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Rice straw open burning: emissions, effects and multiple benefits of non-burning alternatives

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Abstract:

Rice is one of the most important staple foods not just to people in Asia, but around the world. To meet domestic and export demands, farmers in Southeast Asia (SEA) grow 2-3 crop cycles per year, which leaves only a short period for land preparation. Field open burning of rice straw has been widely practiced to quickly clear the surface biomass for the next crop planting. However, this uncontrolled open combustion of rice straw releases large amounts of toxic air pollutants including key conventional pollutants along with carcinogenic compounds like dioxins, polycyclic aromatic hydrocarbons, and benzene, as well as major climate forcing agents. Emissions from rice straw open burning (RSOB) have been shown to significantly elevate ambient levels of $PM_{2.5}$ and surface ozone in adjacent urban areas. During the dry season, when stagnant meteorological conditions are prevalent, intensive open burning activities further intensify haze episodes. Rice straw, however, is a valuable resource that should be recovered and not disposed of by open burning. Indeed, several non-open burning alternatives are available that would bring in multiple benefits to air quality, climate, health, and economy. For example, the production of rice straw fuel pellets for cooking in clean gasifier cookstoves is one promising option. For the successful elimination of RSOB in SEA, technology development along with formulation and implementation of appropriate policies should be in place to mobilise active participation from all stakeholders.

Keywords: **co-benefits, cooking, rice straw open burning, rice straw pellet, toxic pollutants.**

Classification number: **5.3**

Introduction

Rice is the most popular crop in Asia with an annual production comprising of 90% of the world's total production. Rice is also the most important staple food in Asia as it provides 50-80% of the total calories consumed. Several countries in SEA are among the world's top ten rice exporters and, presently, the region collectively produces over 200 million metric tons (tonnes) of rice annually. To meet domestic and export demands, SEA farmers grow 2-3 crop cycles per year. Hence, there is only a short time period left to prepare the land for planting the next crop. Post-harvest RSOB has long been widely utilized by farmers in the region as it can quickly clear the surface biomass to facilitate land preparation. Survey results have shown that farmers in SEA prefer RSOB for land preparation because it requires less labor and also helps control undesirable weeds and pests along with providing ash as nutrients back into the soil [1]. Meanwhile, as farmers become wealthier and farming work becomes more mechanized, the demand for crop residue as cooking fuel or animal feedstock is declining. As a result, RSOB activity is now widespread and during the harvesting period the effects of smoke are felt on both local and regional scales, especially in the dry season.

By nature, RSOB is an uncontrolled combustion of vegetation biomass at low temperatures, hence, huge amounts of products of incomplete combustion (PIC) are released. These PIC are toxic air pollutants and include, for example, particulate matter (PM) that are mainly composed of fine inhalable particles or $PM_{2.5}$ (particles with aerodynamic diameters $\leq$2.5 µm) together with black carbon (BC) and organic carbon (OC) components (among others), gaseous pollutants of carbon monoxide (CO), and a range of volatile organic compounds (VOCs). A wide range of toxic and carcinogenic semi-volatile organic compounds (SVOCs that present in both PM and gas phases) such as polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/PCDFs, hereafter referred to as dioxins), polycyclic aromatic hydrocarbons (PAHs), and organochlorinated pesticides are also found in RSOB smoke [2-13]. Many of these SVOCs are persistent organic pollutants that present over an extended time in the environment and have the ability to bioaccumulate in tissues, which makes them even of more of a health concern [14, 15].

It is worth mentioning that important greenhouse gases (GHGs) like methane (CH_4) and nitrous oxide (N_2O) are also

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emitted from RSOB. While a significant amount of CO_2 is also released from the activity, the cycle is considered climate neutral because it is absorbed by the growth of the next crop. Besides, several toxic pollutants emitted from RSOB, so called "short-lived climate forcers" or "short-lived climate pollutants" (SLCPs), also have climate forcing effects. For example, BC is a strong climate warming agent while OC is a cooling agent [16]. In addition, pollutants released from RSOB can participate in chemical reactions in the atmosphere to form other pollutants that have both air quality and climate effects. As an example, VOCs and NOx in the presence of sunlight participate in photochemical reactions to form the tropospheric ozone, a secondary pollutant that is not only a strong GHG but also a toxic air pollutant to human health and plants and hence can reduce crop yield [17]. Nitrogen oxides (NO_x=NO+NO_2) and sulfur oxides (SO_x) released from the activity are important precursors of secondary inorganic particles, while VOCs are precursors of secondary organic particles. These secondary particles are formed in the atmosphere and they belong to the $PM_{2.5}$ size range.

There are two common burning methods for rice straw currently observed in SEA, namely pile burning and spread burning, which have different emission amounts per kg of rice straw burned [18, 19]. Pile burning is typically practiced after manual harvesting when RS is piled up at a paddy corner (or sometimes inside villages) and burned largely under smoldering conditions with a visible dense smoke plume, containing huge amounts of toxic pollutants (Fig. 1A). Spread burning (Fig. 1B) is normally applied in places where mechanical harvesting equipment is used. The combine harvesters cut the upper parts of rice plants and spread them in windrows while leaving the lower parts (or standing parts) virtually untouched. Spread burning fires normally consume most of the spreading RS but the standing parts, in many cases, are only partially burned especially when RS moisture is high. In Vietnam, pile burning is commonly practiced in the Red river delta region. Emissions from RSOB also strongly depend on the combustion conditions, which, in turn, depend on the moisture content of the RS and paddy soil (e.g., the higher moisture the more emissions), winds, and air humidity, among others.

Fig. 1. Rice straw field burning: (A) pile burning under smoldering conditions around Hanoi, Vietnam, May 2020 (Source: Dan Tri newspaper) **and (B) spread burning in Pathumthani, Thailand** (photo by author).

Results of emission factors from experimental studies

The results of emission factor measurements from the spread RSOB experiments conducted in Thailand [6, 18] are presented in Table 1 for particulate, gaseous, and SVOC pollutants. Other references quoted in Table 1 provide emission factors for RSOB but without indicating the burning methods, namely the spread or pile burning. The emission factors for burning of agricultural crop residues in general, compiled from different laboratory studies by Andreae and Merlet (2001) [12], are also presented in Table 1.

Table 1. Emission factors of pollutants from RSOB (average ± SD), mass of pollutants (g or mg as specified) per kg of dry rice straw.

Pollutants		Rice straw		General agro residue (f)
		Spread RSOB [6, 18]	*Other data sources*	
Particulates				
$PM_{2.5}$, g/kg		8.3±2.2	3.8 (a)	3.9
EC, g/kg		0.53		0.69±0.13
OC, g/kg		2.78		3.3
Water soluble ions*, g/kg		1.5		
Levoglucosan, g/kg		0.47		0.27
Total elements**, g/kg		0.23		
Gaseous pollutants				
CO, g/kg		93±10	180±40 (b); 64±5 (c)	92±84
CO_2, g/kg		1177±140	1216±97 (b); 791±13 (c)	1515±177
Benzene, mg/kg		763±266	870±200 (b)	140
Toluene, mg/kg		232±3.4	1080±350 (b)	26
Ethylbenzene, mg/kg		nd		30
Xylenes, mg/kg		nd		10
SO_2, mg/kg		510±320	180±310 (g)	400
NOx mg/kg		490±210 (NO_2) 1120±480 (NOx)	790±50 (c, NO_2); 620±400 (b, NO)	2500±100 (NOx)
Aldehydes, mg/kg		147±8.0 (hood burning)	3170±880 (b, HCHO)	1400 (HCHO)
Semi-volatile organic compounds				
PAHs (16 USEPA), mg/kg	Particulate	34±35	1.02 (a); 18.6 (d); 3.0 (5% moist.) & 17.2 (20% moist.) (e)	
	Gaseous	230±333		
	Total	264±335	17.8 (a)	25
OCPs, mg/kg	Particulate	0.086±0.052		
	Gaseous	0.141±0.194		
	Total	0.227±0.20		

Data sources: a: [13]; b: [20], values for dry fuel, ash free; c: [21]; d: [22]; e: [23] for 5% and 20% moisture content of RS, included 9 PPAHs (Fth, BaA, BbF, BjF, BkF, BaP, IcdP, DahA and BghiP); f: [12]: estimates based on laboratory studies; g: [24].
*: total 9 water soluble ions (sodium, potassium, ammonium, magnesium, calcium, fluorite, chloride, nitrate, and sulfate).
**: total of 33 detected elements (including four more elements, i.e. Ca, Mg, Cl and K, than that presented in N.T. Kim Oanh, et al. (2011) [18]).

There are very few experimental studies reporting emission factors of pile RSOB. N.T. Kim Oanh, et al. (2011) [18] reported the emission factor of $PM_{2.5}$ for pile RSOB, which was about 18.3 g/kg of dry rice straw, i.e., more than two times greater than that of spread burning (8.3 g/kg). Based on the PM source profile reported in N.T. Kim Oanh, et al. (2011) [18], the estimated emission factors of elemental carbon (EC, an operational definition of BC) is about 1.1 g/kg while that of OC is about 6.1 g/kg.

Emissions from RSOB and effects on local air quality

Emissions from RSOB in SEA and Vietnam: during 2010-2015, about 120 million tonnes of rice straw in SEA was disposed of annually by open burning with about 24 million tonnes from Vietnam alone [5]. Huge emissions are released from RSOB activity in SEA; roughly 1.8 million tonnes of $PM_{2.5}$, 12 million tonnes of CO, 65 g I-TEQ of dioxins (in the unit of toxicity equivalent, to the most toxic congener 2, 3, 7, 8-TCDD, based on the international toxicity scale), 25 thousand tonnes of PAHs, and 29 tonnes of OCPs, together with other toxic air pollutants such as benzene, toluene, and aldehydes (Table 2). By country, in the descending order, Indonesia, Vietnam, Myanmar, Thailand, and Philippines had the largest shares in RSOB emissions and collectively contributed more than 95% of the total SEA emissions from this activity. The emissions from RSOB in Vietnam typically contribute about 16-20% of the SEA's total and varies with pollutants.

N.T. Kim Oanh, et al. (2018) [5] considered crop residue open burning (CROB) of the eight main crop types in SEA and reported that RSOB was the major contributor to CROB emissions by sharing 70-95% of the total amounts of different pollutants released. In 2010, CROB emissions in SEA contributed less than forest fires to the total emissions from these two major biomass open burning source categories (SUM=CROB+forest fires), i.e., CROB contributed about 10-43% to the SUM, varies with species. However, the shares of CROB emissions in the SUM differ significantly between countries. In Vietnam, for example, emissions from CROB were generally higher than the forest fires, i.e., sharing 49-92% of the SUM. In the Philippines, contributions from those two sources were in similar ranges, with the shares ranging between 33-69% that varies with species. However, forest fires had much higher contributions to the SUM in the countries of Indonesia, Thailand, and Myanmar [5]. It is worth emphasising that the effects of CROB emissions receive much less attention from society than catastrophic SEA transboundary haze events caused by forest fires.

Table 2. Annual emissions (in specified units) from RSOB in SEA and Vietnam averaged over the period 2010-2015.

Pollutants	Unit (*)	Vietnam	SEA
CO	Gg/yr	2258	12000
NO_x	Gg/yr	55	290
SO_2	Gg/yr	4.4	23
NMVOC	Gg/yr	170	890
NH_3	Gg/yr	100	500
PM_{10}	Gg/yr	330	2000
$PM_{2.5}$	Gg/yr	295	1800
BC	Gg/yr	13.6	70
OC	Gg/yr	228	800
CO_2	Gg/yr	28600	153900
CH_4	Gg/yr	100	520
N_2O	Gg/yr	2.4	13
Aldehydes	Gg/yr	3.6	19
Benzene	Gg/yr	18.5	97
Toluene	Gg/yr	5.6	29
PAHs	Gg/yr	6.4	25
OCPs	t/yr	5.5	29
Dioxins	g I-TEQ/yr	13	65

*Gg: thousand tonnes. Source: adapted from N.T. Kim Oanh, et al. (2018) [5].

Effects of RSOB on ambient air quality: several studies in SEA show evidence of the effects of RSOB emissions on local air quality. In Pathumthani, a large rice growing province of Thailand, RSOB is especially intensive during the dry months from November to April. The levels of carcinogenic PAHs measured in the ambient air of a rural area of Klong Luang (KL) district during the intensive RSOB days were above 400 ng/m^3 that is 60 times higher than the levels measured in the air in a remote site of Khao Yai (KY) national park [4]. The ambient profile of PAHs in KL during RSOB days (Fig. 2) shows a dominance of 4-ring compounds, most remarkably

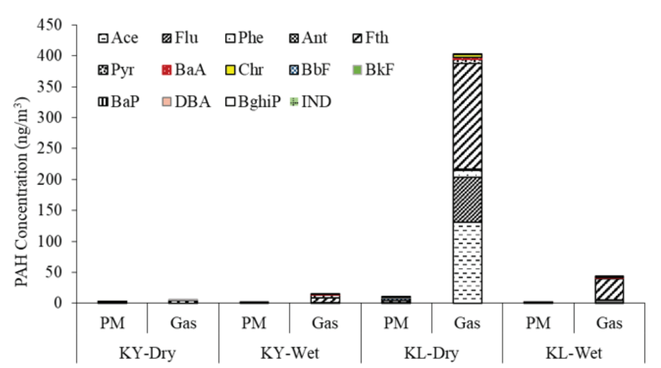

Fig. 2. PAHs levels and individual compound profiles in an intensive RSOB area (KL) and the remote national park (KY) during the dry and wet season (measurement data, extracted from Tipayarom and N.T. Kim Oanh (2020) [4]).

fluoranthene, which indicates a strong influence of rice straw burning emissions on the PAH air quality [3, 25, 26]. The RSOB smoke in KL also contains high levels of OCPs (about 14 ng/m^3), which may be related to the re-emission of compounds accumulated in the paddy soil from the past applications.

Based on the analysis of mass and compositions of $PM_{2.5}$ measured in KL using the receptor modeling approach, ambient $PM_{2.5}$ levels show significant influence from RSOB. During the dry season, RSOB contributed about 14 μg/m^3 to the $PM_{2.5}$ mass concentration (40% of the total measured $PM_{2.5}$ mass), which is well above that estimated in the wet season with 4 μg/m^3 (25% of $PM_{2.5}$ mass) [27]. The air quality dispersion modeling using a 3D chemical transport model (CAMx-MM5) also revealed impacts on the surface ozone air quality by RSOB in the Bangkok metropolitan region [28]. The simulation results for an ozone episode in March showed that RSOB in the modeling domain would cause an increase in the hourly ozone, by an average 4 ppb with a maximum of 10 ppb, in the Rangsit station (located near KL), over the scenario with zero RSOB.

Exposure to RSOB smoke and potential health effects: rice straw field burning emissions have been reported to induce high personal exposure to the toxic air pollutants in Asia, Europe, and the US [29-32]. However, the health effects specifically induced by RSOB have not been intensively studied. Torigoe, et al. (2000) [33] conducted a survey and revealed that emissions from RSOB in a study area in Japan possibly induced or exacerbated asthma attacks in children. The authors recommended the elimination of RSOB activity for the protection of the inhabitants' health, especially of children with asthma. Overall, intensive agricultural waste burning activities can affect air quality, human health, and the climate at continental and global scales [34, 35].

In SEA, large amounts of toxic air pollutants ($PM_{2.5}$, CO, VOCs, PAHs, OCPs, dioxins, etc.) are annually released from RSOB. The high levels of toxic air pollutants measured in areas with intensive RSOB activities suggest a high exposure risk and potential adverse health effects. The fact that agricultural land in Asia is widely distributed in suburban and rural areas, where people live and work, further intensifies the exposure risk. In some areas, such as the Red river delta of Vietnam, multiple small and short-lived RSOB fires can be densely seen during the harvesting months, hence, can seriously deteriorate air quality [36]. The emissions are widely dispersed to cause high air pollution levels not only in the rural areas where RSOB occurs but also in the adjacent urban areas [27, 37]. Furthermore, RSOB activity is more intensively practiced in the dry season when air pollution is already high due to the stagnant meteorological conditions and thus exaggerates haze episodes [4, 37].

Presently, the impacts of CROB including RSOB are often overlooked in many SEA countries and receive less concern from society as compared to catastrophic transboundary haze caused by forest fires. The negative impacts of RSOB, such as the effects of smoke on human health, should be widely disseminated to raise awareness and thereby encourage farmers to use non-open burning alternatives for crop residue management.

Non-burning alternatives for rice straw management

Non-burning alternatives: rice straw is a valuable resource that should be recovered rather than disposed of by open burning. There are non-open burning alternatives including off-site uses of RS as medium for mushroom cultivation, animal feed and bedding, garden mulching, or composting. Further, RS can be converted into biochar, processed fuel such as bioethanol or briquettes/pellets, and building materials [38, 39]. However, the labor and cost for collection and transportation of bulky loose RS remain a challenge. Other constraints exist, for example, the presence of a high silica (Si) content in RS affects the digestion capability of the livestock. The traditional uses of RS in handicraft making (hats, mats, and decoration items) or as construction material could be promoted but need suitable business models to sustain.

A promising alternative of "ploughing for on-site degradation" has been promoted in Thailand. Accordingly, the harvested paddy is ploughed using a powerful machine to incorporate RS into the soil following with the application of water, bio-extracted liquid, and bio-fertilizer to accelerate the degradation. However, local farmers do not generally prefer the method primarily because it still requires a considerable amount of time to make the paddy soil ready for the next crop plantation. In addition, the high cost of such a ploughing machine is also an issue. Therefore, most farmers still prefer to continue RS field burning activities. However, the results of a survey showed that the local farmers are indeed aware of the negative effects of RS field burning on paddy soil quality, e.g., the soil structure becomes hard after RSOB and some organic nutrient substances on the topsoil are burned to ash. The effects of smoke on human health are not yet recognized while those on the safety of on-road transport due to reduced visibility were of concern [40].

Cooking with loose RS in a simple tripod cookstove is traditionally practiced in rural areas of Asia [41, 42]. However, this low efficient cooking system consumes large amounts of fuel and generates huge amounts of emissions that affect both indoor and outdoor air quality. Some densification techniques can be applied to produce RS derived solid fuels that include, for example, roped/bundled straw, briquettes, and pellets, which have higher fuel density and are easier to store and transport than loose RS. Further, clean cookstoves can be used to effectively burn RS-derived fuel while generating less emissions. However, these conversion technologies are not yet fully developed or adapted for RS. Overall, the thermochemical conversion of RS into bioenergy is still not popularly applied due to several technical constraints associated with RS's chemical and physical properties like high ash and silica content, rigorous crystalline structure, and low bulk density [42-44]. Combustion is the most mature technology used to generate energy from RS, but it also encounters several major shortcomings including corrosion/fouling of equipment due to high silica and potassium/alkali contents, ash accumulation and slagging, among others [44, 45].

Production of rice straw pellet fuel for cooking: making RS pellets (pelletization) is one densification method to produce RS-derived solid fuel. This process can significantly increase the bulk density of RS, i.e. up to 600-700 kg/m^3 from, for example, 60-90 kg/m^3 of baled RS [46]. To improve the quality of the produced pellets, RS is usually mixed with woody/bamboo biomass and/or other additives. In particular, woody/bamboo biomass with its high lignin content and low ash content enhances the energy content and improves pellet durability while reducing its inorganic content [47].

The air quality team at the Asian Institute of Technology (AIT) has conducted research on RSOB emissions and assessed the associated impacts on air quality and climate forcing during the last 20 years. The AIRPET (Air pollution research project and network) from 2000-2010, sponsored by Swedish International Development Cooperation Agency (SIDA) and coordinated by AIT in collaboration with 6 Asian national research partners from China, India, Indonesia, Philippines, Thailand, and Vietnam [48], started emission characterization and modeling studies related to RSOB in SEA [49].

Recognizing RS as a valuable resource, the AIT team worked to identify alternatives that recover energy from this agricultural waste allowing farmers to commoditize waste that is prone to burning. In the Partnerships for Enhanced Engagement in Research (PEER) - SEA project "Assessment of impacts of the emission reduction measures of short-lived climate forcers on air quality and climate in SEA" (2012-2016) sponsored by U.S. Agency for International Development (USAID), the team quantified the RSOB emissions in SEA and assessed the impacts on air quality and climate forcing using the modeling tool [50]. A spin-off project under the Sustainable Mekong Research Network (SUMERNET) phase 3, sponsored by SIDA and titled "Turning rice straw into cooking fuel for air quality and climate co-benefit in selected Greater Mekong Subregion countries" (2016-2018), was conducted in cooperation with the Energy program at AIT and research partners in Thailand, Vietnam, and Cambodia to examine several options to turn RS into cooking fuel like RS bundles, briquettes, and pellets.

A laboratory scale pelletizing machine was developed in this project [51] and successfully produced RS pellets that can be burned effectively in a Mimimoto gasifier cookstove (GCS) (https://www.engineeringforchange.org/solutions/product/mimi-moto/). The GSC-pellet cooking system was

Fig. 3. (A) A pelletizing machine in an agricultural machinery company in Hanoi, (B) RS pellets produced, and (C) GCS-pellet cooking system demonstrated in Hanoi [52].

demonstrated at project sites in Cambodia, Thailand, and Vietnam and gained a general acceptance from farmers. A few shortcomings have been documented such as the strongly sintered ash remaining in GSC after pellet burning, which was difficult to remove from the stove and the ash material was found to be too hard for use for soil conditioning.

A supplementary award for PEER-SEA was provided to AIT for translating evidence-to-action in a demonstration project "Technology acceleration to transfer rice straw derived fuel and gasifier cookstove in Vietnam" (2017-2018). The project team successfully produced RS pellets using a full-scale prototype pelletizing machine in cooperation with the local project partners at the Hanoi National University and an agricultural machinery company in Hanoi (Fig. 3). The pellets burned well in the selected Mimimoto GCS without visible smoke. Certain modifications of feeding materials and pelletizing technical conditions make the ash soft enough to be removed easily from the stove and also to apply directly on soil. This cooking system has a high thermal efficiency, hence, consumes less fuel for cooking a meal. The emission measurements showed that the amount of $PM_{2.5}$ emitted from the cookstove when burning 1 kg of RS pellets was only about one-fifth (1/5) of that from RSOB pile burning. The RS pellets can be used for domestic cooking and are even more relevant for commercial cooking to substitute, for example, polluting honeycomb coal briquettes. Thus, this would reduce exposure to both indoor and outdoor air pollution and provide great health benefits.

The production of RS pellets and the selection of the optimal cookstove for burning the fuel create an opportunity to meaningfully recover this valuable agricultural waste and, at the same time, create an income source for farmers through selling RS and/or RS pellets. It provides an alternative to reduce RSOB and brings in benefits of clean air and climate though emission reduction. At the same time, RS pellet production helps cut down the consumption of fossil fuel (to reduce climate impacts) and wood fuel (to save trees), hence, providing multiple benefits.

A complete RS grinding-pelletizing machine should be further developed and demonstrated to bring the technology closer to end-users. Modifications to feeding material mixture compositions and the pelletizing technical conditions may be exploited to produce pellets for other purposes like animal feedstock, organic fertilizers, and soil conditioners. The demand, willingness-to-pay by users, cost-benefit analysis, and potential environmental impacts should be analysed. Business models may be developed that involve participation of the private sector to produce and market RS pellets.

Conclusions

RSOB releases huge amounts of toxic air pollutants that seriously deteriorate local air quality not only in populated rural areas but also in nearby cities. Intensive RSOB in the dry period, when stagnant atmospheric conditions prevail, intensifies the formation of haze episodes. High levels of toxic and carcinogenic compounds in the ambient air during intensive burning periods indicate high exposure risks and potential adverse health effects.

Several non-burning alternatives are available to RSOB but certain constraints exist. The production of RS pellets for cooking fuel is a promising approach to minimize RSOB activities and gain multiple benefits. Further studies should include a detailed cost-benefit analysis of the application and should develop practical guidelines for the production of RS pellets with suitable physical and thermal characteristics of the fuel.

For successful elimination of RSOB in SEA, beside the technology development, formulation and implementation of appropriate policies should be in place to mobilise participation from all stakeholders. A strict "ban" on RSOB alone may not work effectively, but the enforcement should be done along with providing suitable and workable alternatives with subsidies/incentives. Negative impacts of RSOB, specifically the effects of smoke on human health, should be widely disseminated to raise awareness and thereby encourage farmers to opt for non-open burning alternatives for rice straw management. The benefits brought about by non-open burning scenarios to ambient air quality and health should be demonstrated in future studies by using a detailed emission inventory and dispersion modelling approach. Suitable business models involving the private sector should be developed that incorporate sufficient incentives to encourage farmers to stop open burning.

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COMPETING INTERESTS

The author declares that there is no conflict of interest regarding the publication of this article.

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