Development and Climate Change in the Mekong Region

Case Studies

edited by

Chayanis Krittasudthacheewa

Hap Navy

Bui Duc Tinh

Saykham Voladet

7

The benefits of using rice straw-derived solid fuel to reduce open burning emissions in the Mekong Region

Nguyen Thi Kim Oanh, Didin A. Permadi, P. Abdul Salam, Nguyen Nhat Ha Chi, Pham Khac Lieu, Duong Van Hieu, Prapat Pongkiatkul, Ketwalee Kositkanawuth, Kok Sothea, Chea Eliyan, Philip Hopke and Chu Thai Hoanh

The Mekong Region hosts two of the world's top five rice exporters, Thailand and Vietnam (Trade Map 2016). With the shift to multiple cropping each year, farmers need to quickly clear their paddy land of surface residues, comprising mainly of rice straw (RS), after each harvest in order to plant the next crop. Most farmers in the region have preferred to clear the land by burning the rice straw left in the field after each harvest, a practice that is termed field burning or open burning. An estimated 60 million tonnes of rice straw was generated in 2015 in the five Mekong Region countries and, on average, about 50 percent of this was subjected to open burning (Kim Oanh et al. 2018). RS open burning releases large quantities of toxic air pollutants and greenhouse gases (GHGs). A number of short-lived climate forcing pollutants (SLCPs), e.g. black carbon (BC), are also emitted. Thus, the emissions affect not only local air quality but also regional/global climates (Kim Oanh et al. 2011; UNEP and WMO 2011).

The rice farmers, however, have little knowledge about the negative implications of emissions from RS open burning (Kim Oanh et al. 2013). Yet there are several non-open burning alternatives, depending on economic conditions and agricultural practices, e.g., using RS as a medium for mushroom cultivation, animal feed and bedding, or as compost. Each has its drawbacks. For example, the presence of a high silica (Si) content in RS impedes digestion if it is used directly as livestock feed. In addition, the collection and transport of bulky RS for off-site use requires extra labor and transportation costs.

Loose RS has been used as cooking fuel in simple tripod cookstove/s (CS) traditionally in rural areas; however, this is an inefficient cooking system that consumes great amounts of fuel when compared to others (i.e. wood fuel burned in improved cookstoves). Moreover, the high emissions of air pollutants generated through incomplete combustion affects air quality in confined indoor spaces, thereby increasing the health risks of exposure to toxic air pollution indoors.

However, more efficient RS-derived solid fuels can be produced by densification and include, for example, roped/bundled briquettes and pellets that are easier to store or transport than loose RS. However, these conversion technologies have not been fully developed or adapted for RS. Additionally, using RS-derived solid fuels for cooking remains a challenge due to technical issues in the production of suitable products as well as farmers' limited awareness about the adverse effects of open burning. Thus, while the use of RS pellets for cooking is promising, there are obstacles to overcome, both in the pellet production and gaining user acceptance of the RS pellet-CS systems.

Therefore, the successful development of suitable densified fuels from RS for cooking is an opportunity to demonstrate the feasibility of this technology and to encourage farmers not to burn RS in the field. This can result in multiple benefits, e.g. reducing demand for wood and fossil fuels and at the same time eliminating the emissions from open burning. This chapter presents an assessment of the potential co-benefits of turning RS into cooking fuels to minimize open burning practices in Thailand, Vietnam and Cambodia. The assessment is based on information gathered from primary surveys conducted in selected agricultural areas in the target countries to investigate current RS generation and utilization, along with the emission-testing results of developed fuel-CS systems.

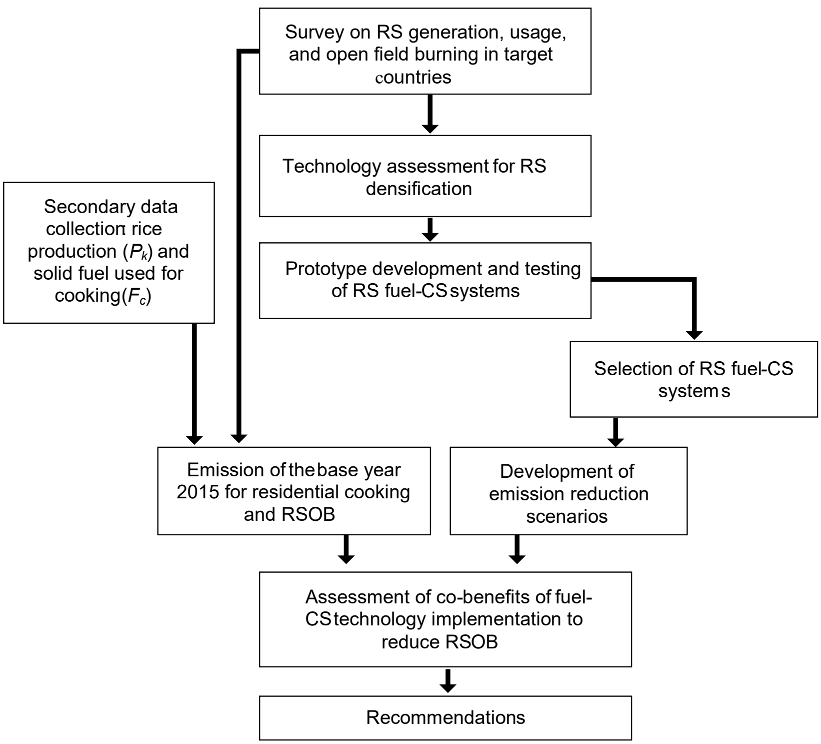
The development of the RS solid fuels and the emissions testing for the developed fuel-CS systems were all conducted at the Asian Institute of Technology (AIT) in Thailand. The activities were carried out under the Sustainable Mekong Research Network (SUMERNET) Phase 3 research project "Turning rice straw into cooking fuel for air quality and climate co-benefit in selected Greater Mekong Subregion (GMS) countries (RS co-benefit)." Induced changes in the emissions of toxic air pollutants and

GHGs due to the elimination of open burning and the simultaneous use of RS-derived solid fuels to replace solid fuels in cooking were quantified under two scenarios involving different fuel-CS systems. The benefits to air quality of each scenario were quantified according to their effects on reducing emissions of toxic air pollutants. Each scenario's potential for climate forcing mitigation was quantified using the Global Warming Potential (GWP) metric in CO_2 eq (20 year-horizon), accounting for both GHGs and SLCPs. The results will provide policymakers with supporting evidence to initiate and facilitate the enforcement of non-burning alternative RS management that can be replicated throughout the Mekong Region and beyond.

Methods

Research framework

Figure 7.1. Study research framework



The overall research framework is presented in fig. 7.1. A survey of current RS generation and utilization was undertaken in selected agricultural areas in Thailand, Vietnam and Cambodia. RS samples were collected during the surveys and analyzed in the laboratory for moisture and dry biomass content. The survey generated information on the fraction of residue-to-production ratio (S_k), fraction of RS subjected to open burning (B_k) and the harvesting methods that were essential in the calculation of the amount of RS biomass subjected to open burning and associated emissions. Available RS-derived solid fuel densification technologies were reviewed and assessed in controlled experiments at AIT. RS-derived solid fuels were characterized for their fuel properties and test burned in selected fuel-CS systems using an experimental hood system available at AIT. This system has been described in detail in our previous studies (Kim Oanh et al. 1999; Kim Oanh et al. 2005).

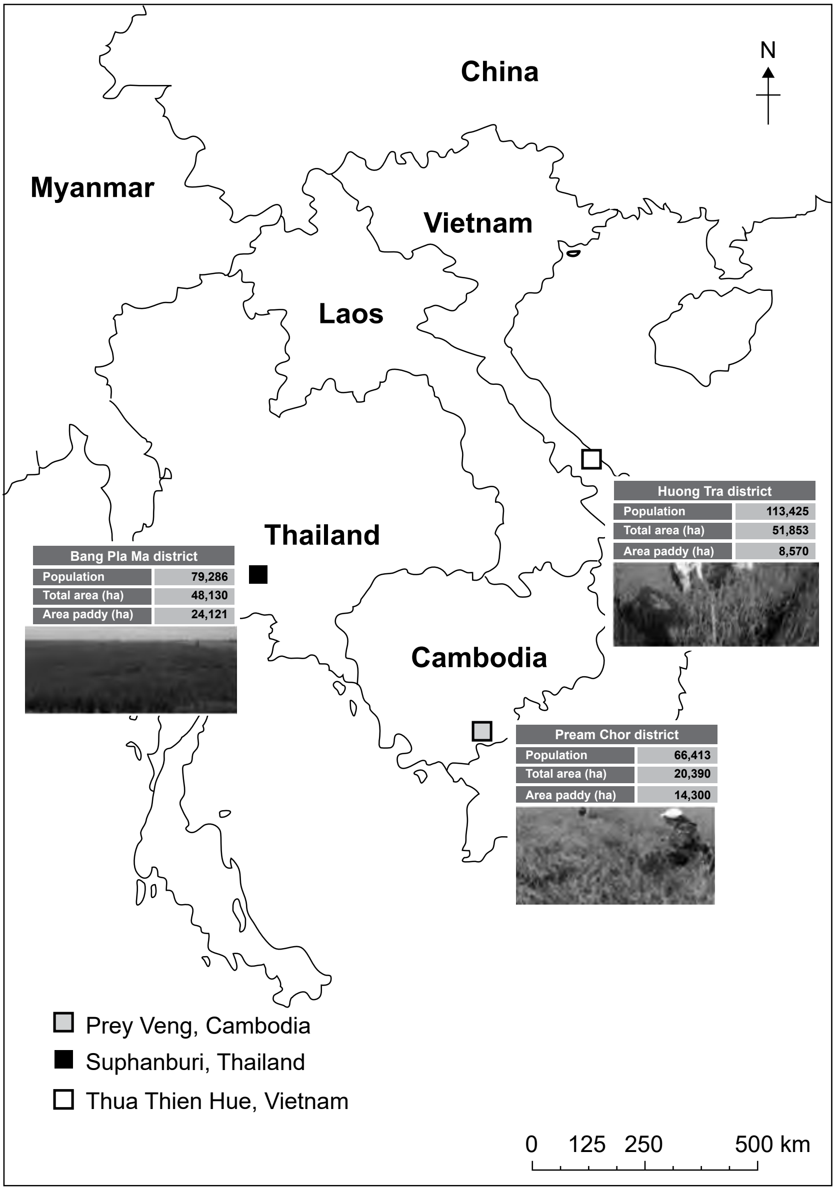
Secondary data on the consumption of solid fuels for residential cooking in Thailand, Vietnam and Cambodia were obtained from the respective national statistics. This information was used to analyze the volume of solid fuels that could potentially be replaced by RS-derived solid fuels for cooking in the three countries. Further, emission scenarios were developed that incorporated the results of RS-derived solid fuel-CS emission testing. Finally, an assessment of the co-benefits of implementing the RS-derived solid fuel-CS technology was undertaken using the changes in the emissions induced by the scenarios as compared to the base year emissions of 2015.

Survey

A survey of selected rice growing areas in Thailand, Vietnam, and Cambodia (fig. 7.2) was conducted to obtain representative information on RS open burning practices.

In Cambodia, the Pream Chor district was selected out of 13 districts in Prey Veng province, known as the largest rice-producing province in the country. Pream Chor district has a total area of 20,390 ha with a population of 66,413. In Vietnam, Huong Tra district, with an area of 8,570 ha and a population of 113,425, was selected from the nine districts/towns of Thua Thien-Hue province. The survey focused on the coastal commune of Huong Phong. In Thailand, the survey was undertaken in Bang Pla Ma district, Suphanburi province, central Thailand, which is also known as a rice-farming area. Bang Pla Ma has a total area of 48,130 ha with a population of 79,290.

Figure 7.2. Survey locations in Cambodia, Thailand and Vietnam



The surveys were conducted from April to September 2015 (in Thailand), May 2015, and August to September 2015 (Vietnam), and March to April 2015 (Cambodia) coinciding with the rice harvesting periods. A total of 290, 200, and 252 households (HHs) were surveyed in Bang Pla Ma (Thailand), Huong Tra (Vietnam), and Pream Chor (Cambodia), respectively. The surveys gathered information on the current utilization of RS and the fraction of RS subjected to open burning in the study areas. The project team in each country undertook the quantification of the RS biomass in the surveyed paddy fields. RS samples were collected from the fields (freshly after harvest) for moisture content determination, residue-to-production ratio, and yield (kg/ha) and used to estimate the total amount of RS dry biomass generated. The total above-ground biomass (available for RS open burning) and cut residue of RS (collectible for off-site use) were determined to represent the conditions of both manual and mechanical harvesting methods.

Development of RS-derived fuels

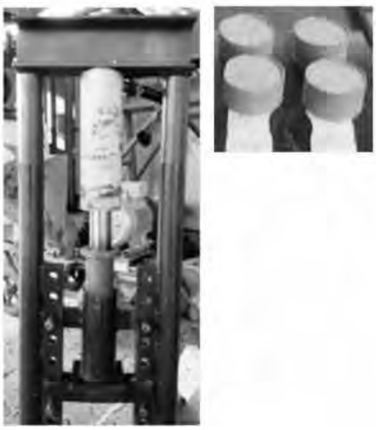
Three densification methods suitable for RS were investigated, namely, roping (making RS bundles), briquetting, and pelletizing. The three approaches were selected for assessment based on the following factors: feasibility, availability of necessary equipment to produce the solid fuel in the market, densification factor, and suitability for burning in available CS. The RS used in these studies were collected from a paddy in Bang Pla Ma, Suphanburi province, four days after being mechanically harvested. The collected RS was characterized using the proximate and ultimate analysis as detailed in several studies (Mai 2015; Rahaman 2015; Yin 2011). The prepared RS-derived solid fuels and the equipment used to produce the fuels are presented in fig. 7.3.

a) RS bundles

RS bundles (roped RS) were made in a range of sizes with a density two to three times higher than loose RS (Mai 2015). Both manual and machine-roped RS (using a roping machine) were produced. Bulk density measurement and proximate analysis were undertaken to characterize the roped RS.

Figure 7.3. Rice straw-derived fuel: Equipment and products

a. Handmade rope Roping machine and rope



b. Cold densification system and briquettes

c. Pelletizing machine and pellets

b) RS briquettes (cold densification)

A small-scale cold densification system was developed at AIT that was able to densify RS biomass with and without pre-treatment. The system allows variation of the operational parameters such as the outer diameter, ratio of the inner hole to outer diameter, moisture content, applied pressure (maximum 79.06 MPa), binder ratio, and briquette height (Rahaman 2015).

c) RS pellets

A pelletizing system was developed to produce RS pellets. Rice straw in particular has a low pelletizing ability (i.e. it is difficult to convert into pellets) hence resulting in low mechanical strength of the pellets produced and at the same time the production process consumes a significant amount of energy. Sawdust, as a binder, was used in combination with chopped RS for improving pellet quality: the lignins in the sawdust provide additional mechanical strength. The physical and thermal properties of the prepared RS pellets were determined in the AIT laboratory using the methodology presented in Cuong (2016).

RS-derived fuels-cookstove system testing

The RS-derived solid fuels of manually (handmade) and machine-roped RS, and RS pellets were evaluated in selected fuel-cookstove (CS) systems and these were compared to the traditional method of burning loose RS in a simple tripod CS. Four fuel-CS systems evaluated for thermal efficiency and emissions: loose RS and tripod; handmade roped RS and Thai biomass CS (BCS); handmade roped RS and Thai improved BCS (IBCS); and machine-roped RS and IBCS. The thermal efficiency of these fuel-CS systems was determined using the conventional water boiling test (Kipruto 2011).

The RS briquettes were too big, so could not effectively be burned in any CS available at AIT, hence were not included in the emission testing study. Pellets, being small in size and of high density, could not be burned directly in simple or improved tripod cookstoves. A forced up-draft gasifier CS (GCS) was selected and was proven to successfully burn the pellets. However, due to time constraints, efficiency and emission testing was not conducted for this RS pellet-GCS system. Instead, secondary data from published literature on the thermal efficiency and emissions of the system were used in the analysis. Thus, the final data analysis included all five systems, four of which were tested during this project.

A hood was used for the emission monitoring to produce emission factors (EFs), expressed as the amount of a pollutant produced per kilogram of dry fuel burned in a selected CS system. The concentrations of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), benzene, toluene, ethylene, and xylenes (BTEX) and particulate matter (PM) were measured from the hood chimney. The amount of fuel burned and the stack gas flowrates were measured to calculate EFs of each considered emission species.

The PM sampling was done using a cascade impactor with eight stages (i.e. eight size ranges of particles) while CO, CO_2 and CH_4 were measured with online gas analyzers (Rosemount Analytical's NGA 2000 MLT). The BTEX samples were collected using charcoal adsorption tubes and were analyzed in the laboratory using gas chromatography. BTEX sampling techniques and analysis were based on Method 1501 of the National Institute for Occupation Safety and Health (NIOSH 2003).

Emission calculation and co-benefit assessment

The emission inventory (EI) tool was used and the EI species included toxic pollutants of PM_{10} (PM with aerodynamic diameter equal or less than 10 μm) and $PM_{2.5}$ (PM with aerodynamic diameter equal or less than 2.5 μm), carbonaceous components of PM including BC and organic carbon (OC), gaseous pollutants of CO, non-methane volatile organic compounds (NMVOC), sulfur dioxides (SO_2) and nitrogen oxides (NO_x) and GHGs (CO_2, N_2O and CH_4).

The emission for residential cooking activity was estimated using Equation 7.1 below.

$$Em_{i,j,k} = \sum Fc_{j,k} \times EF_{i,j,k}$$

Where,

$Em_{i,j,k}$ = Emission of pollutant *i* from fuel type *j*, burned in CS type *k*
Fc_j = Consumption of fuel type *j* (kg/yr) burned in CS type *k*
$EF_{i,j,k}$ = Emission factor of pollutant *i* from fuel type *j*, burned in CS type *k*

The types of fuels and CS used in cooking in the three countries as of 2015 were obtained from the surveys and published records. EFs of various RS fuels–CS systems were mainly taken from the laboratory measurements of this project while for other types of fuels, the relevant secondary values from literature were used. The activity data, i.e. the fuel consumption data for residential cooking for 2015 in three countries, was obtained from the United Nations Statistics Division Energy Statistics Database (UNSDESD 2016) and relevant national databases.

For RS open burning emissions, the activity data that represents the amount of RS subjected to RS open burning (Mk) was calculated using Equation 7.2 below.

$$M_k = P_k \times S_k \times D_k \times B_k$$

P_k = Crop production for crop type k (mass amount per year, in consistent unit with M_k)
S_k = Crop-specific residue-to-production ratio
D_k = Dry matter-to-crop residue ratio (fraction, 0-1)
B_k = Fraction of dry matter residues, that are burned in the field (0-1).

The rice production per year (P_k) in 2015 value was obtained from national statistics (NIS 2016; OAE 2016; GSO 2016) while other parameters in Equation 7.2 were taken from the surveys conducted in this project.

To quantify the potential impacts of emissions on climate forcing,[1] the GWP of the emissions was calculated in term of CO_2 equivalent for the 20-year time horizon. The values used for the GWP calculation of different emission species were taken from the literature and selected to represent Southeast Asia (Fuglestvedt et al. 2009). In addition to GHGs, the climate forcing of SLCPs was also included in the GWP of the base case and scenario emissions. The amount of RS subjected to RS open burning (biomass loading) in 2015 for the three countries were calculated from the field survey results. Finally, energy consumption was calculated using the energy content of fuel in conjunction with CS efficiency to estimate the amount of solid fuels that could be replaced by RS-derived solid fuels for cooking.

Two emission scenarios were considered:

- *Scenario 1*: RS open burning would be eliminated and the amount of collectible RS in 2015 would be converted into roped (bundles) using a rope-making machine. The roped RS fuel would be used as cooking fuel in IBCS.
- *Scenario 2*: RS open burning would be eliminated and the amount of collectible RS in 2015 would be converted into pellets used as fuel in GCS.

The emission reductions under each scenario as compared to the base case of 2015 were quantified for the co-benefit analysis. Both energy content and CS thermal efficiency were considered in the calculation of the total fuel consumption under the scenarios. Finally, based on changes in fuel consumption under the two emission scenarios, the reductions in emissions of toxic air pollutants, GHGs and GWP, as compared to the base case of 2015, were quantified. The results show the volume of emissions that could be avoided by implementing the measures under the two scenarios and the potential co-benefits for air quality improvement and climate forcing mitigation.

Results

Survey results

A summary of the survey results is presented in table 7.1. In Pream Chor, the majority of farmers produce a single crop of rice annually while in Bang Pla Ma and Huong Tra, farmers typically have adopted the practice of annual double rice cropping. Mechanical harvesters are extensively used in all study areas: more than 90 percent by mechanical methods alone in Bang Pla Ma and Pream Chor; a combination of mechanical and manual methods in Huong Tra. Open field burning of RS was practiced by 59–95 percent of the interviewed farmers in the survey areas, and is more prevalent in Bang Pla Ma and Huong Tra than in Pream Chor. In Vietnam, open burning was practiced more widely by farmers who used mechanical harvesting methods. In Pream Chor, farmers tended to collect RS for livestock feed (51 percent) or leave straw in the field to decompose (23 percent), hence only a small proportion (about 16 percent) of RS was subjected to open burning.

The moisture content of spread RS in freshly harvested paddies was typically 22–25 percent, but higher moisture content was obtained for RS in Huong Tra, Vietnam (55 percent). The moisture content dropped to about 8–9 percent after four to seven days of post-harvest exposure to solar radiation in the field. The residue-to-product ratio (S_k) ranges between 0.68–0.74, with the lower value measured in Pream Chor, and a higher value measured in Huong Tra. This parameter was used to estimate the amount of dry RS subjected to open burning using Equation 7.2.

Most of the surveyed households in Pream Chor district used fuelwood (78 percent). In Bang Pla Ma, however, liquefied petroleum gas (LPG) use dominated (90 percent) and only small proportions of households using charcoal (5 percent) and fuelwood (5 percent). A combination of LPG and other solid fuels appeared to be the dominant energy sources in Huong Tra district (77.5 percent) with a small

Table 7.1. Summary of the survey results

Parameter	Prey Veng, Pream Chor district, Cambodia	Suphanburi, Bang Pla Ma district, Thailand	Thua Thien-Hue, Huong Tra district, Vietnam
No. of households surveyed[a]	252	290	200
Crop cycle/ year	One: 51%, two: 46%, and three: 3%	Two: 98% and three: 2%	Two: 100%
Harvesting method	Manual: 9% Mechanical: 91%	Manual:2% Mechanical: 98%	Manual: 10% Mechanical: 53% Both manual and mechanical: 37%
Rice straw utilization	Animal feed: 51%, Onsite decomposition: 23%, Field burning: 16%, and Others: 10%	Field burning: 95%, and Others: 5%	Field burning: 59%, Cooking fuel: 19%, Mushrooms: 2.5% Others: 19.5%
Open burning type	Spread burning: 85% Pile burning: 15%	Spread burning: 100%	Spread burning: 99% Pile burning: 1%
Current fuel used for cooking	Fuelwood: 78%, LPG: 12%, biogas: 0.3%, electricity: 6.6%, and corn cobs: 3.1%	LPG: 90%, Charcoal: 5%, and Fuelwood: 5%	LPG only: 16.5% Fuelwood only: 3.5% Others (RS, rice husk) only: 2.5% LPG with other fuels (i.e. coal, fuelwood, etc): 77.5%
Moisture content of rice straw	Fresh after harvest: 23.5 ± 2.1% A week after harvesting: 8.4 ± 0.6%	4 days after harvest: 8.6 ± 0.3%	Fresh after harvest: 55 ± 8.5%
Residue to product ratio (S_k, for cut and collected RS)	0.68 ± 0.07	0.72 ± 0.42	0.74 ± 0.10
Grain yield (tonne/ha/ cycle)[a]	3.5 - 4.3	3.6 - 3.9	4.8
Biomass of dry cut/collectable RS, kg/m^2	0.67 ± 0.15	0.60 ± 0.48	0.49 ± 0.16

Note: [a] Grain yield was obtained from primary measurements, on a dry weight basis.

proportion of households using only LPG (16.5 percent) or fuelwood (3.5 percent). Loose RS and rice husk were also used by some households in the study area (2.5 percent). Based on the types of fuels used in 2015, the potential for substitution of RS-derived solid fuels for cooking appears to be more favourable in Pream Chor and Huong Tra than Bang Pla Ma.

Most of the interviewed farmers expressed their willingness to stop the practice of open burning if the following two conditions were present: first, a stable market to sell the rice straw, and second, technologies that can be made affordable and available to quickly collect rice straw from the field after the harvest to allow quick preparation of the soil for the next crop.

Farmers also showed interest in adopting RS-derived solid fuels and suitable cookstoves, and stated that they would adopt RS conversion technologies (into cooking fuel) if available. However, all the farmers were concerned with the costs associated with this alternative source of energy. The conversion of RS from waste to an economic product such as cooking fuel could be a potential solution to reduce open burning. However, more research is needed to develop suitable business models that the farmers or community members can adopt more easily.

RS and RS-derived fuel characteristics

The characteristics of the unprocessed/loose RS and RS-derived fuels produced are presented in table 7.2 based on the research conducted. The bulk density of loose RS was 30 kg/m^3. Manually prepared roped RS (handmade) increased the bulk density to 57 kg/m^3 while machine-roped RS had a bulk density of 85 kg/m^3 (table 7.2). Cold densification produced briquettes with a density of around 13–21 times that of the loose RS. The highest densification factor of 20–25 times was achieved by the pelletizing process (table 7.2).

It can be seen that the properties of loose RS and manually roped RS based on the approximate analysis were quite similar, showing that the process would not affect RS properties. The moisture content of the RS-derived fuels was in the range of 8–10 percent, except for the RS pellets, which had the lowest moisture content (4.6 percent) due to the heat generated during the pelletizing process. The volatile content of the RS-derived fuels ranged between 63–71 percent, while the ash content ranged between 10–15 percent. The fixed carbon content of all types of

Table 7.2. RS-derived fuels: Bulk density and properties, approximate analysis

Type of fuel	Bulk density (kg/m^3)	Moisture content (%)	Volatile content (%)	Fixed carbon (%)	Ash content (%)
Loose RS[a]	29.9 ± 0.9	9.4 ± 1.1	65.0 ± 0.8	10.6 ± 0.5	15.0 ± 0.7
Manual-roped RS[a]	56.6 ± 3.9	9.1 ± 0.5	64.9 ± 0.9	11.0 ± 0.8	15.0 ± 0.5
Machine-roped RS[b]	85.0 ± 0.7	8.0 ± 0.01	68.0 ± 0.1	14.0 ± 0.2	10.0 ± 0.1
RS briquettes[c]	383-620	10.3 ± 0.1	64.1 ± 0.2	11.6 ± 0.4	13.4 ± 0.2
RS pellets[d]	605-736	4.6 ± 0.8	71.0 ± 2.0	11.8 ± 0.9	12.0 ± 1.2

Sources: Values from the project results by AIT team: [a] Mai (2015), [b] Donnapa (2016), [c] Rahaman (2015), [d] Cuong (2016).

densified fuels were in the range of 11–14 percent. The machine-roped RS had somewhat different properties than other fuels presented in table 7.2, due to the fact that loose rice leaves were more difficult to feed into the machine, hence the roped RS contained less leaves and more RS stems.

Thermal efficiency and emission testing

The measured emission factors (EFs) and thermal efficiencies of different types of RS-derived fuel-CS are presented in table 7.3. Among the four systems tested in this project, the highest thermal efficiency of 25 percent was achieved with machine-roped RS-IBCS followed by manual-roped RS-IBCS of 13.2 percent and by manual-roped RS-BCS of 12 percent. The loose RS-tripod had the lowest efficiency of 7.6 percent. The emission testing results for the four fuel-CS systems conducted by this project showed that the machine-roped RS-IBCS system produced the lowest EFs for all pollutants. Emission factors for benzene, toluene, ethylbenzene and xylenes from the machine-roped RS-IBCS (Donnapa 2016) were: 110–194 mg/kg, 27–76 mg/kg, ND–3.09 mg/kg, and ND–13.9 mg/kg (ND: not detected), respectively.

Table 7.3. Rice straw-derived fuel-CS systems: Thermal efficiencies and emission factors

RS-Cookstove (CS) system	Thermal efficiency (%)	EFs (g/kg)			
		CO	$PM_{2.5}$	CO_2	CH_4
Loose RS - tripod[a]	7.6	44.0	5.8	1,093	3.3
Manual-roped RS-BCS[a]	12.0	46.0	5.7	1,117	3.0
Manual-roped RS-IBCS[b]	13.2	37.0	3.9	1,285	3.6
Machine-roped RS-IBCS[b]	25.0	34.0	2.1	1,015	2.9
RS-GCS[c]	33.0	17.0	0.6	2,171	1.0

Sources: Values from the project results by AIT: [a] Mai (2015) and [b] Donnapa (2016); [c] values compiled by Jetter et al. (2012) for various biomass pellets and GCS; BCS: biomass cookstove, IBCS: improved BCS.

For the RS pellet-GCS, secondary data were compiled from literature for biomass pellets burned in a GCS (Jetter et al. 2012) which showed an average thermal efficiency of 33 percent. The lower EFs of pollutants but higher emission factors of CO_2 for this system compared to other systems (presented in table 7.3) suggest better fuel combustion conditions and hence lower emissions of the products of incomplete combustion, e.g. CO, CH_4 and PM. All the data generated were used to calculate the emissions changes for the co-benefit analysis under two scenarios.

Fuel consumption scenarios

The aim of this project was to alleviate emissions due to RS open field burning, hence the fuel-CS systems that offer higher efficiencies and lower pollution emissions were selected for the scenario analysis. Accordingly, the machine-roped RS-IBCS was proposed for Scenario 1 and RS pellet-GCS was proposed for Scenario 2. The survey results (table 7.1) were used to estimate the amount of RS subjected to open burning in Thailand and Vietnam, as compared to Cambodia (table 7.4). This study assumed that there was no open burning and all collectible RS in each country would be used as fuel/derived fuel for cooking to substitute for other solid fuels. The first priority for replacement was fuelwood, for which a reduction in consumption can also contribute to reduced deforestation. If there is RS remaining, then it would replace coal (fossil fuel), and then charcoal use, in each of these countries.

The thermal efficiencies of the existing fuelwood and charcoal used in various traditional CS in Thailand and Vietnam were obtained from Bhattacharya et al. (2002) while for coal-fueled CS in Vietnam, the value was taken from a study (1996) by the United Nations Development Programme (UNDP) and Energy Sector Management Assistance Program (ESMAP). For the roped RS-IBCS, thermal efficiencies were taken from measurements by Mai (2015) and Donnapa (2016) while for the pellet-GCS system, the efficiency was obtained from Jetter et al. (2012). Consumption of different types of fuel for cooking in each of the three countries and their potential replacement by RS-derived fuel under the two scenarios are detailed below.

Figure 7.4. Proposed fuel-CS systems for 2 scenarios

a) Scenario 1: Machine-roped RS + IBCS (Efficiency: 25%)

b) Scenario 2: RS pellets + GCS (Efficiency: 33%)

Scenario 1 (RS open burning would be eliminated and the amount of collectible RS in 2015 would be converted into roped RS produced by a rope-making machine). The machine-roped RS would be used as cooking fuel in IBCS (fig. 7.4a). Under Scenario 1, in Thailand, the useful energy of machine-roped RS (burned in the IBCS with thermal efficiency of 25 percent) would be sufficient to replace 100 percent of fuelwood used in the traditional CS (13.3 percent efficiency, Bhattacharya et al. 2002) and 100 percent of charcoal in a conventional charcoal cookstove (17.5 percent efficiency, Bhattacharya et al. 2002). The remaining RS energy of 20 percent could be made available for other uses. Using the same calculation

Table 7.4. Fuel consumption in cooking and RS open burning: Modeled scenarios, 2015

Scenario	Fuel consumption, Gg/yr					
	RS open burning[a]	RS-derived fuel[b]	Wood[c,e]	Coal[c]	Charcoal[c]	Remaining RS,%
Base case 2015						
Thailand	13,355	0	8,526[e]	0	4,386[e]	
Vietnam	26,276	0	20,447	2,404	601	
Cambodia	830	0	3,745	0	883	
Scenario 1: Roped RS + IBCS						
Thailand	0	13,355	0 (100%)[d]		0 (100%)[d]	20
Vietnam	0	26,276	0 (100%)[d]	0 (100%)[d]	0 (100%)[d]	46
Cambodia	0	830	2,219	0	883	
Scenario 2: RS pellets + GCS						
Thailand	0	13,355	0 (100%)[d]	0	0 (100%)[d]	40
Vietnam	0	26,276	0 (100%)[d]	0 (100%)[d]	0 (100%)[d]	59
Cambodia	0	830	1,731	0	883	
Changes in fuel consumption under scenario 1						
Thailand	13,355	13,355	8,526	0	4,386	
Vietnam	26,276	26,276	20,447	2,404	601	
Cambodia	830	830	1,526	0	0	
Changes in fuel consumption under scenario 2						
Thailand	13,355	13,355	8,526	0	4,386	
Vietnam	26,276	26,276	20,447	2,404	601	
Cambodia	830	830	2,014	0	0	

Notes: [a] Amount of RS subjected to open burning was estimated using Equation 2. [b] Assuming that 100% of RS subjected to open burning was converted to RS-derived fuels, hence no amount left for open burning in the scenario emissions. [c] Data retrieved from: https://knoema.com/UNSDESD2016/un-statistics-division-energy-statistics-database-2016. [d] The % in brackets indicates the portion of the 2015 fuel consumption replaced by RS-derived fuel. [e] Values for Thailand are from Thailand Department of Alternative Energy Development and Efficiency, http://www.dede.go.th/ewt_news.php?nid=42079.

method, 100 percent of fuelwood, coal (tradional CS with a thermal efficiency 15 percent) and charcoal, respectively, used in Vietnam could be replaced by the amount of roped RS while the remaining 46 percent of RS energy can be used for other purposes. In Cambodia, the available RS could only replace 41 percent of fuelwood.

Scenario 2 (RS open burning would be eliminated and the amount of collectible RS in 2015 would be converted into pellets to be used as cooking fuel with GCS). The pellet-GCS system is presented in figure 7.4b. Under Scenario 2, in Thailand, RS pellets burned in a GCS (33 percent efficiency) would replace 100 percent of fuelwood and charcoal, respectively. Higher thermal efficiciency of the pellets-GCS system would consume less fuel, hence more RS can remain for other uses (40 percent). In Vietnam, the available energy of produced RS pellets could replace 100 percent of all fuel types used in residential cooking with even more RS (59 percent) remaining for other uses. In Cambodia, 54 percent of the fuelwood can be replaced by the produced RS pellets. It can be seen that, as compared to emission Scenario 1, the RS pellets-GCS proposed in Scenario 2 has a higher efficiency, hence more solid fuels can be substituted in Cambodia, while in Thailand and Vietnam, the amount of RS left over for other uses would be higher.

Co-benefits of using RS-derived fuels for cooking

The changes in the emissions were quantified according to the changes in the fuel consumption under the two scenarios as compared to the base case of 2015. Table 7.5 presents the emission reduction by the implementation of scenarios 1 and 2, respectively, with simultaneous elimination of the practice of open burning in the three countries. In Vietnam, significant emission changes occurred because of a larger amount of RS available for producing RS-derived solid fuels to substitute the solid fuels used for cooking in the base case. Under both scenarios, the total reductions of toxic pollutants and GHGs, respectively, were 2.7 Tg and 39 Tg for Vietnam, while the corresponding values for Thailand were 1.5 Tg and 23 Tg. Less emission changes were obtained for Cambodia, as expected, because the amount of RS-derived solid fuels produced (by elimination of the RS that was subjected to open burning) were only sufficient for a partial replacement of fuelwood consumption in residential cooking. The total reductions under Scenario 1 were 0.16 Tg of toxic air pollutants and 2.3 Tg of GHGs, and higher reductions were seen for Scenario 2, i.e. 0.22 Tg toxic pollutants and 3.1 Tg GHGs for Cambodia.

Table 7.5. Emission changes: RS-derived fuels for cooking under two scenarios, no open burning (Gg/yr)

Species	Thailand		Vietnam		Cambodia		Total	
	SC-1	SC-2	SC-1	SC-2	SC-1	SC-2	SC-1	SC-2
CO	973	973	1,875	1,875	118	156	2,967	3,005
NOx	6	6	7	7	0.3	0.4	13	13
SO_2	12	12	7	7	0.01	0.02	19	19
NMVOC	99	99	199	199	14	18	312	316
PM_{10}	11	11	27	27	2	3	40	41
PM_{2-5}	96	96	134	134	8	10	238	240
NH_3	90	90	118	118	6	9	214	217
BC	11	11	27	27	2	3	40	41
OC	21	21	25	25	1	2	48	48
CH4	229	229	257	257	12	16	498	501
Total toxic pollutant mass[a]	**1,547**	**1,547**	**2,676**	**2,676**	**164**	**216**	**4,387**	**4,439**
CO_2	23,215	23,215	38,593	38,593	2,365	3,122	64,174	64,930
N_2O	1	0.51	1.33	1.33	0.09	0.12	1.9	2.0
Total GHG mass	**23,216**	**23,216**	**38,594**	**38,594**	**2,365**	**3,122**	**64,176**	**64,932**
GWP-20yr[b]	54,390	54,390	105,131	105,131	6,963	9,191	166,484	168,712

Notes: SC-1: scenario 1 (Machine-roped RS-IBCS); SC-2: scenario 2 (RS pellets-GCS); [a] OC and EC are included in PM mass; [b] GWPs of SLCPs and GHGs are included in this total GWP value

The GWP of the emissions (in CO_2 eq) for the 20-yr horizon were also calculated to evaluate the potential benefits introduced by the scenarios for climate forcing mitigation. The reductions in the GWP 20-yr emission in CO_2 eq were 54 Tg, equally for both scenarios for Thailand, while the value for Vietnam would be almost double, 105 Tg. Smaller reductions could be realized for Cambodia, i.e. 7.0 and 9.0 Tg of CO_2 eq under scenarios 1 and 2, respectively. Collectively for all three countries, under Scenario 1, a reduction of 166 Tg of CO_2 eq would be achieved, while under Scenario 2, a slightly higher reduction of 169 Tg CO_2 eq would be achieved.

Discussion

The surveys conducted by the project team revealed the status of RS management in Cambodia, Vietnam and Thailand. Multiple rice crop cycles are evident in Vietnam and Thailand, two to three crop cycles per year, as compared to the prevalence of a single crop cycle in Cambodia. In the survey areas of Cambodia, only 16 percent of interviewed households practiced open burning. This proportion increased to 59 percent in Vietnam while in Thailand most of the farmers (95 percent) practiced open burning. Several factors contributed to the lower proportion of open burning in Cambodia, e.g. the use of RS for animal feeding (51 percent) and RS in-field decomposition (23 percent). Most farmers in the target area in Cambodia had livestock and those who did not, could sell the RS to farmers who raised livestock. In particular, in-field decomposition was possible in this area because the single cropping cycle per year would allow enough time for the RS to decompose before the next crop is sown. The more common off-site uses of RS for cooking and mushroom growing in Vietnam also reduced the percentage of households practicing open burning; in the survey area of Thailand, no substantial off-site uses were reported.

Mechanical harvesting is more common in Cambodia and Thailand than in Vietnam. The use of mechanical harvesters spreads RS across the fields, making it more difficult to collect, and hence open burning is more commonly practiced in Cambodia and Thailand. With manual harvesting methods, however, the RS is collected along with the harvested grains. The rice straw is then separated and piled in a corner of the paddy field and burned. The survey results confirmed that burning of spread RS (spread burning) is commonly done in all the survey areas of these three countries.

Spread burning generated less emissions per kg of RS burned than pile burning, which tends to smoulder over an extended period and produce more smoke (Kim Oanh et al. 2011).

As they become wealthier, farmers are seen to have a tendency to practice open burning (Cao et al. 2008). This is particularly so because gas stoves become affordable for these farmers and there is minimal use of RS for cooking purposes. Also, in order to maximize the number of crop cycles per year, the farmers practice open burning as it is the fastest way to get rid of the "unwanted" biomass to prepare the soil for the next crop. Depending on demand and climate conditions, farmers in the three countries can have more than one rice crop cycle per year (table 7.1).

Farmers are aware of the harmful effects of the smoke from open burning, however, they feel that open burning only takes place over a short period each year. They ignore the fact that "short open burning" occurs in a number of places in the same area during the same days which results in high air pollution levels. When discussing the potential health effects from exposure, most farmers agreed to stop open burning if they had viable alternatives that allowed for quick removal of RS and its use for other purposes such as cooking fuel. In particular, farmers who use fuelwood for cooking were interested in using RS-derived solid fuels if they cost less. But farmers were less concerned about any potentially adverse impacts of open burning on the soil quality and crop yields.

Some farmers were also concerned about the need to return nutrients back to the soil by allowing the straw to decompose in the field after harvest. In this case, the off-site use of RS seems not to provide benefits. However, only the cut portion of the rice straw would be collectible from the field for off-site use while the standing RS (20–30 percent of the total above-ground biomass estimated from our survey results) would still remain in the field for decomposition. In addition, on-site composting of all produced RS (both cut and standing parts) can be practiced only when there is a sufficient gap between cropping cycles. The ploughing and on-site composting (with enzymes added) method has been promoted in Thailand, but has not gained popularity among farmers due to several factors, including the need for more labor (when compared to open burning), and powerful ploughing machines. Moreover, on-site composting also requires a longer fallow period to prepare the land for the next crop (Kanokkanjana and Bridhikitti 2007).

The current study has found that pelletizing and briquetting produced highly densified fuels with a densification factor of 13–25 times compared to manual or machine roping that increased density by only 2–3 times above that of loose RS. The densification methods did not significantly change the properties of RS-derived fuels. Handling processed RS products is easier in terms of storage and transport compared to the loose RS. But the key remaining challenge is the collection of rice straw from the paddy fields after the harvest. Innovative research is needed to develop technologies that can collect and convert RS into processed fuels on-site, for example, by following the mechanical harvesting machines.

Suitable cookstoves should be selected to specifically burn the RS-derived solid fuels. The improved biomass cookstove (IBCS) prepared in this project for burning roped RS can increase thermal efficiency while producing lower emissions than traditional BCS: the machine-roped RS-IBCS system can achieve a 25 percent efficiency with relatively lower emissions. The selected GCS can efficiently burn the RS pellets with a high thermal efficiency of 33 percent and lower emissions of toxic pollutants (products of incomplete combustion). The portable gasified cookstove (GCS) is available in the market and is convenient to use. It is, however, more expensive than the IBCS, hence may require a subsidy to make it affordable for farmers in the Mekong Region.

Emission changes due to the elimination of open burning and substitution of solid fuels with RS-derived solid fuels in residential cooking under both scenarios were significant. Large volumes of toxic air pollutants (including SLCPs) and GHGs emissions could be avoided. Turning RS into cooking fuel may incentivise farmers to stop open burning given the economic value of RS-derived fuels. Reducing dependency on fuelwood for cooking would also help to reduce deforestation. In Vietnam, there is significant potential for utilizing RS biomass resources and this could be managed in order to avoid open burning and associated emissions. In Cambodia, the amount of available RS subjected to open field burning is less than in Thailand or Vietnam (given that there is generally only a single crop cycle per year, and that RS has other uses, as shown in table 7.1). Significant emissions reductions can still be achieved in Cambodia by avoiding open burning. In addition, as compared to the burning of RS-derived fuels in selected CS, RS field open burning emits larger amounts of toxic pollutants in principle because of uncontrolled combustion conditions (Kim Oanh et al. 2011; Kim Oanh et al. 2015).

The analysis of the emissions changes indicates that the measures proposed under Scenario 1 and Scenario 2 to eliminate open burning would significantly contribute to reductions in toxic air pollutants (also SLCPs) and GHGs hence bring about significant co-benefits in air quality improvement (subsequently to human health, crops and ecosystems) and climate forcing mitigation (GWP 20-yr in CO_2 eq). These measures would also have other benefits, including reducing the deforestation rate by lowering fuelwood consumption for cooking as well reducing expenditure on other solid fuels. Further studies are required to analyze all the costs and benefits of the RS-derived solid fuels, as well as to develop a business model which involves the production of RS pellets and the production and selection of suitable cookstoves for the region.

Conclusions

The study's findings included the following:

1. Open field burning of RS has been practiced for many years in the agrarian countries of GMS. Surveys conducted in this study confirmed that farmers in the selected agricultural areas in the three countries practiced open burning and the proportion of RS subjected to open burning depended on several factors, i.e. number of crop cycles per year, prevalent off-site uses of RS, and harvesting method (mechanical or manual).
2. In the places where farmers use fuelwood for cooking, they were willing to use RS-derived solid fuels instead, while in areas where the use of LPG dominated, adoption would be contingent on cost.
3. Pelletizing and briquetting methods were able to produce highly densified RS-derived solid fuels with a densification factor of 13–25 times that of loose RS, while roped RS had a densification factor of 2–3.
4. Machine-roped RS-IBCS can achieve 25 percent efficiency with lower emission factors of pollutants than the manual-roped or loose RS burned in traditional BCS. The RS pellet-GCS has a high efficiency of 33 percent and produced lower emissions of toxic air pollutants, but greater amount of CO_2 due to more complete combustion.
5. Under both scenarios, the roped RS burned in IBCS would be more than sufficient to substitute 100 percent of the solid fuel consumed

in the residential sector in Thailand and Vietnam. The remaining RS, of which there is more under Scenario 2 due to the higher thermal efficiency of the pellets-GCS, can be used for other purposes. In Cambodia, however, only a part of the fuelwood currently used for cooking could be replaced by available RS.

6. The use of RS-derived fuels and the selected CSs can help to eliminate open burning and produce significant co-benefits in reducing emissions of toxic air pollutants, GHGs, and GWP 20-yr.
7. Training and workshops on the adverse effects of open burning on human health, soil quality and crop yield, along with the climate effects, should be targeted at farmers because they are the most important stakeholders in adopting non-open burning alternatives.
8. Further research should aim to develop convenient ways to collect and convert RS into cooking fuel, preferably on-site in paddy fields, and create a business model to realize its potential benefits. Other non-open burning alternatives such as on-site composting, mushroom growing, etc., should also considered.
9. The governmental boundary partners have been very supportive in providing information related to their policies on open burning while nongovernmental (NGO) partners were keen on sharing their experiences of CS testing and the promotion of clean CS. The involvement of boundary partners in the project provided an efficient way to convey the project's key findings.
10. The science-based information provided in this project should be disseminated to policymakers to intervene and eliminate the practice of post-rice harvest open burning in GMS countries and beyond.

Acknowledgments

The project team highly appreciates the funding support from the Swedish Government through Swedish International Development Cooperation Agency (Sida). SUMERNET is acknowledged for its support and effective management of the research project network. All involved students and researchers in the project are thanked for their significant contribution to the research. Boundary partners involved in the project are also thanked for providing support and assistance during the study.

Note

[1] See further National Oceanic and Atmospheric Administration, US Department of Commerce, Climate forcing, *Climate.gov*, https://www.climate.gov/maps-data/primer/climate-forcing (last accessed May 14, 2019).

References

Bhattacharya, S. and A.P. Salam. 2002. Emission factors of wood and charcoal-fired cookstoves. *Biomass and bioenergy* 23, 6: 453–69.

Cao, G.L., X.Y. Zhang, Y.Q. Wang and F.C. Zheng. 2008. Estimation of emissions from field burning of crop straw in China. *Chinese Science Bulletin* 53, 5: 784–90.

Cuong, N.D. 2016. A study on production and combustion behavior of rice straw pellets. Master's Thesis, AIT, Pathumthani.

Donnapa, J. 2016. Characterization of emission from cookstoves using rice straw derived fuel for quantification of air quality and climate co-benefits. Master's thesis, AIT, Pathumthani.

Fuglestvedt, J.S., K.P. Shine, K.P. Cook et al. 2009. Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment* 44: 4648–77.

General Statistics Office (GSO). 2016. National statistical data 2015 of Vietnam. Hanoi: GSO. http://www.gso.gov.vn/Default_en.aspx?tabid=766.

Jetter, J., Y. Zhao, K.R. Smith and B. Khan. 2012. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ. Sci. Technol*. 46, 19: 10827–34.

Kanokkanjana, K. and A. Bridhikitti. 2007. Sustainable rice straw management for urban air pollution reduction in Bangbuathong, Nonthaburi province, Thailand. Final report of the CIDA–AIT Partnership, Alumni demonstration project. Pathumthani: Asian Institute of Technology.

Kim Oanh, N.T. 2013. Integrated approach to rice straw management for reduction of field-burning activity. In *Integrated air quality management: Asian case studies*, ed. N.T. Kim Oanh. Boca Raton, FL: CRC.

Kim Oanh, N.T., D.O. Albina, L. Ping and X.K. Wang. 2005. Emission of particulate matter and polycyclic aromatic hydrocarbons from select cookstove-fuel systems in Asia. *Biomass and Bioenergy* 28, 6: 579–90.

Kim Oanh, N.T., T.L. Bich, D. Tipayarom, B.R. Manandhar, P. Prapat and C. Simpson. 2011. Characterization of particulate emission from open burning of rice straw. *Atmospheric Environment* 45, 2: 493–502.

Kim Oanh, N.T., D.A. Permadi, P. Hopke, K. Smith, N.P. Dong and N.A. Dang. 2018. Annual emissions of air toxics emitted from crop residue open burning in Southeast Asia over the period of 2010–2015. *Atmospheric Environment* 187: 163–73.

Kim Oanh, N.T., L.B. Reutergårdh and N.T. Dung. 1999. Emission of polycyclic aromatic hydrocarbons and particulate matter from domestic combustion of selected fuels, *Environmental Science and Technology* 33, 16: 2703–09.

Kim Oanh, N.T., A. Tipayarom, T.L. Bich, D. Tipayarom, C.D. Simpson, D. Hardie and L.-J.S. Liu. 2015. Characterization of gaseous and semi-volatile organic compounds emitted from field burning of rice straw. *Atmospheric Environment* 119: 182–91.

Kipruto, W. 2011. A review of the cook stove test methods and their applicability in small scale CDM cook stove projects. https://energypedia.info/images/a/a7/Review_of_cook_stove_test_methods_29_Ma r_11.pdf.

Mai, N.H. 2015. Assessment of the impact of using rice straw derived cooking fuel on the emission of air pollution and climate forcers. Master's thesis, AIT, Pathumthani.

National Institute of Statistics (NIS). 2016. *Statistical yearbook of Cambodia 2016*. Phnom Penh: NIS. https://www.nis.gov.kh/.

National Institute of Occupational Safety and Health (NIOSH). 2003. NIOSH Manual of Analytical Method (NMAM): Method 1501—Hydrocarbon, Aromatic.

Office of Agricultural Extension (OAE). 2016. Agricultural statistics of Thailand 2015. Bangkok: OAE.

Rahaman, S.A. 2015. Development and evaluation of a densification system for rice straw, Master's thesis, AIT, Pathumthani.

Trade Map. 2016. Trade statistics for international business development: exports of rice commodity. http://www.trademap.org/.

United Nations Development Programme (UNDP) and Energy Sector Management Assistance Program (ESMAP). 1996. Vietnam household energy technical assistance: Improved coal briquetting and commercialized dissemination of higher efficiency biomass and coal stoves. Activity Completing Report No. 178/95. Washington, DC: ESMAP, World Bank; New York: UNDP.

United Nations Environment Programme (UNE) and World Meteorological Organization (WMO). 2011. *Integrated assessment of black carbon and tropospheric ozone*. Nairobi: UNEP, WMO.

United Nations Statistics Division Energy Statistics Database UNSDESD. 2016. *United Nation Statistics Division Energy Statistics Database*. https://knoema.com/UNSDESD2016/un-statistics-division-energy-statistics-database-2016.

Yin, C.Y. 2011. Prediction of higher heating values of biomass from proximate and ultimate analyses. *Fuel* 90, 3: 1128–32.