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Health Impacts and Cost Assessment of Fine Particulate Matter Formation from Rice Straw Utilization in Thailand

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Abstract

Air pollution problems attributed to open burning of agricultural wastes have constantly affected the air quality and subsequently the human health in Thailand. To take advantage of the resource potential in rice straw, several alternative management practices have been carried out in Thailand. Hence, it is imperative to evaluate the potential health impacts of fine particulate matter emitted from the different rice straw utilization techniques. Thai spatially differentiated characterization factors were determined and applied to characterize the damage on human health related with $PM_{2.5}$ emission from the selected rice straw utilization scenarios. The results of the study depicted that open burning of the total rice straw generated increases health impact by 81.1% compared to Business-As-Usual (BAU) scenario, which supports the effectiveness of the different agricultural residue management methods integrated in the BAU scenario instead of open burning 100% of the rice straw generated. Furthermore, assessing the impact of alternative scenarios demonstrated that adopting rice straw management techniques such as fertilizer, animal feed and electricity production individually also can reduce health damage efficiently as compared to open burning. The BAU scenario extended vast economic benefit of 242 billion THB, compared to 100% open burning of rice straw. In addition, each of the alternative scenarios (except open burning) also provided large economic benefit in comparison with BAU scenario. Hence, both the health impact and economic benefit assessments were able to corroborate the efficiency of alternative rice straw utilization techniques in comparison to open burning, both when integrated or carried out individually. Due to the use of Thai spatially differentiated characterization factors, the study was able to project results specific to the context of Thailand.

Keywords : Fine Particulate Matter; Rice Straw Utilization; Health Impact; Economic Benefit; Thai Spatially Differentiated Characterization Factors

Introduction

Ambient fine particulate matter pollution is an important health risk factor that significantly contributes to increasing global mortality. In 2019, Global Burden of Disease (GBD) study ranked $PM_{2.5}$ exposure as the 6^{th} global mortality risk factor and the 7^{th} leading risk factor in Thailand [1]. Amongst the major sources resulting in high levels of $PM_{2.5}$ emission (including industries, transportation, biomass burning and transboundary haze [2]), the extent of agricultural waste burning and its adverse implication on air quality is pronounced in Thailand [3, 4]. Thailand is an agricultural-based economy and agriculture accounts for about 47% of the total land cover of Thailand [21]. Rice is one of the major crops of Thailand that is planted throughout the country [5]. In 2017-2018, about 32.24 million tonnes of rice was produced ranking Thailand as the sixth largest global producer of rice [7]. Thailand is also among the leading countries that export rice, holding about 24% of global rice export market share [6]. Along with the production statistics, rice also has a high crop to residue ratio such that rice residue is the highest-ranking crop residue that is openly burned in Thailand annually (70% of total residues of Thailand) [3]. Moreover, Thailand had the 10^{th} highest amount of biomass burned globally in 2016 [3]. The detrimental impacts of $PM_{2.5}$ emission attributed to open burning of agricultural waste on ambient air quality [8, 9, 12] and human health [2, 10, 11] is evident. Ongoing efforts by the government of Thailand have focused on addressing the problems of open burning agricultural wastes by providing control measures and promoting alternative measures to manage the crop residue generated [9, 13]. Several practices for alternative management of rice residue are carried out such as bio-energy generation, incorporation as fertilizer, utilization as animal feed, mushroom plantation, etc., to advantage of its resource potential [3, 5, 14, 16-20]. Life cycle impact assessment (LCIA) can be adopted to efficiently analyze the health impacts associated with $PM_{2.5}$ emission [32]. Studies specific to the context of Thailand that have evaluated the environmental impacts of different rice straw management techniques have either not focused on $PM_{2.5}$ formation impact category, applied global LCIA methods or have limited study area [16-20]. Thus, the aims of the study were: 1) to determine spatially differentiated characterization factors of $PM_{2.5}$ formation specific to 77 provinces of Thailand; 2) to assess the health impacts of $PM_{2.5}$ formation from different rice straw utilization techniques at provincial and country level; and 3) to determine the economic benefit of each of the alternative rice straw utilization techniques.

Methodology

The methodology focuses on determination of human heath impact and cost of fine particulate matter formation from rice residue utilization in 77 provinces of Thailand. The assessment was carried out as per the ISO 14040:2006 standardized framework for LCA [15].

Goal and Scope Definition

Evaluation of the human health impacts and costs of different rice residue utilization scenarios at the provincial and country levels of Thailand was the goal of the study and the unit of analysis was rice straw generated from annual production of rice in 2019. The air pollutants under scrutiny were primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors i.e., nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3). The primary focus of this study was on agricultural waste management, so the system boundary of the analysis does not cover rice cultivation process and only the residue management part. The health impacts and economic benefits of each rice straw management scenarios considered have been determined for 77 provinces of Thailand following the framework shown in Figure 1, and the results of the study were represented at provincial and country-levels.

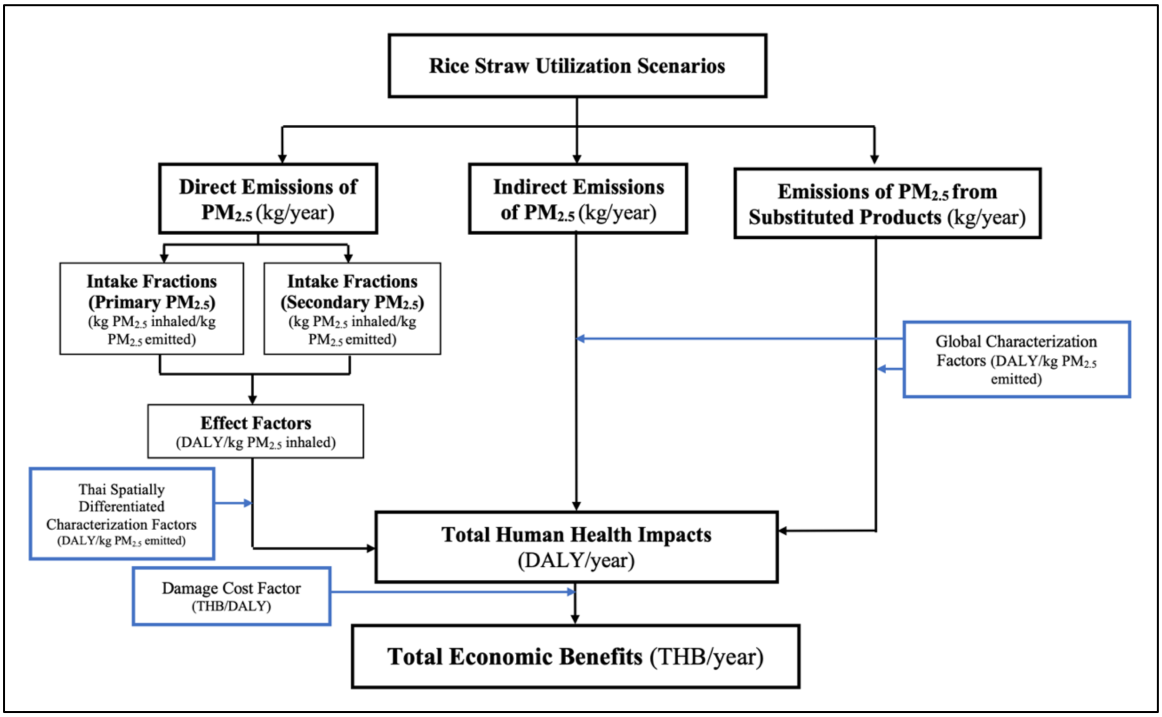


Figure 1 Overall Research Framework

Scenario Description

The study first involves determining the impacts of Business-As-Usual (BAU) scenario, followed by comparing it with alternative scenarios. In the BAU scenario, the total share of rice straw has been apportioned between 5 pathways (Table 1). While 100% of rice straw generated was utilized in the 4 alternative scenarios considered (Table 2). The percentage share of major (harvested in wet season i.e., September-April) and minor (harvested in dry season i.e., October-December) rice straw utilized in the BAU scenario (Table 1) has been adapted and modified from a study that conducted questionnaire survey to examine rice cultivation and residue management behavior during 2014/2015 crop season of Thailand [5]. Each scenario involves processes that lead to direct (that occur in Thailand) or indirect (that occur outside Thailand) emissions. The products obtained by utilization of rice straw in the considered scenarios lead to avoiding emissions that would have otherwise occurred from production of the substituted products. The substituted products as a result of each of the defined scenarios have been considered in the study and are provided in Table 2.

Table 1 Rice Straw Share (%) for Business-As-Usual (BAU) Scenario [5]

Rice Straw Utilization Pathways	Share of Rice Straw Utilization (%)									
	North		Northeast		Central		South		Thailand	
	Major	Minor	Major	Minor	Major	Minor	Major	Minor	Major	Minor
Fertilizer	0.28	0.23	0.07	0.14	0.25	0.15	0.31	0.14	0.24	0.18
Animal Feed	0.32	0.24	0.38	0.36	0.11	0.36	0.32	0.32	0.18	0.31
Mushroom Plantation	0.08	0.05	0.06	0.11	0.01	0.05	0.17	0.07	0.05	0.07
Open burning	0.20	0.26	0.01	0.21	0.36	0.18	0	0.02	0.30	0.21
Left in the field	0.11	0.22	0.48	0.18	0.26	0.26	0.19	0.45	0.23	0.23

Table 2 Overall Scenario Description

Scenario		Process	Emission	Substituted Product
Business-As-Usual (BAU) Scenario	BAU 1: Fertilizer ***(21%)****	Incorporation into the field**	Direct Emission	Nitrogen-Phosphorous-Potassium Fertilizer (Global Market)
		Straw Chopping**		
		Diesel Production	Indirect Emission	
	BAU 2: Animal Feed ***(24%)****	Straw Chopping**	Direct Emission	Animal Feed (Global Market)
		Baling Operation**		
		Transportation**		
		Diesel Production	Indirect Emission	
	BAU 3: Mushroom production ***(6%)****	Straw Chopping**	Direct Emission	-
		Baling Operation**		
		Transportation**		
		Diesel Production	Indirect Emission	
	BAU 4: Open Burning ***(26%)****	Open Burning	Direct Emission	-
	BAU 5: Left in Field ***(23%)****	Left in field	Direct Emission	-
Scenario 1: Open Burning ***(100%)****		Open Burning	Direct Emission	-
Scenario 2: Fertilizer ***(100%)****		Incorporation into the field**	Direct Emission	Nitrogen-Phosphorous-Potassium Fertilizer (Global Market)
		Straw Chopping**		
		Diesel Production	Indirect Emission	
Scenario 3: Animal Feed ***(100%)****		Straw Chopping**	Direct Emission	Animal Feed (Global Market)
		Baling Operation**		
		Transportation**		
		Diesel Production	Indirect Emission	
Scenario 4: Electricity Generation ***(100%)****		Straw Chopping**	Direct Emission	Grid Electricity (High Voltage) (Local Market)
		Baling Operation**		
		Transportation**		
		Electricity Generation		
		Diesel Production	Indirect Emission	

*Percentage share of rice straw utilized; **Emission from diesel combustion

Emission Inventory Development

Emission inventories for the different scenarios of this study were developed for: direct emission, indirect emission and substituted product emission (Table 2). The emission inventory data were obtained from secondary sources. The rice production yield (tonnes/ha) and harvested area (ha) data were gathered from the year book “Agricultural Statistics of Thailand – 2019” [21]. The ratio for residue to crop and dry matter to crop were taken as 1.19 of 0.85 respectively, to obtain the rice residue generated (dry weight) [22]. The rice straw percentage shares provided in Table 1 and Table 2 are adopted for calculation of the equivalent share of residue for all considered scenarios.

Direct Emission: The direct emission was determined by combining emission factor with activity data. The input data adopted for calculating the direct emissions from the different processes considered have been provided in Table 3. Round trip transportation distance of 10 km by 7-tonne diesel vehicle (from field to collection center) was assumed for utilization as animal feed and mushroom plantation [20]. Whereas round-trip transportation distance of 90 km by 15-tonne diesel vehicle (from field to electricity generation plant) was assumed for rice straw-based electricity generation, with 10% transportation loss [20, 19]. The emission factors in case of diesel combustion from transportation and diesel required per tkm were obtained from the ecoinvent database v3.7.1, for 7.5-16 tonne, EURO 3 lorry (freight transport) [25].

Indirect Emission: To compute the indirect emission from diesel production, total diesel (kg) required for all processes involved in each scenario were determined (such as straw chopping, incorporation into the field, baling operation and transportation). The density of diesel i.e., 0.85 kg/L has been adopted [29]. The $PM_{2.5}$ emissions from diesel production (global market) were directly calculated from the ecoinvent database v3.7.1 available from SimaPro v9.2.0.1 [25].

Table 3 Input data for direct emissions

Process	Parameter	Value	Unit	Reference
Incorporating residue into the field	Nitrogen (N) content	6	kg/tonne of rice straw (dry weight)	[23]
	Phosphorous (P) content	1	kg/tonne of rice straw (dry weight)	[23]
	Potassium (K) content	19	kg/tonne of rice straw (dry weight)	[23]
	Emission Factor (NH_3)	0.12	kg NH_3/ kg of N	[24]
	Emission Factor (NO_X)	0.04	NO_X/kg of N	[38]
Diesel combustion (agricultural machinery)	Energy content (diesel)	38.42	MJ/L	[40]
	Diesel requirement (straw chopping)	78	L/ha	[19]
	Diesel requirement (incorporation into the field)	16	L/ha	[19]
	Diesel requirement (baling operation)	1.2	L/ha	[19]
	Emission Factor (NOx)	866	g/GJ	[25]
	Emission Factor (SO_2)	22.4	g/GJ	[25]
	Emission Factor ($PM_{2.5}$)	109	g/GJ	[25]
Diesel combustion (transportation)	Diesel requirement	0.04	kg/tkm	[25]
Open burning	Combustion Factor	0.87		[22]
	Emission Factor ($PM_{2.5}$)	8.3	g/kg rice straw	[26]
	Emission Factor (NOx)	3.34	g/kg rice straw	[26]
	Emission Factor (SO_2)	0.48	g/kg rice straw	[26]
	Emission Factor (NH_3)	4.1	g/kg rice straw	[26]
Electricity Generation	Energy content (rice straw)	14.2	MJ/kg	[5]
	Plant Efficiency	23	%	[27]
	Emission Factor ($PM_{2.5}$)	133	g/GJ	[28]
	Emission Factor (NOx)	81	g/GJ	[28]
	Emission Factor (SO_2)	10.8	g/GJ	[28]

Substituted Product Emission: The products that utilization of rice straw as fertilizer substituted are N, P and K fertilizers (global market). The data on nutrient content per tonne for rice straw generated was used. Rice straw utilization as animal feed substitutes feed energy (global market). The feed energy per kilogram of rice straw (dry weight) is 8.45 MJ [30]. Rice straw-based electricity generation substitutes grid electricity generation in Thailand (high voltage). The $PM_{2.5}$ emissions from all substituted products were calculated directly using the ecoinvent database v3.7.1 available from SimaPro v9.2.0.1 [25].

Health Impact Assessment

The health impact assessment follows an impact pathway that characterizes the emission of $PM_{2.5}$ and health impact associated with subsequent inhalation by exposed population [31]. Characterization Factor (CF) for fine particulate matter formation is the parameter that translates the chain of effects in the impact pathway from emission to human health damage. The CF represents impacts on human health from exposure to $PM_{2.5}$ and is indicated as disability-adjusted life year (DALY) per kilograms $PM_{2.5}$ emitted. CF calculation comprises integrating intake fraction (iF) with effect factor (EF) [32]. The iF represents ratio of $PM_{2.5}$ that the exposed population inhales to total $PM_{2.5}$ emitted at source. While EF relates population exposure to $PM_{2.5}$ with health effects. The spatially differentiated iF and EF for 77 provinces of Thailand have been calculated by adapting and updating input parameters in existing iF and EF models [33, 34]. The determination of the province specific CF involves considering the effect of $PM_{2.5}$ emission in an urban area (i.e., specific province in Thailand) and the surrounding rural area (i.e., Thailand and Indochina) [32-34, 39]. The iF model also considers city-specific outdoor emission on both indoor and outdoor compartments.

$$CF_i^{urban} = iF_{i \leftarrow i}^{urban} \times EF_i^{urban} + iF_{k \leftarrow i}^{urban} \times EF'^{total}_{k} \quad (1)$$

where, $CF_i^{\text{urban}} =$ Characterization Factor (DALY/kg $PM_{2.5}$ emitted) for province (*i*)

$iF_{i \leftarrow i}^{\text{urban}}$ =Total urban inhalation iF (kg $PM_{2.5}$ inhaled/ kg $PM_{2.5}$ emitted) for province (*i*)

$iF_{k \leftarrow i}^{\text{urban}} =$ Total rural inhalation iF (kg $PM_{2.5}$ inhaled / kg $PM_{2.5}$ emitted) for rural area excluding province (*i*) (denoted as *k*)

EF_i^{urban} = Effect factor (average slope) for province (*i*) (DALY/kg $PM_{2.5}$ inhaled)

EF'^{total}_{k} Effect factor (average slope) for rural area excluding province (*i*) (DALY/ kg $PM_{2.5}$ inhaled)

The input parameters revised in the iF model to determine spatially differentiated values were province-specific population, urban area, linear population density (LPD), ambient $PM_{2.5}$ concentration, mixing height, wind velocity and dilution rate. Similarly, the input parameters revised in EF model to obtain province-specific factors were mortality data, severity factors, population and $PM_{2.5}$ concentration. Since the current framework of iF does not involve secondary $PM_{2.5}$, global average iF values of secondary $PM_{2.5}$ precursors have been used [35]. Since the global intake fractions were not differentiated for urban and rural areas, effect factor covering a larger area, i.e., Thailand has been used. The total health impact (HI) scores for direct emissions from each scenario were calculated as a summation of the product of spatially differentiated CF_i for $PM_{2.5}$, NO_X, SO_2 and NH_3 with their respective province specific emissions.

$$HI = \sum HI_i = \sum (Emission_i \times CF_i) \quad (2)$$

In case of indirect and substituted product emissions, health impacts (DALY) were calculated directly in SimaPro v9.2.0.1 using Impact World+ Endpoint [36] which is a method for life cycle impact assessment. Total health impacts were calculated by subtracting health impacts of substituted products from sum of health impacts of direct and indirect emissions.

Economic Benefit Valuation

The human health impact score was monetized using damage cost factor that translates value of 1 DALY into Thai Baht (THB) [37]. The factor has been calculated based on budget constraint approach which considers 1 DALY equivalent to an individual's annual income earned at the state of full-wellbeing and is the maximum amount an individual is willing to pay for additional year of full-wellbeing [37]. The value of 1 DALY in 2011 was equivalent to 512,000 THB. Future valuation of 1 DALY considered the time value of money applying inflation rate of Thailand averaged over period of 2011-2019 (reference year) [39]. Hence, the future value of DALY in 2019 was determined as 572,736 THB. The economic benefit provided by each of the alternative scenarios were determined by relating it with the total health impacts reduction as compared to BAU scenario.

$$Economic\ Benefit = Damage\ Cost\ Factor \times (HI_{BAU} - HI_{scenario}) \quad (3)$$

The summarized information on overall work process of the study has been presented in Figure 2.

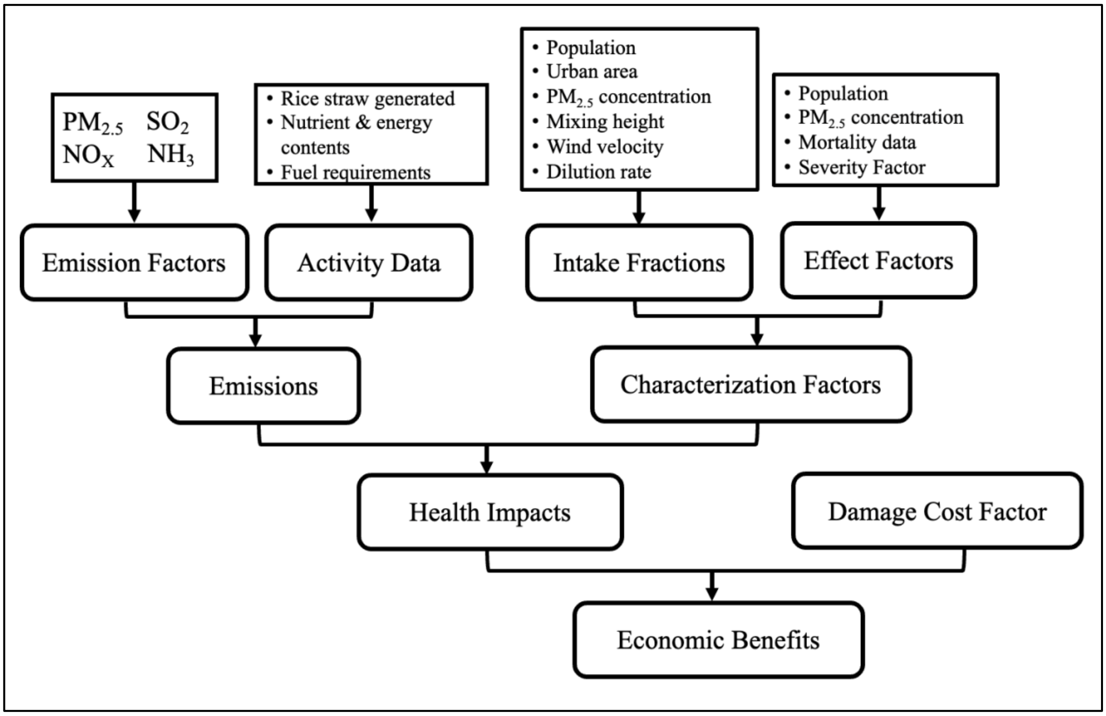


Figure 2 Summarized workflow diagram

Results and Discussion

Spatially differentiated characterization factors

The spatially differentiated CFs were determined for $PM_{2.5}$ by combining iF and EF, at provincial-level of Thailand. The determined CF for primary $PM_{2.5}$ of 77 provinces have been presented in Figure 3. The provinces having population density and ambient $PM_{2.5}$ concentration at higher range were found to have higher iF values. While provinces having atmospheric dilution rate at lower range were found to have higher iF values [39]. The provinces having ambient $PM_{2.5}$ concentration at higher range were found to have lower EF values. This is because the relative risk of $PM_{2.5}$ exposure is characterized by an exposure-response model that is non-linear, such that with increment in the $PM_{2.5}$ exposure concentration the slope of health effects decreases gradually [34]. In case of secondary $PM_{2.5}$ precursors gases, global iF and country-specific EF was used such that the obtained CF is spatially differentiated at country-level. The determined CFs for NO_X, SO_2 and NH_3 are 1.90E-05, 9.40E-05 and 1.61E-04 DALY/kg $PM_{2.5}$ emitted respectively. Hence, the health damage resulting from primary $PM_{2.5}$ have greater impact as range of CF for primary $PM_{2.5}$ (Figure 3) is higher compared to secondary $PM_{2.5}$ precursors. Nonetheless, the obtained CF was widely varying between provinces which shows that the health impact assessment using global CF would not be able to adequately reflect the variable effect emission sources have on health impact.

Health impacts of BAU scenario at provincial level

The health impacts imposed by rice straw utilization in BAU scenario for all 77 provinces of Thailand has been depicted in Figure 4. The top five provinces with highest health impacts were Nakhon Sawan (12,837 DALYs), Suphan Buri (10,138 DALYs), Phetchabun (8,229 DALYs), Kamphaeng Phet (5508 DALYs) and Phichit (4,816 DALYs). While the lowest health impact was observed in Phuket (0.006 DALY). In general, the province with rice straw generation (tonnes) and CF (DALY/kg $PM_{2.5}$ emitted) in the higher range were found to have higher health impact.

Phichit had the 3rd largest rice straw available however, it ranked as 5th highest health impact because its CF was in the lower range. This depicted the importance of applying the spatially differentiated CF because if global CF were used then the results would only be proportional to rice straw generation data and the effect of regionalized health impact would not have been revealed in the results. Amongst all the underlying pathways of BAU, open burning consistently contributed to the highest health impact in all the 77 provinces (95% of total BAU health impact). The health impact imposed by BAU1 (Fertilizer), BAU2(Animal Feed), BAU3 (Mushroom Plantation), and BAU5 (Left in Field) were 2.5%, 0.8%, 0.4% and 1.2% respectively, which were diminutive compared to BAU4 (Open Burning). Furthermore, the percentage share of rice straw utilization varies regionally, as shown in Table 1. For instance, open burning has the highest share of rice straw in central region of Thailand (27%), while lowest share of rice straw undergoes open burning in the southern region (1%). This also explains why the top 5 provinces of Thailand with highest health impact were located in central region while the province with lowest health impact was located in the southern region of Thailand.

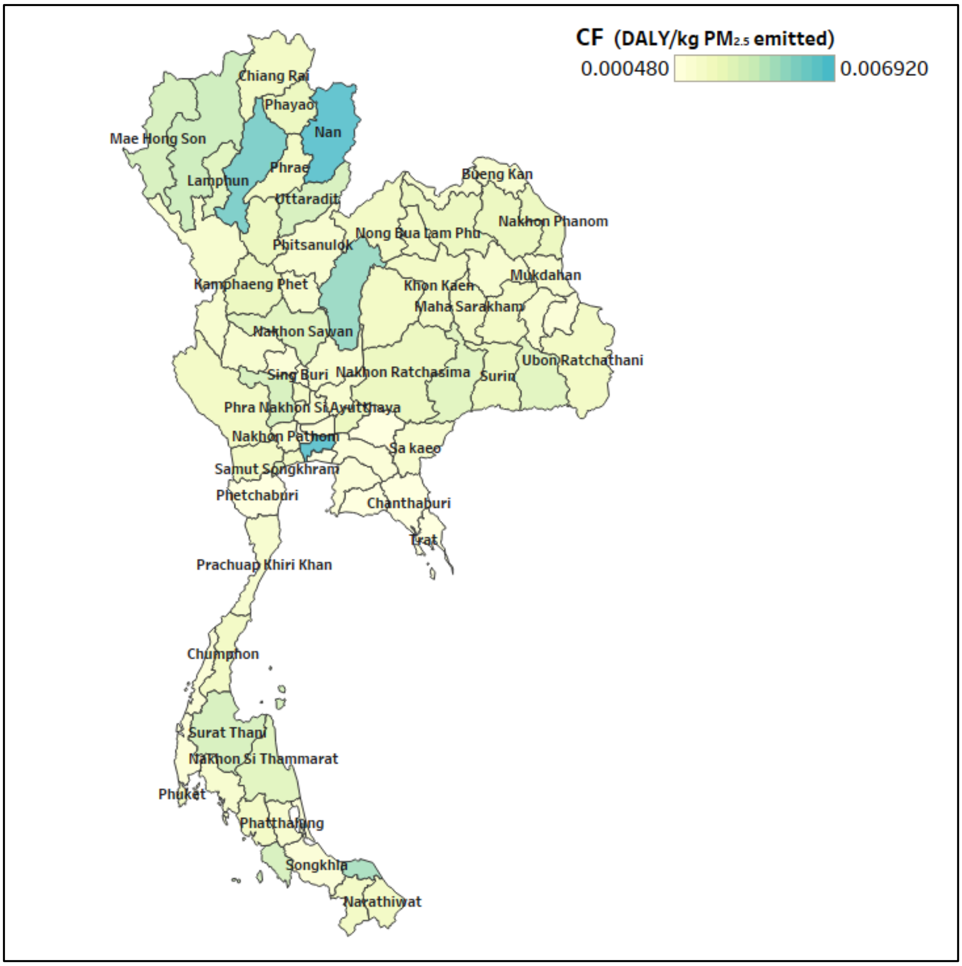


Figure 3 Spatially differentiated CF for primary $PM_{2.5}$

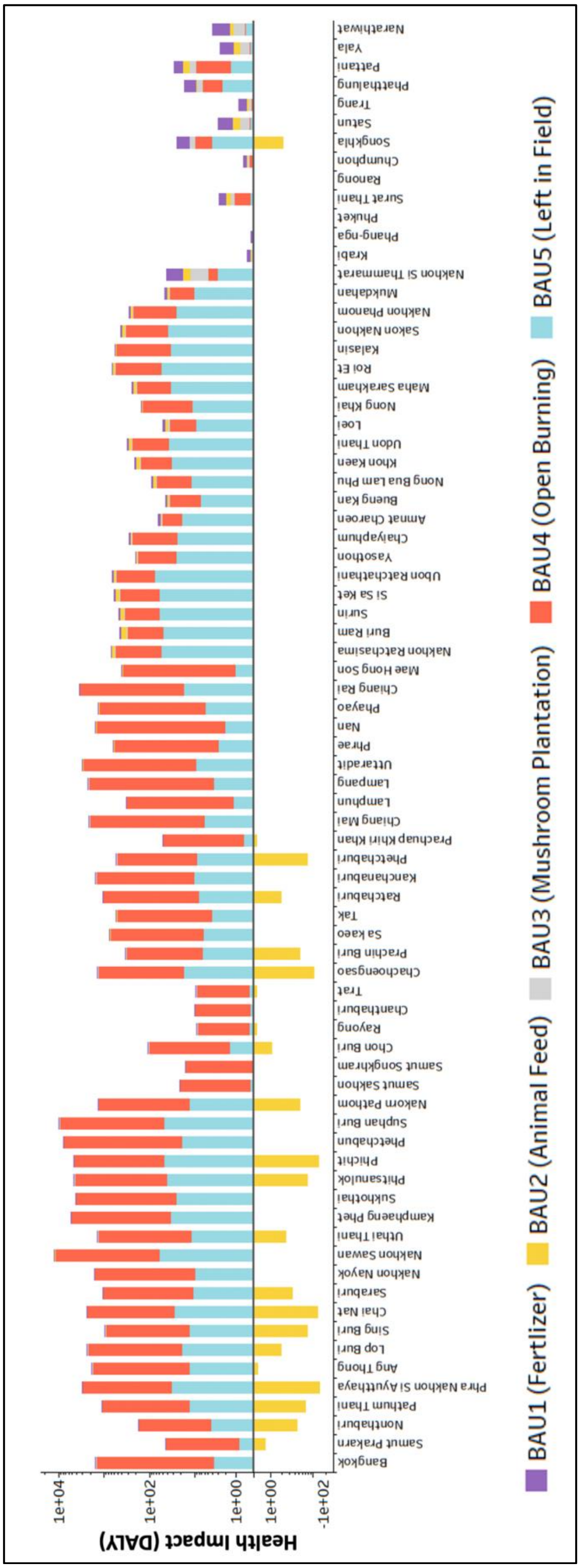


Figure 4 Health impacts of BAU scenario at provincial level (Logarithmic scale)

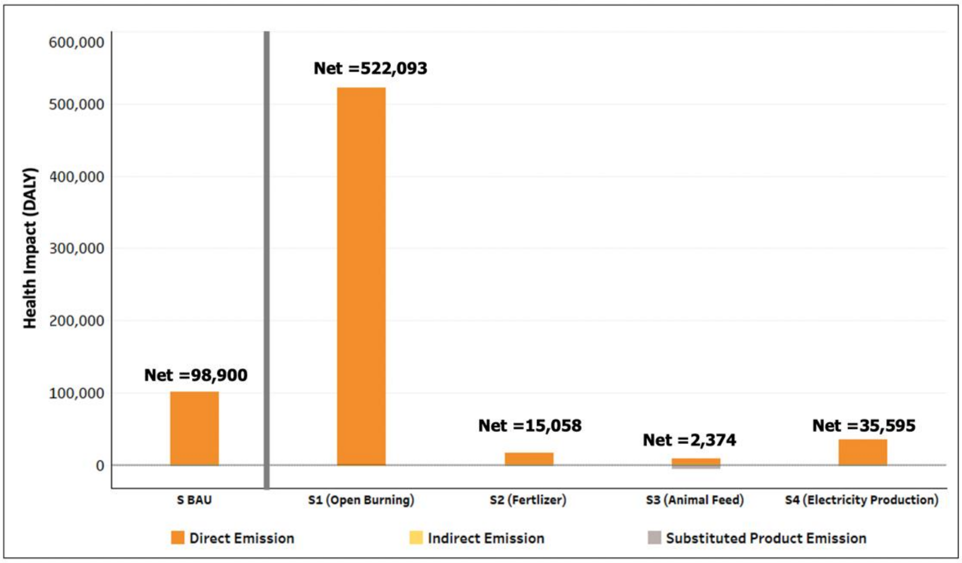
Total health impacts of alternative scenarios

The total health impacts have been determined by combining the effects of direct, indirect and substituted product emission of all 77 provinces of Thailand. Total health impacts of the four alternative scenarios have been compared with the BAU scenario in Figure 5. The scenario having the highest total health impact was Scenario 1 (Open Burning) and it was also the only scenario having higher impact than BAU i.e., 423,193 DALYs more than BAU. The remaining 3 alternative scenarios (i.e., electricity production, fertilizer and animal feed) have lower health impact than BAU scenario i.e., health benefits. Scenario 3 (Animal Feed) was the alternative scenario that contributed the lowest health impact i.e., health benefit of 96,526 DALYs. Scenario 1 involves only direct emission by open burning 100% of rice straw generated. In Scenario 2, direct emission predominantly leads to about 16,222 DALYs, while indirect emission leads to only 412 DALYs and substituted product emission reduces 1,576 DALYs. While in Scenario 3, direct emission leads to about 7,985 DALYs, indirect emission leads to only 265 DALYs and substituted product emission reduces 5,876 DALYs. Similarly in Scenario 4, direct emission leads to about 35,334 DALYs, while indirect emission causes 264 DALYs and substituted product emission reduces only about 3 DALYs. Hence, direct emission caused highest health impact in all the four alternative scenarios but avoided emission from substituted product significantly helps in reducing the impact only for Scenario 3 (Animal Feed). Diesel combustion due to agricultural machinery and transportation cause direct emission of $PM_{2.5}$ in Scenarios 2, 3 and 4. Additionally, $PM_{2.5}$ was also emitted in electricity generation plant for Scenario 4, which was still very less compared to emission of $PM_{2.5}$ by open burning of rice straw in the field.

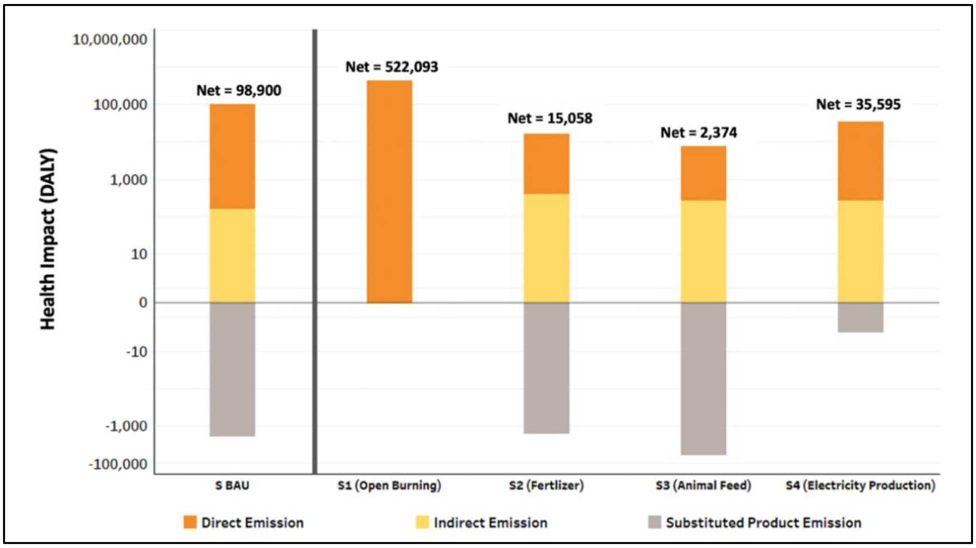
Furthermore, the results showed that Scenario 1 increases the health impacts by 423,193 DALYs compared to BAU scenario which extends the effectiveness of incorporating different agricultural residue management methods instead of open burning all the rice straw that was generated. But, BAU still has higher health impact than Scenarios 2, 3 and 4 as open burning was one of the integrated pathways of BAU. As 5 pathways were combined in BAU, the alternative Scenarios 1, 2 and 3 helped to understand the health effect each scenario has individually. Moreover, Scenario 4 has been formulated because rice straw has potential of electricity generation [5] but it was not included in BAU. Through the results we can see the adverse effect open burning has on human health and the capability of alternative scenarios to counteract the negative impact of open burning, both when integrated (in BAU scenario) or carried out individually (in alternative scenarios 2, 3 and 4).

Total economic benefits of alternative scenarios

To better comprehend the total cost/benefit of the alternative scenarios, the health impacts increment/reduction with respect to BAU have been translated into monetary terms combining the results of all 77 provinces. From Figure 6, Scenario 3 (Animal Feed) has the highest total economic benefit of 55 billion THB as large amount of $PM_{2.5}$ emission was avoided because of substitution of animal feed with rice straw. It was followed by Scenario 2 (Fertilizer) whose economic benefit was slightly less, i.e., 48 billion THB. Scenario 4 (Electricity Production) ranks 3rd with an economic benefit of 36 billion THB. While Scenario 1 (Open Burning) rendered health cost of 242 billion THB rather than benefit in comparison with BAU, which is in line with the results obtained in total health impact analysis (i.e., direct emission from open burning has highest impact). Although BAU scenario consisted of approximately 26% of rice straw open burning, it still has economic benefit of 242 billion THB compared to 100% open burning of rice straw. Moreover, Scenarios 2, 3 and 4 were subjected to higher economic benefits as the BAU scenario has open burning integrated as agricultural residue management technique. Scenarios 2, 3 and 4 extend economic benefit of 120%, 123% and 115% respectively in comparison with Scenario 1 (Open Burning). Hence, the results show that replacing open burning with other alternative scenarios can efficiently increase economic benefits.



(a)



(b)

Figure 5 Total health impacts of alternative scenarios (a) normal scale and (b) logarithmic scale

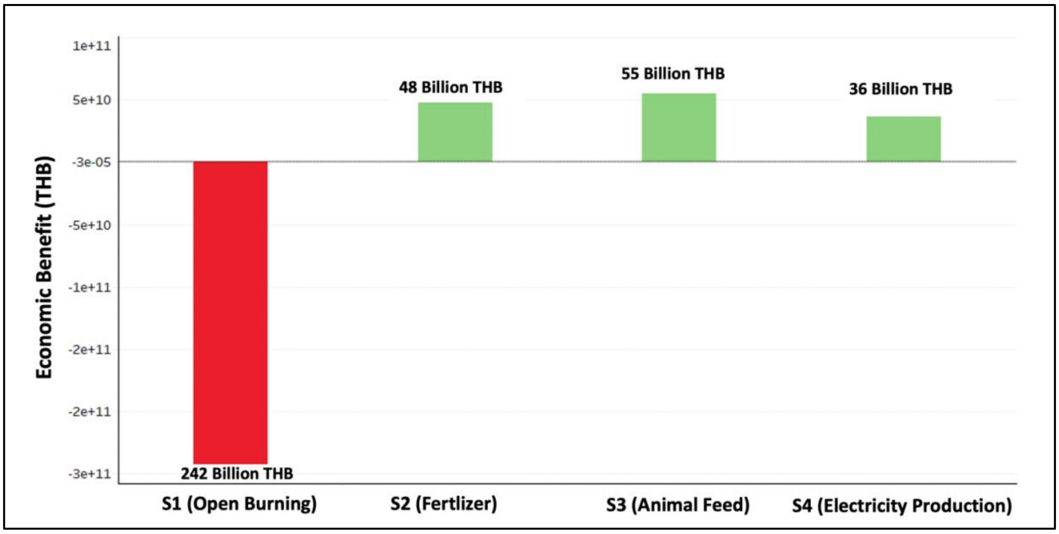


Figure 6 Total economic benefits of alternative scenarios

Conclusions

The health impact and economic benefits of fine particulate matter formation was determined for different rice straw utilization practices of Thailand. To calculate the health impact, spatially differentiated characterization factors (CFs) of $PM_{2.5}$ were determined for the 77 provinces of Thailand. The calculated CFs varied extensively between provinces which demonstrated that the health impact assessment using global CFs would not be able to capture the contribution of region specific $PM_{2.5}$ exposure-response relationship. Province-specific health impact was evaluated for Business-As-Usual (BAU) scenario which had 5 different rice straw utilization methods integrated together. Provinces with the highest and lowest health impact attributed to BAU scenario were Nakhon Sawan and Phuket respectively. Open burning pathway in BAU scenario contributed the highest health impact i.e., 95% of total BAU health impact in all the 77 provinces. Total health impacts of the four alternative scenarios (i.e., open burning, fertilizer, animal feed and electricity production) were compared with the BAU scenario to analyze the individual effects of each residue management method. The results show that the BAU scenario was capable of decreasing health impact by 81.1% compared to the open burning scenario, which supports the effectiveness of combining agricultural residue management methods instead of open burning of the entire rice straw generated. In comparison with alternative scenarios such as fertilizer, animal feed and electricity production, the BAU scenario contributes to higher health impact as open burning is one of the integrated management methods. Hence, individually assessing the impact of each alternative scenarios with respect to the BAU scenario demonstrated the higher efficiency of these alternative rice straw management techniques. Furthermore, the economic benefit assessment helped in providing a better perspective by translating the health impact assessment results into monetary terms. The results depicted that the BAU scenario extended vast economic benefit compared to 100% open burning of rice straw (i.e., 242 billion THB). In addition, the alternative scenarios (fertilizer, animal feed and electricity production) also provided large economic benefit individually as compared to BAU. Hence, both the health impact and economic benefit assessments were able to corroborate the efficiency of alternative rice straw utilization techniques in comparison to open burning, both when integrated or carried out individually. Moreover, due to the use of Thai spatially differentiated CFs, the study was able to obtain outcomes that were particularly for the case of Thailand. As alternative residue management methods like fertilizer, animal feed and electricity production demonstrated positive results, future studies can be carried out to develop scenarios by integrating diverse residue management techniques and allocating different proportions of crop residue to each of the considered techniques which will help in recommending the best scenario for effective agricultural residue management in Thailand. Finally, the overall outcomes are subjected to uncertainties because of the methodology adopted, assumptions made, and data utilized in calculation of the $PM_{2.5}$ emissions for the processes considered and the spatially differentiated $PM_{2.5}$ characterization factors.

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