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Original Research

Sustainable Options for Reducing Open Burning of Corn Residues: Case Study of Mae Chaem District, Thailand

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Abstract

Mae Chaem is the biggest corn plantation district in Chiang Mai, Thailand. Corn farmers in Mae Chaem use open burning to manage corn residues which has led to environmental problems, i.e., greenhouse gas emissions, air pollution, and soil degradation. Corn monocultures produce a large amount of corn residues annually. After harvesting, corn residues are left in the field without utilization and have caused severe pollution problems stemming from open burning for over a decade. Although there are many technologies for corn residue utilization, the highest rejection of the technologies for reducing open burning is found in corn farmers. The goal of this research was to identify sustainable options for reducing open burning of corn residues, which in turn would reduce environmental problems and enhance economic and social benefits. The research method employed was an Analytical Hierarchy Process-based multi-criteria decision-making approach with three main criteria, nine sub-criteria and nine alternatives. Questionnaires with pair-wise comparison matrices were used for interviewing and weighting by experts. The results show that sustainable options for reducing open burning should be prioritized to achieve environmental benefits in reducing air pollution, economic benefits, and social acceptance by corn farmers. The most suitable technological and non-technological alternatives were biomass electricity and mixed cropping. This study identified and ranked the technological and non-technological options for mitigating open burning.

Keywords: open burning, corn residues, mitigation options, Analytical Hierarchy Process

Introduction

A large amount of corn residues are produced annually and often remain partly or wholly unutilized, causing environmental problems. Open burning of corn residues has been the usual practice by farmers around the globe for a long period of time [1-3]. Corn residues have been openly burned to eradicate stalks and leaves out of plantation areas after harvesting and before the farmers prepare the plantation areas for the next season [1, 4-6]. Out of the total crop residues openly burned in the world, 48% are corn residues, 24% rice residues,

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23% wheat residues and 5% sugarcane residues [1]. The short period after harvesting and before planting the next crop is a significant problem for farmers in preparing the plantation areas. The open burning practice of wholly or partly burning relies on the utilization of corn residue, corn farmers' knowledge, and technology adoption [7-9]. Over the past decades, a significant quantity of agricultural residues has been openly burned in many developing countries, such as Thailand, Indonesia, India, China, and Brazil [1]. Population growth is a key driver of demand for food and the expansion of crop plantation areas [10]. In the past decade, corn monoculture has sharply increased in the Mae Cheam District to satisfy the higher demand for food. Mae Cheam is one of twenty-five districts of Chiang Mai, which is the biggest province for corn plantation in the Upper North of Thailand [11]. Seventy percent of corn production in Chiang Mai is from Mae Cheam.

Corn plantation areas have sharply increased from 7,770 hectares in the year 2005 to 20,619 hectares in 2020. Corn production in Mae Chaem has risen from 22,000 tons in 2005 to 87,630 tons in 2020 [12]. Corn production in Mae Cheam generates more than 10 million tons of corn residues which is a significant source for open burning of agricultural residues [2, 13]. Thus, increasing corn residues and severe open burning of corn residues have occurred continuously in Mae Cham [6, 14]. After harvesting, corn residues were left in the plantation areas without utilization, and they were usually burned by the farmers after harvesting [4]. Although open burning in agricultural areas has been restricted since 2013, open burning in the corn plantation areas of Mae Chaem is the highest [12, 14-15] among Chiang Mai's economic crops, such as rice and sugarcane.

Open burning of corn residues impacts the environment, the economy, and society. The Thai agricultural sector is facing serious issues of open burning of corn residues, which lead to environmental impacts such as greenhouse gas (GHG) emissions, air pollution, and soil impacts [6-7, 16]. Open burning of corn residues in the field contributes to atmospheric pollution, emitting gaseous pollutants i.e., CO_2, CH_4, CO, N_2O and particulate matter [17]. Ninety percent of emissions and air pollution in Chiang Mai have come from open burning of corn residues [18], which leads to exceeding the $PM_{2.5}$ standard in Chiang Mai during the burning season [15]. Open burning of corn residues causes air pollution and overheats the soil, which causes loss of soil microbes, soil carbon, and soil organic material [18-20]. In terms of economic impacts, collecting and managing corn residues from the field not only requires energy and intensive labor but also creates delays in sowing the next crop. The added cost of residues reduces the total profits of the farmers [21]. However, smallholder corn farmers never receive incentives or governmental support in adapting a zero-burning mode for sustainable production [18]. In terms of social impacts, the worst effects of illegal biomass burning between February and April are disruption of tourism with adverse affects people's livelihoods and health [22-24]. The loss in Chiang Mai's tourism sector amounted to 477 million baht (1 USD equal to 33.42 THB) and health expenditures amounting to 15,000 baht per person during the open burning period [24-25].

The 12th National Economic and Social Development Plan (2017-2021) [26] and Strategies in Climate Change and Agriculture Plan of Thailand (2017-2021) [16] highlighted the importance of finding a solution to open burning of corn residues for reducing GHG emissions, air pollution, and soil impacts. Moreover, among Thai economic crops, corn residues were found to be the highest open-burned residues in the field and the lowest utilized compared to other residues, such as rice and sugarcane residues. Although there are many technologies for the utilization of corn residues, the highest rejection rate of the technologies for reducing open burning was found among corn farmers. Currently, there are no sustainable options for utilization of corn residues that can reduce open burning, whereas using of baling technology for rice straw and sugar mills' policy of not buying sugarcane with pre-harvest open burning effectively reduced the open burning of these residues [7].

Therefore, this study's goal is to identify sustainable options for reducing the open burning of corn residues which could reduce environmental problems and enhance economic and social benefits.

Data and Methods

Study Area

The selected study area, Mae Chaem, Chiang Mai, is not only the 4th largest district in Thailand but also the biggest corn plantation district in Chiang Mai, with 20,619 hectares [12]. While Thailand has a total corn plantation area of 1,124,746 hectares [27], the most severe open burning of corn residues taking place for more than a decade has been in Mae Chaem. Mae Chaem is located at 18°6′0″ to 19°10′0″N and 98°4′0″ to 98°34′0″E, with an area of 3,853 km^2. The topography of Mae Chaem is a basin with surrounding steep elevations between 260 and 2,540 m above sea level [28].

Methodology

The Multi-criteria Decision-making Approach (MCDA) with Analytical Hierarchy Process (AHP) is used in this study to identify the best options for reducing the open burning of corn residues. MCDA is applied in broad areas such as sustainability of agricultural production [29], energy, waste management [30], public policy [31], and climate change [32]. AHP

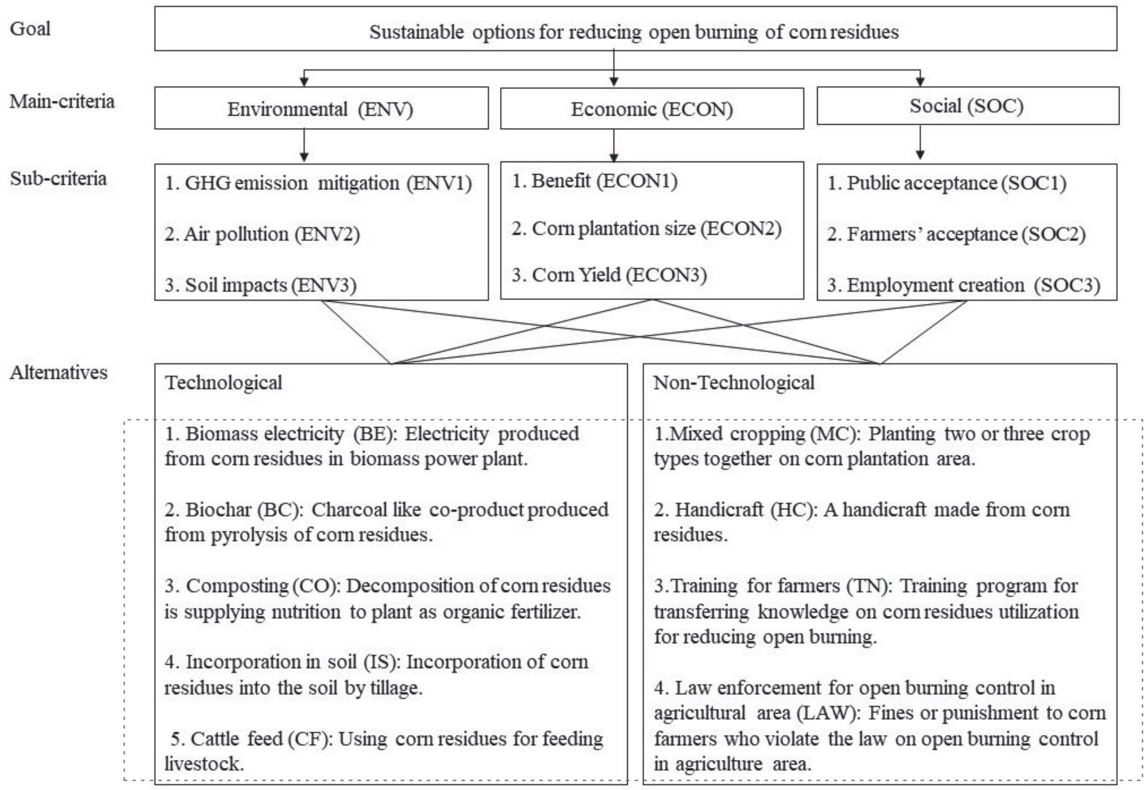

Fig. 1. AHP model used in this study (adapted from Ravindra et al. [10], Bartzas and Komnitsas [29]).

helps researchers define problems and structure main criteria, sub-criteria, and alternatives into a hierarchy of goals. Then, an assessment of the relative importance of the criteria is conducted by weighting the pair-wise comparison matrices of the alternatives with respect to the criteria [29-30]. The consistency ratio (CR) calculated by AHP shows each criterion's and alternatives' consistency [33]. AHP is a commonly used method in MCDA that allows a small group of experts (maximum 20 persons) to easily comprehend problems in terms of relevant criteria, sub-criteria and alternatives. The applications of MCDA are relevant to environmental management, stakeholder involvement, and area-based management. The advantages of multi-criteria analysis in assessing the sustainable options are: 1) experts who are working in various fields and having different goals can make a decision together; 2) qualitative and quantitative data can both be used as criteria; 3) weighting a pairwise comparison of criteria, qualitative data can be converted into numerical data [29-30]. The AHP in this study was structured by reviewing the literature on open burning and its impacts, and utilization of corn residues. The main criteria, sub-criteria and alternatives identified were based on current open burning situations in the study area and technologies available worldwide. AHP in this study is structured based on three pillars of sustainability which are environmental, economic and social components [34]. Three main criteria, nine sub-criteria, and nine alternatives (given explanation in Table 3 and Figure 1) are employed under the goal of identifying the sustainable options for reducing open burning of corn residues, which could have positive impacts of reducing environmental problems and enhancing economic and social benefits. The AHP model (as shown in Fig. 1) was then validated by 13 experts and policy-makers who specialized in the fields of environment, climate change mitigation in agriculture, air pollution, and energy. Experts involved in this study were 1) the Permanent Secretary Ministry of Natural Resources and Environmental, 2) the Chiang Mai Governor, 3) the Mae Chaem sheriff, 4) the Chief of Mae Chaem District Agricultural Extension Office, 5) the Director of the Provincial Office of Natural Resources and Environment, Chiang Mai, 6) the Director of Chiang Mai Provincial Agricultural Extension Office, 7) the Director of the Chiang Mai Energy Office, 8) the Director of Chiang Mai Disaster Prevention and Mitigation, 9) the Director of Chiang Mai Agriculture and Cooperatives, 10) the director of the Chiang Mai Farmers' Council, 11) the Manager of the Warm Heart Foundation, 12) a national expert on air pollution and 13) a national expert on climate change mitigation in agriculture.

Data Collection and Analysis

A set of questionnaires with pair-wise comparison matrices was used for interviewing the 13 experts. Then, the experts weighted and identified sustainable

Table 1. Definition of the AHP weights ranged from 1 to 9.

Numerical scale	Definition
1	Two elements are equally important (Equally important)
3	One element is slightly more important than another (Moderately important)
5	One element is strongly more important compared to another (Strongly important)
7	One element is very strongly more important over another (Very strongly important)
9	Absolute dominance of one element over another (Extremely important)

options for reducing the open burning of corn residues with respect to the main criteria and sub-criteria (as shown in Fig. 1). Next, the weights were calculated by converting them into numbers 1 to 9 (as shown in Table 1). The weights given by the experts were analyzed by using an AHP Excel template version 15.09.2018 initiated by Goepel [35]. The option with the highest weight was identified as the best option. Each of the criteria and alternatives were accepted when the consistency ratio (CR) was less than 0.10 (significance level of 10%). Consistency is the most critical issue in practical applications of AHP [36]. The three main criteria were environmental, economic, and social factors. Nine sub-criteria were three environmental sub-criteria (GHG emission mitigation, air pollution, soil impacts), three economic sub-criteria (benefit, corn plantation size, corn yield), and three social sub-criteria (public acceptance, farmers' acceptance, employment creation). Nine options for reducing the open burning of corn residues in the study were devised and separated into technological and non-technological options. Technological alternatives considered for reducing open burning of corn residues were biomass for electricity, biochar, composting, and incorporation in soil and cattle feed. Non-technological alternatives considered were mixed cropping, handicraft production, training for farmers and law enforcement for open burning control in agricultural areas.

Results and Discussion

Weighting Priorities of Main Criteria

Table 2 shows the results of the comparison matrix, weights, and consistency ratio of the main criteria with respect to sustainable options for reducing the open burning of corn residues. It shows that experts agreed that the environmental dimension was the most important criterion in choosing options for reducing open burning of corn residues. The environmental main criterion had the highest weight of 43.94%, followed by economic and social criteria, with weights of 31.18% and 24.88%, respectively. The three main criteria were consistent and acceptable, with a consistency ratio of less than 0.10. Many studies found that open burning of corn residues was a major cause of GHG emissions and air pollution, such as $PM_{2.5}$, $PM_{10,}$ and haze [6, 19, 37-38]. The Northern Thailand and Chiang Mai areas are affected by seasonal haze pollution from agricultural and forest fires throughout the open burning season, usually from January to April. This is a serious concern for the economy and health of local people [23-24, 39].

Weighting Priorities of Sub-Criteria

The local and global weights for sub-criteria were calculated based on the comparison matrices, as shown in Table 3. The local weights represent the relative scores of the criteria/sub-criteria in a group, e.g., environmental, while their global weights were obtained by multiplying the local weights with the global score of their corresponding group. The results show that the environmental criterion, air pollution (reducing air pollution from open burning of corn residues), is the most important sub-criteria with the highest local weight of 0.6580, i.e., sharing of 65.80% importance among environmental sub-criteria. GHG emission mitigation ranks second, followed by soil impacts with a local weight of 0.2135 and 0.1285, respectively. All nine sub-criteria were consistent and acceptable due to consistency ratios less than 0.1. Similarly, many studies found that reducing open burning of corn residues was a co-benefit in reducing greenhouse gases and other pollutants that limit the adverse impacts of climate change [10, 23-24], such as the trends of increasing temperature, decreasing rainfall, and prolongation of drought [40-41].

Table 2. Comparison matrix, weights and consistency ratio of main criteria with respect to sustainable options for reducing open burning of corn residues.

Main criteria	Environmental	Economic	Social	Weights	CR of main criteria
Environmental	1	1 1/2	2	0.4394	0.0238
Economic	5/6	1	1	0.3118	
Social	1/2	1	1	0.2488	

Table 3. Description, local weights, global weights and consistency ratio of sub-criteria.

Main criteria (Local weights)	Sub-criteria	Local weights	Global weights	CR of Sub-criteria	Ranking
Environmental (ENV) (0.4394)	GHG emission mitigation (ENV1): Reduction of GHGs emitted, such as CO_2, N_2O and CH_4 from open burning corn residues in the field.	0.2135	0.0938	0.0103	2nd
	Air pollution (ENV2): Reduction of air pollution (i.e., CO, PM_{10}, $PM_{2.5}$, OC and BC) from open burning corn residues in the field.	0.6580	0.2891		1st
	Soil impacts (ENV3): Open burning corn residues causes loss of soil organic matter and soil degradation.	0.1285	0.0565		3rd
Economic (ECON) (0.3118)	Benefit (ECON1): Benefits that corn farmers gained from selling corn residues or by-product of corn residues	0.3950	0.1232	0.0993	1st
	Corn plantation size (ECON2): Corn farmers' land holding size has positive effect on corn productivity and volume of corn residues.	0.3051	0.0951		2nd
	Corn yield (ECON3): Corn production is one of the factors affecting the economic performance of farms. It is measured by corn yield per hectares.	0.2999	0.0935		3rd
Social (SOC) (0.2488)	Public acceptance (SOC1): Public-accepted technology for reducing open burning of corn residues which does not present negative impacts to quality of people life.	0.2604	0.0648	0.0041	2nd
	Farmers' acceptance (SOC2): Farmers' acceptance of technology for reducing open burning corn residues.	0.4886	0.1216		1st
	Employment creation (SOC3): Employment created for corn farmers or local people after employing technology to reduce open burning of corn residues.	0.2510	0.0624		3rd

Based on the calculated weights assigned to economic criteria, the benefits that corn farmer gained from selling corn residues were ranked as the most important sub-criterion, with the highest local weight of 0.3950. Corn plantation size followed by corn yield with a local weight of 0.3051 and 0.2999 were identified as second and third under this sub-criterion. It shows that corn plantation size is related to corn yield. Similarly, Zimbabwe's farmers benefited from collecting and selling corn residues to the energy industry [42]. The corn residues generated on corn plantation in Mae Chaem were enough to supply the energy industry and to be converted to biochar, composting, and cattle feed as applied in Belgium, Greece, and India [4-7, 10, 29].

Among the social sub-criteria, the most important sub-criterion was the farmers' acceptance of options for reducing the open burning of corn residues, with the highest local weight of 0.4886. Public acceptance had a slightly higher weight than employment creation, with a local weight of 0.2604 and 0.2510, respectively. Attavanich [7] reported that farmers' acceptance of technology for reducing open burning is related to the technology adoption of corn farmers. Especially, corn farmers have the highest rejection of the technology for reducing open burning compared to rice and sugarcane farmers. Similarly, Supaporn et al. [9] found that farmers easily accepted the technology with low complexity to utilize crop residues. In the case of India, it was found that corn residues and their use in corn plantation areas as biochar, compost and incorporation in the soil were environmentally friendly and generated local employment, economic benefits to corn farmers, and acceptance by people [10]. As found in Mae Chaem's community enterprise, which was run by women corn farmers. This community enterprise created off-farm jobs for ten members and generated extra income of 12,000-20,000 THB/person/month from making handicrafts, such as artificial flowers, wreaths from corn residues and other natural materials from local agriculture [43]. Note that average Thai farmers have a monthly income of 15,000 THB/household [44].

Weighting Priorities of Technological Alternatives

The results of weighted comparisons and the consistency ratios of nine alternatives (5 technological alternatives and four non-technological alternatives) are presented in Table 4. The results show that all alternatives were consistent and acceptable due to

Table 4. Weights, consistency ratio and ranks of the alternatives for sustainable options for reducing open burning of corn residues.

Main criteria/ Sub-criteria	Alternatives for sustainable options for reducing open burning of corn residues										
	Technology					CR of alter-native	Non-technology				CR of alter-native
	BE	BC	CO	IS	CF		MC	HC	TN	LAW	
ENV	0.2449	0.2036	0.1953	0.1732	0.1828		0.4723	0.2368	0.1840	0.1048	
ENV 1	0.3076	0.2447	0.1438	0.1461	0.1578	0.0417	0.4540	0.2337	0.1991	0.1131	0.0386
ENV 2	0.2318	0.1971	0.2050	0.1706	0.1954	0.0147	0.4611	0.2522	0.1815	0.1051	0.0764
ENV 3	0.2084	0.1688	0.2310	0.2320	0.1597	0.0201	0.5756	0.1635	0.1718	0.0891	0.1024
ECON	0.3358	0.2531	0.1639	0.1099	0.1371		0.4792	0.2619	0.1610	0.0979	
ECON 1	0.3060	0.2710	0.1732	0.0863	0.1635	0.0465	0.4857	0.2822	0.1566	0.0755	0.0575
ECON 2	0.3799	0.2448	0.1367	0.1188	0.1198	0.0445	0.4767	0.2109	0.1942	0.1183	0.0218
ECON 3	0.3304	0.2382	0.1795	0.1318	0.1201	0.0124	0.4965	0.2575	0.1594	0.0866	0.0963
SOC	0.2376	0.2064	0.2204	0.1643	0.1710		0.4404	0.2713	0.1918	0.0966	
SOC 1	0.1974	0.1776	0.2372	0.2075	0.1802	0.0131	0.4529	0.2397	0.1684	0.1390	0.0938
SOC 2	0.1921	0.2134	0.2393	0.1700	0.1851	0.0198	0.4688	0.2517	0.1994	0.0801	0.0800
SOC 3	0.3671	0.2227	0.1664	0.1084	0.1345	0.0307	0.3722	0.3421	0.2014	0.0843	0.0136
Overall score (Global weight)	0.2727	0.2210	0.1932	0.1491	0.1643		0.4640	0.2567	0.1789	0.1000	
Rank	1	2	3	5	4		1	2	3	4	

consistency ratios less than 0.1, except for one non-technological alternative. Biomass for electricity (BE) ranked as the highest alternative technology for reducing open burning of corn residues with a priority of 27%, followed by the biochar (BC) of 22%, composting (CO) of 19%, cattle feed (CF) of 17% and incorporation in soil (IS) with the lowest priority of 15%.

Biomass for electricity (BE) was identified as the most important alternative technology that positively impacts the environment in GHG emission mitigation with a priority of 30.76%. In terms of economic impact, corn plantation size and production have positive impacts in supplying BE with priorities of 37.99% and 33.04%, respectively. In the social dimension, BE has a positive impact on creating employment for local people, with a priority of 36.71%. These findings are relevant to the case in Portugal in that biomass power plants are one of the few renewable energy sources that may be used as technologies contributing to the reduction of external energy dependency and greenhouse gas emissions [45]. A major problem for Mae Chaem is an unreliable electricity supply which leads to the low development of the city [5]. In Belgium, increasing the use of biomass power resulted in a secure energy supply [46].

The Electricity Generation Authority of Thailand (EGAT) found that corn residues available in Mae Chaem District have the potential to generate 3 MW of power. Corn farmers can supply corn residues as feedstock for electricity production. Biomass power plants can reduce greenhouse gases and pollutants from open burning by up to 99.9% and also can create jobs for local people [5]. One ton of corn residues (corn cob/ corn husk) can produce 1,089 kWh of electricity. The cost of energy production from corn residues is 0.074-0.147 Baht/MJ, which is cheaper than the energy produced from Natural Gas for Vehicles (NGV) and Gasoline (Benzene) which is 0.224 Baht/MJ and 1.019 Baht/MJ, respectively [4]. Using corn residues as an energy source presents an opportunity to reduce the pressure on electric system instability in compliance with sustainability criteria such as compatibility with the environment and climate, and social compatibility issues while offering comprehensive economic efficiency [46].

Biochar (BC) was also identified as the second most important technological alternative having a positive impact on the environment in GHG emission mitigation with a priority of 24.47%. In terms of economic benefits, corn farmers can benefit from selling corn residues while using biochar as a soil amendment in the corn field with a priority of 27.10%. In terms of the social dimension, biochar production can create employment for corn farmers and local people, with a priority ranking of 22.27%. Biochar (BC) was another important technological alternative that is suitable for reducing the open burning of corn residues in Mae Chaem. The pyrolysis of corn residues can burn the carbon compounds resulting in lower gas emissions and particulate emissions than the open burning of corn residues [47]. Producing biochar can sequester CO_2 at a ratio of 3:1 (sequestered CO_2: biochar). The conversion rate of corn residues to biochar is 25 percent. Corn farmers can sell biochar for 35 Baht/kg [48]. When corn farmers adopt and produce biochar, they can save transportation costs of corn residues out from their fields and gain more profit from corn production. However, the major challenge of biochar production in highland areas is that a large amount of labor is needed, which requires 45 man-min/m^2 for collecting corn residues and 15 man-min/m^2 for loading corn residues into a biochar kiln [47]. Applying biochar in the field not only improves soil properties but also promotes carbon sequestration, mitigates greenhouse gas emissions, reduces soil nutrient leaching, and improves corn yield, as reported in India and Greece [10, 49].

Composting (CO) was identified as the third important technological alternative that positively impacts the environment in reducing soil impacts with a priority of 23.10%. Regarding economic impacts, corn farmers can turn corn residues into compost and benefit from using corn residues as compost with priorities of 19.95% and 17.32%, respectively. In terms of the social dimension, composting is widely accepted by corn farmers with a priority of 23.93%. Open burning has causes soil erosion and a decline in soil fertility in Mae Chaem [6]. Crop residues have the potential for use as composting material. Decomposition of corn residues can supply nutrients to soil and plants. As per a study carried out by Lal [50] in the USA, Corn stover has 0.983% Nitrogen (N), 0.100% Phosphorous (P), and 1.504% Potassium (K) as major nutritional supplements for plants. Corn residues are widely used for composting by corn farmers, as reported in the rural USA and India [10, 50].

Cattle feed (CF) was identified as the fourth important technological alternative that positively impacts the environment in reducing air pollution, with a priority rating of 19.54%. Regarding economic impacts, corn farmers can benefit from turning corn residues into cattle feed with a priority of 16.35%. In terms of the social dimension, cattle feed is widely accepted by corn farmers with a priority of 18.51%, such as in the USA, where corn is the most important component of livestock feed. Although corn is lower in protein than other feeds, corn is an important source of protein due to the volume fed. Corn also contains important minerals and vitamins for animal nutrition. Genetic varieties have been developed that have enhanced nutritional value for livestock [51]. In Mexico, corn residues are often left in farmers' fields for in situ stubble grazing or are harvested for ex-situ use and used as green or dry forage (with various processing and feed supplements). In Mexico, by feeding cows with corn residue bales, farmers save cattle feed costs from buying hay diets at $131.67/ton [52].

On the other hand, incorporation in soil was identified as the fifth most important technological alternative that has positive impacts on the environment in reducing soil impacts with a priority of 23.20%. In terms of economic impacts, the volume of corn residues (calculated from corn yield) is appropriate for incorporation in soil, with a priority of 13.13%. In terms of the social dimension, incorporation of corn residues in the soil is highly accepted by the public, with a priority of 20.27%. Corn residues in Mae Chaem are available by more than 10 million tons per year [13]. As found in the USA, the application of crop residues incorporated with the soil at a rate of 6-8 tons per hectare (i) minimizes soil water losses such as soil water runoff and soil water evaporation; (ii) reduces soil erosion and its risk; (iii) enhances soil organic carbon in the soil; (iv) increases fauna, flora and soil microbials; (v) enhances soil structure and decreases soil compaction and (vi) improves and sustains soil water and its quality and quantity [50]. Incorporation in the soil is also widely adopted by farmers in rural India. Incorporation of corn residues in the field not only reduces the open burning of corn residues but also returns nutrition from corn residues into the soil. Corn farmers can save cost by applying less chemical fertilizer in the next crop [53].

Weighting Priorities of Non-Technological Alternatives

Mixed cropping (MC) was identified as the most sustainable non-technological alternative for reducing open burning of corn residues with a priority of 46%, followed by handicraft (HC) production of 26%, training (TN) of 18%, and law enforcement for open burning control (LAW) of 10%. Mixed cropping (MC) was identified as the most important in reducing soil impacts from open burning of corn residues. MC has positive effects on the environment, with a priority of 57.56%. In terms of economic benefits, corn yield was the most important for mixed cropping, with a priority of 49.65%. In the social dimension, farmers' acceptance was the most important for accepting mix cropping (MC) as a non-technological alternative, with a priority rating of 46.88%. Arunrat et al. [54] reported that MC was the most important non-technological alternative suitable for reducing open-burning corn residues in Mae Chaem. MC systems could bring more income to farmers and generate lower GHG emissions than planting a single crop.

Moreover, mixed cropping of corn with other vegetables results in less GHG emissions and pollutants from open burning than solely corn production [54]. Mixed cropping generated higher net profits than single-crop corn production [55]. In Zimbabwe, corn farmers who planted corn while raising cattle provided enhanced forage and increased corn yields by mixing the corn residue with cow dung [56]. Corn farmers can save on the costs of buying chemical fertilizer by mixing corn residues with cow dung in a ratio of 1:1 and leaving it in the open air. With this method, a ton of corn residues could generate 0.7 ton of organic compost [4].

Handicraft (HC) production was also identified as an important alternative non-technology that could have positive impacts on the environment in mitigating air pollution, with priorities of 25.22%. Regarding economic effects, corn farmers could benefit by selling HC produced from corn residues instead of open burning, with a priority of 28.22%. In terms of the social dimension, corn farmers easily accept HC, with a priority of 34.21%. Rural communities in Brazil, making HC products with corn residues for sale generated extra income and employment. Increasing handicraft products for domestic and foreign markets makes the activity very profitable [57].

Training for farmers (TN) was identified as the third important non-technological alternative that could positively impact on the environment in reducing GHG emissions and air pollution from open burning corn residues with priorities of 19.91% and 18.15%, respectively. In terms of economic impacts, training is appropriate with corn plantation areas in Mae Chaem with a priority of 19.42%. In terms of the social dimension, training can create employment for corn farmers with a priority of 20.14%. As was previously found, small-scale farmers often lack opportunities to access new knowledge and technologies. Training programs for farmers are needed to enhance farmers' knowledge and for improving agriculture practices [58]. There is a need to train farmers to adopt such eco-friendly approaches, which will also reduce the practice of open burning and improve the crop yields by making compost, biochar, incorporation in soil, cattle feed, and mixed cropping [10]. Trained farmers have achieved higher productivity and income than non-trained farmers [59].

Law enforcement for open burning control in agricultural areas (LAW) was identified as the fourth important non-technological alternative that could positively impact the environment in reducing GHG emissions and air pollution from open burning corn residues with priorities of 11.31% and 10.51%. In terms of economic impacts, LAW is appropriate with a corn plantation size as in Mae Chaem, with a priority of 11.83%. In terms of the social dimension, LAW is accepted by the public with a priority of 13.90%. Many countries have enforced LAW to reduce open burning. In Northern Thailand, the nation's largest corn plantation area, open burning is strictly controlled from January-April, with the goals of reducing greenhouse gas emissions, air pollution, and haze generated by open burning of corn and agricultural residues. However, the zero-burning policy should be expanded all year round to prevent the prolongation of open burning agriculture residues and the smoke haze situation [15].

Also, in the central Mexican highlands, laws have been implemented banning the open burning of crop residues together with the introduction of intensive farming. Therefore, slash and burn agriculture has decreased, and many farmers have shifted to intensive agriculture [60]. Similarly, China introduced laws to convert croplands to forests. China reduced GHG emissions and air pollution from open burning [34]. Thailand also has a no-burn policy implemented by the sugar mills, which has discouraged sugarcane farmers from pre-harvest open burning and prevented sugar mills from buying burned sugarcane. Farmers have also reduced open burning of sugarcane residues rather than facing punishment under the law or being fined [7]. However, major challenges for corn residue utilization were collection of crop residues, transportation [10], labor force availability and costs [9], high cost for enabling technologies, and unprofitable mitigation practice for farmers [34]. GHG emissions from open burning crop residues can be mitigated by policy regulation and by commercializing energy production using corn residues [10, 61]. The reduction in GHG emissions can also be traded, leading to co-benefiting energy generation and pollution mitigation [10]. Lastly, the government should provide infrastructure and knowledge [62], which is favorable for developing rural areas and corn farmers to overcome the open burning of corn residues.

Conclusions

This study aimed to identify sustainable options for reducing the open burning of corn residues in Mae Chaem, considering environmental, economic, and social aspects. Analytical Hierarchy Process (AHP) based multi-criteria decision-making approach was used to identify the sustainable options. The 12th National Economic and Social Development Plan (2017-2021) and Strategies in Climate Change and Agriculture Plan of Thailand (2017-2021) highlighted the importance of finding a solution to the open burning of corn residues. As highlighted by the experts in this study, sustainable options for reducing open burning of corn residues in Mae Chaem should prioritize mitigating environmental problems by first reducing air pollution. The most suitable technological option for reducing open burning of corn residues is biomass electricity (BE) 27%, followed by biochar (BE) 22%. While the most suitable non-technological option is mixed cropping (MC) 46%, followed by handicraft (HC) production 26%.

The findings of this study could be useful for Mae Chaem and Thailand to cope with the open burning of corn residues. The new policy should support corn farmers in enabling technologies for reducing open burning so that corn farmers can gain profit in mitigation practices. Moreover, the findings of this study support the plan of the Electricity Generation Authority of Thailand to build a biomass power plant using corn residues in Mae Chaem. Generating electricity using corn residues also improves energy security, lowering pollution and GHG emissions and creating employment for Mae Chaem. Moreover, effective policies are needed to be implemented to support corn farmers in Mae Chaem for 1) increasing the utilization of corn residues as biochar, that can increase CO_2 sequestration from air into the soil and improve soil properties, 2) increasing mixed cropping instead of planting only corn to generate more income for farmers and produce less air pollution from open burning of corn residues, 3) enhancing markets for handicraft and biochar production from corn residues, that can generate extra income for corn farmers and create employment in corn farmers' households. Mae Chaem could overcome the open burning problem by the implementation of the sustainable options identified in this study. Considering that the characteristics of the technological and non-technological alternatives may vary in other countries, the results obtained in this study may not be the same for the other countries but may be similar.

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Conflict of Interest

The authors declare no conflict of interest.

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