (SO_2, CO, and NO_2) are not harmful to human health and environment for both WHO guidelines and MOE limits, except PM2.5 which exceeds the WHO limits and closes to the national standard that is harmful to environment and human health, significantly for vulnerable people such as children, the elderly, and individuals with respiratory or cardiovascular conditions.

5.2 Best Practices

Although burning of rice straw emitted harmful pollutants to environment and human health, there are alternatives to burning of rice straw including cutting rice straw to be made into various products such as animal feed (for cows or buffaloes), mushroom cultivation, bedding, composting, and garden mulching; investment in converting rice straw into biochar and fuels like bioethanol or pellets/briquettes; In situ crop residue management with the super straw management system (SMS) and turbo happy seeder (THS) is one of the most sustainable and effective methods recommended; incorporating straw residue into the soil or using machinery to clear straw residue; and applying controlled burning techniques or prescribed burning. However, there are challenges to adoption of those sustainable practices such as low economic value of rice straw, lack of accessible alternatives or markets, limited access to technology and machinery, weak enforcement of regulations, and cultural embeddedness of burning as a traditional practice.

5.3 Policy Recommendations

To enable widespread adoption of sustainable practices, a set of policy recommendations can be suggested to the government, essentially the Ministry of Environment, Ministry of Agriculture, Forestry and Fisheries, and related line ministries.

1. Enforcement of existing regulation frameworks
    - Ban or phase out open burning of agricultural residues with clear timelines using Circular No. 1 on Measures to Prevent and Reduce Ambient Air Pollution, adopted in 2020.
    - Set emission standards for CO (currently missing in Cambodia's MOE air quality standards).
    - Introduce penalties and incentives by applying the punishment of open burning and rewarding alternative practices.

2. Develop market-based incentives
    - Create value chains for rice straw-based products (biochar, animal feed, compost).
    - encourage private sector to invest in straw processing technology.

3. Strengthen extension services
    - Train farmers on sustainable residue management.
    - Deploy mobile units or demonstration farms showcasing alternatives such as composting pits, biochar kilns.

4. Provide financial and technical support
    - Subsidize machinery for in-situ management and straw collection.

- Facilitate access to low-interest loans or grants for smallholder farmers.

5. Raise public awareness
    - Conduct health-focused campaigns on the risks of straw burning.
    - Promote climate-smart agriculture through school programs, radio, and farmer field schools.

6. Invest in research and data systems
    - Continue and expand real-time air quality monitoring.
    - Research long-term health effects and economic impacts of residue burning.

REFERENCES

Akahoshi, K., Zusman, E., Hanaoka, T., Kim Oanh, N. T., Huy, L. N., Wangwongwatana, S., Homyok, P., Malley, C. S., Hirayama, T., Goto, Y., Kawashima, K., & Amann, M. (2024). The Prospects of Controlling Open Burning of Crop Residues in Thailand: A Quantitative Assessment of Implementation Barriers and Costs. *Atmosphere 2024, Vol. 15, Page 1309*, *15*(11), 1309. https://doi.org/10.3390/ATMOS15111309

Bai, S., Zhao, X., Liu, Y., Lin, S., Liu, Y., Wang, Z., Du, S., Liu, X., & Wang, Z. (2022). The effect window for sulfur dioxide exposure in pregnancy on childhood asthma and wheezing: A case-control study. *Environmental Research*, *204*. https://doi.org/10.1016/J.ENVRES.2021.112286

Bhatt, R., Giang, A., & Kandlikar, M. (2023). Incentivizing alternatives to agricultural waste burning in Northern India: trust, awareness, and access as barriers to adoption. *Environment Systems and Decisions*, *43*(3), 358–370. https://doi.org/10.1007/s10669-022-09892-w

Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, *16*(5). https://doi.org/10.3390/ijerph16050832

Building Partnerships for Innovative Rice Straw Management: Key to a Greener Future | International Rice Research Institute. (2024, November 5). https://www.irri.org/news-and-events/news/building-partnerships-innovative-rice-straw-management-key-greener-future

Dinh, V. P., Duong, B. N., Nguyen, T. P. T., Tran, T., Nguyen, D. K., Ngo, T. C. Q., Hoang, B. N., & Nguyen, T. Q. (2024). Assessing People's Awareness of Environmental and Health Impacts of Straw Burning in Southeast Vietnam Through Factor Analysis and Proposing Sustainable Solutions. *Environmental Health Insights*, *18*. https://doi.org/10.1177/11786302241296692

GAFSP. (2022, March 30). *Strengthening Rice Production in Cambodia | Global Agriculture and Food Security Program*. https://www.gafspfund.org/news/strengthening-rice-production-cambodia

Innovative rice straw composting technology earns accolades at Can Tho City Technical Innovation Competition | International Rice Research Institute. (n.d.). Retrieved March 7, 2025, from https://www.irri.org/news-and-events/news/innovative-rice-straw-composting-technology-earns-accolades-can-tho-city

IRRI News: Cambodia scales up rice straw management. (n.d.). Retrieved March 7, 2025, from https://news.irri.org/2019/01/cambodia-scales-up-rice-straw-management.html

Jyethi, D. S. (2016). Air quality: Global and regional emissions of particulate matter, SOx, and NOx. In *Plant Responses to Air Pollution* (pp. 5–19). Springer Singapore. https://doi.org/10.1007/978-981-10-1201-3_2

Kamai, E. M., Ruiz, B. C., Van Horne, Y. O., Barahona, D. D., Bejarano, E., Olmedo, L., Eckel, S. P., Johnston, J. E., & Farzan, S. F. (2023). Agricultural burning in Imperial Valley, California and respiratory symptoms in children: A cross-sectional, repeated measures analysis. *Science of the Total Environment*, *901*. https://doi.org/10.1016/j.scitotenv.2023.165854

Kim Oanh, N. T. (2021). Rice straw open burning: emissions, effects and multiple benefitsof non-burning alternatives. *Ministry of Science and Technology, Vietnam*, *63*(4), 79–85. https://doi.org/10.31276/vjste.63(4).79-85

Kim Oanh, N. T., Ly, B. T., Tipayarom, D., Manandhar, B. R., Prapat, P., Simpson, C. D., & Sally Liu, L. J. (2011). CHARACTERIZATION OF PARTICULATE MATTER EMISSION FROM OPEN BURNING OF RICE STRAW. *Atmospheric Environment (Oxford, England : 1994)*, *45*(2), 493. https://doi.org/10.1016/J.ATMOSENV.2010.09.023

Lasko, K., & Vadrevu, K. (2018). Improved rice residue burning emissions estimates: Accounting for practice-specific emission factors in air pollution assessments of Vietnam. *Environmental Pollution (Barking, Essex : 1987)*, *236*, 795. https://doi.org/10.1016/J.ENVPOL.2018.01.098

Lundberg, J. O., & Weitzberg, E. (2022). Nitric oxide signaling in health and disease. *Cell*, *185*(16), 2853–2878. https://doi.org/10.1016/J.CELL.2022.06.010/ASSET/194A4E7F-7B36-4029-8F70-575418DD7E5F/MAIN.ASSETS/GR4.JPG

Miura, Y., nutrition, T. K.-S. science and plant, & 1997, undefined. (2012). Emissions of trace gases (CO_2, CO, CH_4, and N2O) resulting from rice straw burning. *Taylor & FrancisY Miura, T KannoSoil Science and Plant Nutrition, 1997•Taylor & Francis*, *43*(4), 849–854. https://doi.org/10.1080/00380768.1997.10414651

Mor, S., Bhukal, S., Narsi, A., & Bishnoi, R. (2022). Crop residue burning: impacts, management techniques and policies. *Annals of Biology*, *38*(2), 245–251. https://agribiop.com/wp-content/uploads/2019/11/245-251.pdf

Naresh, R. K., Dhaliwal, S. S., Chandra, M. S., Malhotra, S. K., Harish, J., Singh, P. K., Kumar, V., Baliyan, A., & Gawdiya, S. (2021). Alternative Uses, in and off-Field Managements to Reduce Adverse Impact of Crop Residue Burning on Environment: A Review. *International Journal of Environment and Climate Change*, 100–118. https://doi.org/10.9734/ijecc/2021/v11i130347

Research, S. H.-G. E., & 2024, undefined. (2023). Tackling Air Pollution from Agricultural Residue Burning: The Aakash Project: Challenge for Reduction of Rice-Stubble Burning in the Indian Punjab Region. *Airies.or.JpS HAYASHIDAGlobal Environmental Research, 2024•airies.or.Jp*. https://www.airies.or.jp/attach.php/6a6f75726e616c5f32372d31656e67/save/0/0/27-1_01.pdf

Romasanta, R. R., Sander, B. O., Gaihre, Y. K., Alberto, M. C., Gummert, M., Quilty, J., Nguyen, V. H., Castalone, A. G., Balingbing, C., Sandro, J., Correa, T., & Wassmann, R. (2017). How does burning of rice straw affect CH_4 and N2O emissions? A comparative experiment of different on-field straw management practices. *Agriculture, Ecosystems & Environment*, *239*, 143–153. https://doi.org/10.1016/J.AGEE.2016.12.042

Shore, S. A., Kariya, S. T., Anderson, K., Skornik, W., Feldman, H. A., Pennington, J., Godleski, J., & Drazen, J. M. (1987). Sulfur-dioxide-induced bronchitis in dogs. Effects on airway responsiveness to inhaled and intravenously administered methacholine. *American Review of Respiratory Disease*, *135*(4 I), 840–847. https://doi.org/10.1164/ARRD.1987.135.4.840

Singh, G., Gupta, M. K., Chaurasiya, S., Sharma, V. S., & Pimenov, D. Y. (2021). Rice straw burning: a review on its global prevalence and the sustainable alternatives for its effective mitigation. *Environmental Science and Pollution Research*, *28*(25), 32125–32155.

https://doi.org/10.1007/S11356-021-14163-3

Van Der Vliet, A., Eiserich, J. P., & Cross, C. E. (2000). Nitric oxide: A pro-inflammatory mediator in lung disease? *Respiratory Research*, *1*(2), 67–72. https://doi.org/10.1186/rr14

Wangwongwatana, S. (2021). Review of Existing Good Practices to Address Open Burning of Agricultural Residues. *APCAP Joint Forum*. https://cleanairweek.org/wp-content/uploads/Review-of-existing-good-practices-to-address-open-burning.pdf