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# Criteria prioritization for the sustainable development of second-generation bioethanol in Thailand using the Delphi-AHP technique

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## Abstract

**Background:** The availability of underexploited agricultural residues in Thailand opens up the opportunity to supply second-generation bioethanol production. The national implementation of residues-to-biofuel can potentially boost the bioeconomy and greenhouse gas mitigation but requires the involvement of multiple stakeholders in the development of effective policy recommendations. This study aims to optimize the implementation of the national strategy through the use of a multi-criteria approach that involves participatory prioritization by current stakeholders in order to evaluate certain aspects and important indicators for second-generation bioethanol development.

**Methods:** The Delphi-AHP technique was used to analyze the degree of importance of different criteria. The evaluation process was conducted with various stakeholders and used a pairwise comparison of 4 dimensions (main criteria) and 12 indicators (sub-criteria). Participants were asked to rate factors related to technical feasibility, environmental impacts, economic feasibility and social impacts in terms of importance.

**Results:** Bioethanol stakeholders in Thailand from five different sectors (industry/business, NPO/NGOs, the governmental sector, academic/research institutes and financial institutions/banks) participated in the Delphi survey. The 20 experts' evaluation of the four dimensions ranked economic feasibility (32.7%) highest in terms of level of importance, followed by environmental impacts (25.1%), technical feasibility (24.9%) and social impacts (17.3%). When assessing the sub-criteria, the participants selected 'final price per liter', 'added value of input materials' and 'net energy balance' as the top three most important indicators among the 12 sub-criteria. In terms of a link between the preferred criteria and the participants' expertise, the results encouraged taking different backgrounds and affiliations into account in the policy planning phase.

**Conclusions:** The stakeholder survey indicated the importance of economic aspects, highlighting the need to take governmental driven policy into consideration. However, implementation scenarios have to be embedded in a broader range of aspects because all the dimensions were rated as being highly impactful. For future sustainable bioenergy, the inclusion of stakeholders' opinions can result in multifaceted scenarios that can be linked to social acceptance and benefits for all relevant players when developing policy recommendations for advanced bioenergy.

**Keywords:** Second-generation bioethanol, Stakeholder's perception, Delphi-AHP method, Participatory criteria prioritization

## Background

Thailand's greenhouse gas (GHG) reduction goal has prompted an urgent search for sustainable energy sources in its pursuit of effective GHG mitigation. Thailand

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signed on to the Paris Agreement at the COP21 meeting, committing to a 20–25% reduction in GHG intensity from business as usual by 2030 [1, 2]. A steadily increasing demand for energy leads to the need for a sustainable energy transition to stay within the greenhouse gas emission budget. Taking advantage of the country's agricultural products, Thailand is attempting to substitute the consumption of fossil fuels with bioenergy production from agricultural crops. At present, bioenergy production in Thailand consists of bioethanol and biodiesel. In particular, cassavas and sugarcane are cultivated for bioethanol production to provide biofuels to the transportation sector. The long-term promotion of bioethanol, supported by the Alternative Energy Development Plan (AEDP 2015), aims to produce 4136 million liters [3] by 2036, an increase of 157% over 2019 production volumes [4].

Thus far, this conventional bioethanol development has played a crucial role in decreasing the dependency on fossil fuels. However, along with the government's promotion of biofuels comes the controversial issue of expanding crop production for bioenergy. For instance, the higher need for crop cultivation results in stress on water consumption and competition with food production over land use [5, 6]. Due to limited yields per area, the national policy to promote bioethanol as a substitution for fossil fuels is projected to expand land use [7–9], which also affects land use for the cultivation of food and other crops [8]. Thus, the conflict between crop supply and increasing bioethanol demand needs to be taken into consideration if a sustainable, long-term bioethanol policy is to be achieved in Thailand.

Today, the sustainability of future bioenergy development is being scrutinized extensively. Although the conventional production of biofuel has admittedly provided the benefit of fossil fuel replacement, the widespread commercialization of the biofuel industry in recent decades has been inevitably associated with environmental side-effects involving conflicts over land use for the cultivation of food crops [5, 10, 11]. Researchers and stakeholders have recently paid more attention to pursuing a sustainable transition of bio-based products or bioenergy systems by addressing indicators from a holistic point of view based on the United Nation's Sustainable Development Goals (SDGs) [12–14]. An example of this framework can be observed in the policy of the European Union (EU), which has shown more concern for sustainability and environmental harmonization in the implementation of biofuels and bioliquids [10].

In terms of sustainability, one of the implementable concepts is the utilization of regional residual biomass resources (e.g., wood-based waste) as raw materials in bioenergy production or the wood panel industry

[15–17]. This strategy would not only produce environmental and economic benefits, investment in bio-based industries would also provide social benefits, such as increasing employment in local businesses, educational opportunities, and research projects to enhance innovation [13, 18, 19].

In the debate over sustainable resource use in the energy sector, agricultural residues are considered potential resources that can enable waste management and increase GHG mitigation in comparison with fossil fuels [20]. In addition, reusing agricultural residues in the energy sector would expand material flow streams, resulting in the potential reduction of waste generation, which also supports the concept of a circular bioeconomy [21–23]. In particular, bioenergy from lignocellulosic biomass has been shown to be beneficial in promoting the utilization of agricultural waste and saving land use alongside direct and indirect socio-economic benefits, such as food security [13, 24–26].

Agricultural residues are being generated and then left unused on farms across Thailand. The regional availability of biomass gives Thailand the opportunity to use them in the production of higher-value products. The cultivation of major crops, such as rice, sugarcane, cassavas and palms, has produced excessive amounts of agricultural residues [27, 28]. Nonetheless, the practical application of these agricultural residues is limited to primary utilization, such as animal feed, fertilizer, and as a raw material for electric power plants [29–32].

Against this backdrop, the dimensions for the successful implementation of second-generation bioethanol in Thailand are expected to be manifold. Apart from using biofuels in energy supply, which supports the concept of controlling land use expansion, utilizing leftover lignocellulosic materials is projected to mitigate the environmental impact of open field burning [33, 34].

Although the conversion of lignocellulosic biomass to bioethanol has been developed at the pilot level [21], the concept of utilizing agricultural residues for biofuel purposes has never been proposed to the stakeholders or considered at the policymaking level. In order to promote the commercialization of second-generation ethanol within the sustainable bioenergy framework, the crucial elements would involve decision-making based on the different backgrounds and complexities of the stakeholders. It is nearly impossible to solely take the factor of technological feasibility into account, as the production chain consists of several industrial and service branches such as agriculture, logistics, and at times production facilities [35].

When planning bioenergy development policies, aside from techno-economic feasibility, estimating the social and environmental impacts has become a vital concern

in determining the most sustainable system [36]. System optimization must be taken into account from an environmental perspective; however, it may come into conflict with technical or economic development [37, 38]. Therefore, instead of approaching from only a single dimension, which may lead the decision-making to be coupled with risks, conflicts, and trade-offs [39], the impact of multi-dimensional aspects must be evaluated and selected based on the perceived concerns of the stakeholders. In this regard, multi-criteria decision analysis (MCDA) becomes a functional tool for dealing with multi-disciplinary objectives. The MCDA approach allows the decision-making process to be conducted on the basis of a reconciliation of different perspectives [36, 40]. Policymaking needs to coordinate the support from the science and commercial sectors with the support from public organizations. This approach is believed to create process transparency [41]. There are several types of MCDA tools that can be used to support complex decision-making, such as the analytic hierarchy process (AHP), TOPSIS and PROMETHEE, which can be applied for different purposes [42]. Even though numerous studies have conducted MCDA in the field of bioenergy assessment [38], to the authors' knowledge, second-generation bioethanol production in Thailand has not yet been evaluated by eliciting stakeholder opinions through a participatory assessment. The novelty of this study is the incorporation of expert perspectives in the system evaluation of advanced bioethanol production.

#### **Foreseeable constraints of first-generation bioethanol implementation in Thailand—a literature review**

Promoting bioethanol development in Thailand benefits the transport sector by, among other things, lessening its dependence on imported fossil fuels. Thailand has been examined with respect to the availability of agricultural crops that could potentially be used to secure its energy supply [43]. Since 2004, commercialized bioethanol has seen constant growth due to policies that foster production and consumption. However, Thailand's bioethanol development plan and policy, namely the Alternative Energy Development Plan (AEDP, 2015–2036), has barely integrated the socio-economic dimension since it involves crossing-disciplinary fields and authority from governmental organizations.

Instead of achieving fossil fuel replacement, the long-term policy is prone to encounter constraints for several reasons, which may become roadblocks for the bioethanol development policy in Thailand in the future. In a study by Chanthawong et al., a multi-criteria evaluation conducted with relevant stakeholders in the biofuel market revealed their perceptions of the current bioethanol policy implications [9]. Although the participants agreed

that Thailand's bioethanol policy supports the country's energy security, the approach used to promote biofuels still lacks a concrete strategy for improving the management of crop cultivation as part of the long-term development goal. Limited farmland represents a bottleneck in stabilizing biofuel supply sources required to meet the production goal in the future. In addition, the prices of raw materials, as well as the production costs are considered significant influences. Since biofuel production mainly depends on the crop price, a fluctuation in the feedstock price is a worrying issue that the government needs to tackle.

Relating to the issue of instability of raw material prices, the biofuel pricing mechanism in Thailand is based on a subsidization system [43]. The stakeholders of bioethanol businesses projected that demand can still grow steadily as long as there are incentives to drive this demand, such as compulsory blending, tax cuts and subsidies [9]. These subsidies are collected from non-biobased fuels as oil funds. The oil funds are the instrument for stabilizing the retail price of bioethanol blended gasoline, which also encourages the consumption of biofuels by maintaining the discount for users of bioethanol blended gasoline types E20 and E85 (20% and 85% ethanol blending rates, respectively) [43]. Nevertheless, the reliance on government subsidies has also been criticized as a cause of the distortion of the actual price which could have a long-term negative effect on the market [44]. By controlling the retail price for consumers, the lower price of gasoline is likely to increase energy consumption [44, 45].

Apart from the issue concerning the market mechanism for biofuels, policymaking has been unclear regarding the sustainable strategy of bioethanol development. In a study by Lecksiwilai et al., the lack of attention to the environmental impacts stemming from the current policy was highlighted as being an urgent topic that needs to be addressed [46], especially with regard to land use change as a result of an increase in agricultural production [8]. Since the crop yields of sugarcane and cassavas have not gone up significantly in recent decades [47, 48], future scenarios are likely to induce increased land use for crop cultivation in order to reach ethanol production targets [8, 49]. While land use changes to expand cultivation areas must deal with CO<sub>2</sub> extracted from soil carbon stock [8, 50], enhancement of crop yields, which was contemplated as a possible solution under land use restrictions, might demand a higher input of fertilizers and pesticides. Consequently, the expected limited crop yields would decrease the GHG mitigation effect of the biofuel, resulting in environmental trade-offs from life cycle GHG emissions [8, 46]. In addition, the cultivation of cassavas and sugarcane is associated with an intensive water footprint per ton of crop production. Investigations

have found that the water footprint of a cassava plantation requires twice as much water as a sugarcane plantation [51].

The current policy also has to deal with a socio-economic aspect. As part of the traditional practice of sugarcane plantation, agricultural residues are managed by field burning [52, 53]. To prepare the fields, sugarcane residues are burned at the end of each cultivating season and before the start of a new round of cultivation. This procedure impacts not only the environment, but is also disadvantageous to the health of the farm workers who are directly affected [54]. In terms of the agricultural labor system, fluctuating crop prices result in unstable incomes for farmers, and unequal protection by national labor laws affect the quality of farming jobs. Thus, it is not an overstatement to claim that the bioethanol policy affects several dimensions which need to be evaluated for sustainable, long-term development [55].

The information provided by the studies mentioned above reflects the existing issues and prospective barriers in the bioethanol policy in Thailand, particularly in terms of feedstock supply. Exploring a substitution to the conventional feedstocks is recognized as a promising option, especially with respect to the available agricultural residues [26, 27]. The utilization of lignocellulosic biomass for second-generation bioethanol has shown to reduce the effect of GHG emissions based on the ethanol conversion potential [34, 56]. The future of residues derived from crop plantations is optimistic due to their availability, the fact that they are a non-food material, and the promising results they achieve with respect to GHG reduction [57]. Nonetheless, an assessment of the studies conducted thus far affirms that production cost is the primary constraint that still needs to be tackled before they can be developed into an advanced biofuel on a commercial scale [58–60].

### Objective of the study

When the drawbacks and possible constraints of the current first-generation bioethanol technology are taken into consideration, transitioning from conventional ethanol production to the second-generation technology shows promising solutions. During the policy planning process for advanced bioethanol development, aside from technical and economic viability, estimating the social and environmental impacts is vital for identifying the most sustainable system [36]. The commercialization of the advanced biofuel technology involves many uncertainties, multi-disciplinary aspects, standards and measures, as well as relevant stakeholders, such as the crops growers, private firms, governments and end-product users [38, 61, 62].

The decision-making process inevitably causes trade-offs between organizations and players as it must take multi-dimensional aspects into consideration. Therefore, when proposing a policy framework for the development of second-generation bioethanol that can maximize the benefits for the majority of the stakeholders, the alternative system should comprehensively consider multi-disciplinary aspects and the bottom-up opinions collected from the actual organizations in the bioethanol value-chain.

The objective of this study is to address the following research question: what main criteria, sub-criteria and concerns should be focused on when creating the second-generation bioethanol policy in Thailand? The priority of indicators and the prioritization weights are expected to represent the main topics and preferences that bioethanol stakeholders are encountering at the current stage. The results of the criteria prioritization by the stakeholders from this study will be incorporated in the scenario analysis as further study steps to determine the consensual sustainable strategy for developing the policy framework for second-generation bioethanol. This can potentially reduce conflicts in the decision-making process.

Consolidating the different viewpoints of the stakeholders from various branches by applying the Delphi-AHP method in the context of second-generation biofuel policy in Thailand is considered a novelty. This approach provides the stakeholders with the opportunity to reflect on their insights, which can be used in the development of the second-generation bioethanol policy. The stakeholders are also given the opportunity to rethink their preferences from the first survey round. By following the Delphi-AHP method, it is expected that policymakers will be able to objectively implement the efficient and justified indicators in their policy design since the technique employs expert opinions and there is a lower degree of panelist confrontation. All divergent perspectives are included and interpreted to produce mutually agreed outcomes through the process of repetitive response.

## Methods

### Integrated approach of Delphi-AHP

#### Delphi survey

To achieve a collective policymaking decision from the stakeholders' perspectives, the current study applied the Delphi technique when conducting the survey. The Delphi technique was first developed by the RAND Corporation in the 1950s for use in a military project [63]. The original concept of the Delphi technique is to attain a convergence of opinions from participants with a range of knowledge and experience. This technique encourages independent opinions without the dominance of



other perspectives as is likely to occur in surveys conducted with a physical panel. The fundamental feature of the process used in this study is the transparency of the answers among participants and the repetition of survey rounds based on the disclosures in order to reach a consensus point [64].

Linstone and Turnoff described the Delphi method as a way to effectively facilitate group communication between a diverse group of professionals in order to achieve the study objective [65]. Anonymity during the survey minimizes the effect of being influenced by other participants, something which commonly happens in a group brainstorming session [65]. Nonetheless, as mentioned by Gordon and Pease, the objective of Delphi is not necessarily to obtain a consensus [66]. In addition to the convergence of opinions, the process of collecting responses can contribute insightful ideas to the main objective. At present, the Delphi survey is a useful tool that has been developed in a wide range of areas, for instance, Delphi for upcoming technologies [67, 68], Delphi for policymaking [69], and Delphi for problem-solving [70].

#### Analytic hierarchy process (AHP)

An evaluation of cross-dimensions and indicators inevitably involves trade-offs. The analytic hierarchy process (AHP) is a form of multi-criteria decision analysis (MCDA) which is a functional tool for dealing with various indicators and selecting alternative scenarios for strategic planning [71]. The AHP was initially developed by Saaty, being used broadly in the policymaking process [72]. It is a type of value measurement model that helps decision-makers prioritize their preferences for set alternatives and criteria using a scoring system. The criteria are compared two at a time and given weights based on levels of importance or preferences [72]. The method results in relative weights for each specific criterion that shares the same goal of the study [73]. In our study, there is a hierarchical structure of alternatives and criteria which are categorized under main criteria and sub-criteria.

According to the steps of the AHP, the relative weights between the set criteria can be classified on two levels: global weights and local weights [74]. In the context of this study, the local weights refer to the relative weights of main criteria and relative weights of the sub-criteria that fall under the respective main criteria, whereas the global weights represent a comparison of all sub-criteria weights across the categories of the main criteria. The global weights of the sub-criteria are the values of the local weights of the main criteria multiplied by the values of the local weights of the sub-criteria in the same category. The local weights of all main criteria and the

sub-criteria under the each of the main criteria equal 100%. For the global weights, the total value is also 100%.

#### Preparing and conducting the survey

The workflow of the survey and data analysis is summarized in Fig. 1. The steps mainly comprise survey planning, designing the questionnaire, structuring the expert panel, the Delphi survey rounds and consensus.

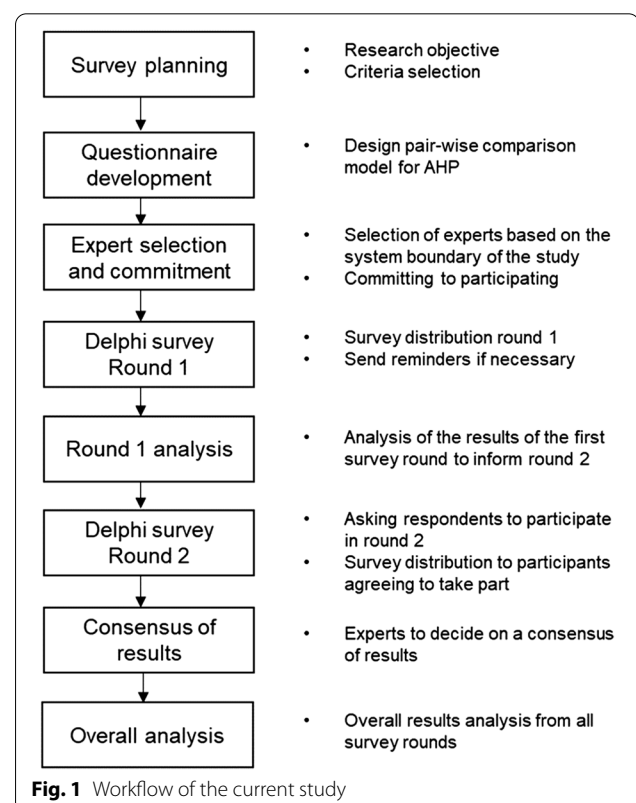
#### Survey planning

The first step was to develop the research question in line with the objective of the study. This step also included a literature survey to find a relevant set of sub-criteria and to sort these under the main criteria of technical, economic, environmental, and social aspects. The criteria fell within the system boundaries—from sources of agricultural residues to ethanol production.

#### Designing the questionnaire

Following that, the format of the questionnaire was designed to let the respondents rate the level of importance of the main criteria and sub-criteria by comparing two different indicators based on the AHP pairwise comparison method with 9 levels of importance [72].

In addition to comparing the criteria, the questionnaire also asked the experts to freely express their opinions and



raise other concerns. The sample questionnaires for criteria comparison are presented in the supplementary information section (Additional file 1).

### Structure of the expert panel

As the objective of the study was to guide the direction of policymaking in the implementation of second-generation ethanol, the panel was structured to reflect diverse points of views in order to obtain opinions and concerns based on a range of expertise, responsibilities and organizations. Principally, the specialists do not acknowledge one another in order to avoid interference between respondents.

Experts were invited to participate in the survey who had experience in the field of bioethanol production and other topics related to the bioethanol supply chain that corresponded to the system boundaries of the assessment in this study. These included biomass feedstock providers, ethanol producers and energy corporations as purchasers of bioethanol. The experts were systematically selected from five distinct types of organizations: (1) governmental sector; (2) business sector; (3) non-profit or non-governmental organizations; (4) academic or research institutes and (5) financial institutions and banks. However, since the governmental sector works closely as a facilitator and regulator of the private sector, it is more familiar with the essential policymaking. Therefore, the governmental experts made up the major proportion of the expert panel.

### Delphi survey rounds and consensus

In the first round, the Delphi surveys were distributed to the targeted experts. After gathering all scores from the participants, AHP was applied to calculate the weight

of the criteria and to establish the level of importance. The main criteria and sub-criteria in the same hierarchical levels were ranked using the equations presented in the section “Analysis of the survey data using the AHP method”. Next, the results from round one of Delphi-AHP were distributed to the participants. The results compiled from the first round of the survey were arranged into charts and tables for better visualization and integrated into the questionnaire used in the second round. In round two, an additional question was added to confirm the participants willingness to modify the answers. The experts were informed of the preliminary results in order to provide the opportunity to participate in the second round of the survey. After each round, the participants were asked to consent to the results or re-evaluate the survey. Based on the principles of the Delphi survey, showing the experts the results from round one would encourage them to revise their judgements from the earlier survey round [75].

### Criteria selection

The criteria in this study were selected from the publications related to the field of energy analysis, as summarized in Table 1. The goal was to prioritize the criteria that should be focused on for second-generation bioethanol. The scores derived from the ranking of criteria become parameters in the system analysis for proposing policy recommendations around second-generation bioethanol.

The criteria were selected based on the principle that they are independent of one another, but correspond to the goal of the study. The criteria scores contribute to the scenario study as a further step of the research. The set of criteria relatively affects the results of the multi-criteria

**Table 1** Sets of indicators used to evaluate bioenergy application

Main criteria	Sub-criteria	Units	References
Technical feasibility	Biomass availability and collectability	$\text{Kg ha}^{-1} \text{y}^{-1}$	[76–78]
	Ethanol productivity	$\text{Liters kg}^{-1}$	[79, 80]
	Biomass logistics	$\text{Ton day}^{-1}, \text{km}^2 \text{day}^{-1}$	[81–83]
Economic feasibility	Net present value	US\$	[84–86]
	Final price per liter	$\text{US\$ liter}^{-1}$	[42, 87]
	Added value of input materials	$\text{US\$ ton}^{-1} \text{y}^{-1}$	[88–90]
Social impacts	Job creation	$\text{Persons y}^{-1}$	[26, 91, 92]
	Food security	$\text{US\$ tons crops}^{-1}, \text{Tons ha}^{-1} \text{or Kcal capita}^{-1}$	[6, 93, 94]
	Change in household income	$\text{US\$ y}^{-1} \text{or US\$ household}^{-1} \text{y}^{-1}$	[95–97]
Environmental impacts	Indirect land use change	$(\text{Biomass growing capacity}) \text{ha}^{-1} \text{y}^{-1} \text{or kg CO}_2\text{-eq} (\text{biomass growing capacity})^{-1}$	[98, 99]
	GHG balance	$\text{Tons CO}_2 \text{equiv. y}^{-1}$	[100–102]
	Net energy balance	$\text{GJ ha}^{-1} \text{y}^{-1}$	[103–105]

decision-making outcomes. To achieve the goal of this study, the set of criteria constituted technical, environmental, economic, and social aspects. The indicators covered aspects from cradle to gate, ranging from farm areas to ethanol production as boundaries in this study.

The criteria selected for this study had to be quantitative factors that could be processed in the MCDA. The aspects to be studied were categorized into four main criteria, each of which were divided into three sub-criteria. This provided a total of 12 sub-criteria to be evaluated. A simple illustration of the hierarchical structure is shown in Fig. 2. Pair-wise comparisons were performed in the same hierarchical level, meaning that the main criteria were pairwise compared among the four main criteria. Meanwhile, the participants were asked to conduct pair-wise comparisons of the sub-criteria among the sub-criteria that fall under the same main criteria.

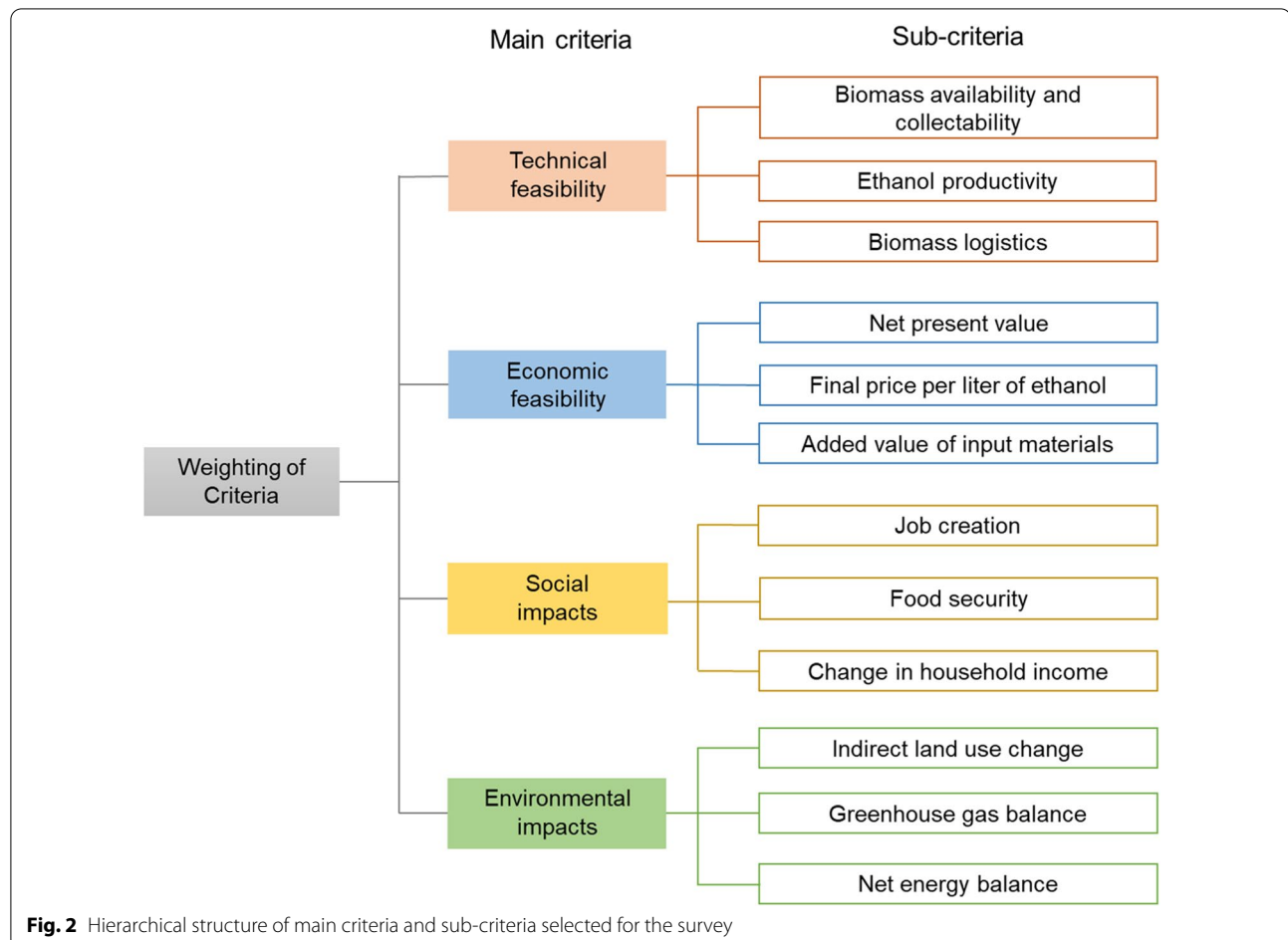
#### Technical feasibility

Second-generation bioethanol has undergone technical improvements in line with the development of commercialized production in recent decades [21]. Nevertheless,

the potential of this advanced technology has to be verified in the context of Thailand. First, biomass availability is a criterion that determines whether enough agricultural residues are being generated to sufficiently supply the production units. Moreover, the availability of input materials indicates where potential facilities can be installed and determines production capacities [76, 77].

Next, to verify input material potentials, ethanol conversion efficiency from the available feedstocks needs to be taken into consideration. The ethanol productivity from lignocellulosic materials plays a major role in evaluating cost benefits [106] since ethanol conversion efficiency can be lower due to the constraints caused by the complex structures of lignocellulosic components [107]. Therefore, the conversion process is tied to higher operating costs and requires more input energy than conventional production [58].

In terms of the elements related to the production boundaries, biomass logistics is a key factor in assessing technical feasibility. This factor refers to distances and transferable amounts of biomass from the supply areas to the ethanol production facilities and the end-use stations.



Logistics also involves harvesting, collecting, baling, and handling [107]. The logistics system interconnects the sources of the feedstocks and the bioenergy industry and is directly connected to the size of the production units, plant location, transportation system [81, 108]. In addition to the conversion of the feedstocks to energy, which influences the production costs, logistics management can optimize plant scales and establish the location based on the optimal distance from the supply site. This can minimize costs [82, 83].

### **Economic feasibility**

Three indicators examined in this study that fall under economic feasibility include 'net present value (NPV)', 'final price per liter', and 'added value of input materials'. NPV indicates the profitability from future cash flows during the lifetime of the investment after subtracting the present value. It is a parameter used to analyze the attractiveness of a project investment [84, 109]. NPV can be calculated from the expenses generated from all elements in the production chain, such as the capital costs from equipment installation, and the operational costs from biomass management and production [84]. An estimated price of ethanol, including all costs in the supply chain, is also needed to determine the project's feasibility.

The final selling price can be referred to as the structure of the minimum ethanol selling price. Principally, the final price of biofuel is made up of the costs of the raw material and production process under the condition of a 10% internal rate of return (IRR). The production cost of bioethanol from lignocellulosic feedstocks comprises the capital costs of the production plants and the operational costs. Even though cellulosic raw materials cost less than conventional sugar- or starch-based biomass [110, 111], the competitiveness of second-generation bioethanol has always been lower than first-generation bioethanol in terms of economic viability, especially due to the cost of the conversion process which includes cellulase enzymes and microbes for fermentation [24, 112]. Nonetheless, in terms of the bioethanol retail price in Thailand, there are several elements which stimulate the growth of bioethanol on the market, for instance tax exemptions and subsidies [43]. Currently, the price of ethanol in Thailand has not been regulated by the government but rather determined by the actual ethanol trading price between ethanol manufacturers and oil traders [113].

In addition to an economic analysis of the production process, the possibility to extend the added value of input materials is also a crucial factor to consider. Conversion of biofuel from residues has a high value-added potential depending on the type of input material and output product. The added value of the biomass from conventional production can increase through technological

development [88, 114]. Compared with the biofuel produced from energy crops, utilizing lignocellulosic biomass as an input material for higher added value was found to provide more economic and socio-economic benefits, such as increasing employment rates [115]. In recent years, industrialized ethanol production from lignocellulosic biomass has shifted from only ethanol production to value-added co-products. For example, lignin plastic composite materials can be derived from the fermentation process of the residual by-products in parallel with biorefinery production [116].

### **Social impacts**

The social benefits and drawbacks for locals should be taken into consideration when implementing production plant projects by referring to influential indicators for policy implications [91]. The criteria under this topic are selected based on social impacts, including 'job creation', 'food security', and 'change in household income'. Brinkman et al. found that macroeconomic impacts, such as income and employment rates, are often used in the field of bioenergy [117].

Job creation can relate to several indicators, such as employment rate, income generated, and the ratio of skilled/unskilled laborers [117]. Commonly, job creation is the key indicator used in socio-economic assessments [26, 71, 118], which is conducted as a bottom-up analysis by depicting the production process [117]. The model of decentralized production plants is an especially attractive scenario for creating higher employment rates and is beneficial for regional development [59]. Factors such as job creation and added value are also important when evaluating the bioeconomy since an enhancement of the bioeconomy potentially increases the value added per person due to improvements in labor productivity [115].

When the production of food crops is linked to non-food purposes, it is necessary to take food security into account. The increase in biofuel demand has led a rise in the price of maize. This has affected the proportion of grain production for the food industry which has become smaller due to the expansion of land use [119]. The parameters related to food security imply that inhabitants are adequately supplied with food within their physical, social, and economic means. The indicators are associated with, for example, sufficient food availability, changes in areas for food crops, food accessibility, reasonable prices, and sufficient calorie intake [93, 119]. Utilizing agricultural residues is expected to lessen the conflicts with conventional counterparts over food price competition from land use [120].

Another important variable in the study of the socio-economic aspects is household income. This indicator is used to monitor economic growth as part of sustainable



bioeconomy development [16]. Household income can be used to indicate equality by evaluating the income distribution in the rural and urban areas, since a diversity of income exists, particularly in developing countries [95]. In the case of conventional bioenergy, agriculturally oriented households are motivated to shift to producing energy crops by the biofuel policy and by the prospective household income [121]. In contrast, for advanced bioenergy projects, the expected incomes rely significantly on jobs in plant construction, plant operation, and plant capacities [122]. Moreover, the process of collecting agricultural residues would be a favorable incentive for local crop producers, as it might provide additional income in addition to crop cultivation [123].

### **Environmental impacts**

Promoting biofuels is an effective way to replace fossil fuels; however, extensive production and consumption generate several adverse effects, including expanded land use and GHG emissions [49, 124]. Environmental indicators are prioritized in our study with the aim of achieving a sustainable development of bioenergy. Three parameters, namely 'indirect land use change (iLUC)', 'net energy balance' and 'greenhouse gas (GHG) balance', were selected for the survey.

The iLUC indicator is widely used in the evaluation of biofuels since it is a direct indicator of the consequences of shifting cropland activities to target bioenergy production. This indicator is more complex than direct land use since the evaluating method includes areas surrounding the monitored biomass production [98]. In the case of cultivation land in Thailand, the land used for bioenergy production mainly expands by displacing other existing forms of crop cultivation. Risks associated with iLUC have been investigated with respect to the current bioethanol production from cassavas and sugarcane and compared to fossil fuels. The study revealed that GHG emissions per liter from conventional feedstocks were around 40–80% of those emitted from fossil fuels after taking iLUC into consideration [99].

In terms of energy analysis, net energy balance is a parameter used to assess environmental impact and indicates how efficient the bioenergy production process is. Accordingly, it can be applied by way of a life cycle assessment to evaluate CO<sub>2</sub> balance [125]. This indicator defines the comparison between required input energy and achievable ethanol to measure the positive or negative outcome. It takes into consideration the process of converting raw materials into ethanol, which varies heavily with respect to primary energy consumption. Along with the flow of energy input–output, the process not only directly involves CO<sub>2</sub> emissions but also cost factors, which can determine a project's feasibility [85].

Net energy yield has also been analyzed in terms of gross energy yield per area as evaluated by Vries et al. The assessment helps select adequate bioenergy production resources that provide the highest net energy yield [103]. However, the value is not limited to energy per area as it also involves energy factors required during the production process, such as farm machinery, fertilizing systems and product transportation [85, 103]. Referring to the investigation by Mishra et al., bioethanol production from wheat straw resulted in a positive net energy ratio greater than 1 (NER > 1) [126]. Nonetheless, the study remarked that the NER could be offset depending on the type of energy consumed in the process.

The GHG balance refers to the reduction of GHG emissions throughout the production phases, which relies on various factors, such as types of fossil fuels and fertilizers used in crop cultivation [100]. GHG balance has been attractive to researchers studying conventional bioenergy since it shows the negative balance (input > output) from energy crop cultivation and soil carbon sequestration [96]. In addition to the GHG emissions from land use change, the life cycle CO<sub>2</sub> from farm to end-product is a factor for comparing CO<sub>2</sub> mitigation between conventional biofuel production and fossil fuels since the types of fuel used as an input energy influence the total GHG balance [101]. Meanwhile, it is now possible to reduce output GHGs by generating co-products in the biofuel production system [127].

### **Analysis of the survey data using the AHP method**

After retrieving quantitative and qualitative opinions from the participants of the Delphi survey conducted as part of this study, AHP is applied to interpret the subjective opinions and systematically transform them into objective information. AHP is a tool that helps make decisions from complex sets of alternatives to reach the goal of multi-attribute decision-making [128]. It enables the complexity of a variety of quantitative data to be reduced down to one-dimensional figures. According to Saaty, the AHP method is usually performed in two steps: creating the hierarchical structure and rating the elements through pairwise comparisons [72].

Using the provided rating scores, the criteria were compared two at a time based on the degree of importance in line with definition as shown in Table 2. Since the format of criteria weighting was designed so that participants could rate the criteria by selecting a degree of importance from multiple choices (Additional file 1), the criteria and rankings needed to be converted into the matrix A, as described in Eq. 1, in order to process the data according to AHP. If the respondents prioritized the criteria listed in the left-hand column more than the criteria in the right-hand column, the scales of

**Table 2** Scales of importance for use in a pairwise comparison

Level of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	The scores used when compromise is needed

1–9 were filled out in the matrix  $A$ , indicating elements  $a_{ji} = \{1, 2, 3, \dots, 9\}$ , to specify that left-hand criteria in matrix  $A$  were more important. Conversely, if the scores were located towards the right-hand column in the form of the questionnaire forms, then the left-hand criteria in matrix  $A$  were ranked less important. Thus, the reciprocal numbers;  $a_{ji} = \{1, 1/2, 1/3, \dots, 1/9\}$  have to be placed for restructuring.

Matrix  $A$  is structured from  $n \times n$  criteria as presented in Eq. 1.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2j} & \dots & a_{2n} \\ \dots & \dots & \ddots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & \dots & a_{ii} & \dots & a_{in} \\ \dots & \dots & \dots & \dots & \ddots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nj} & \dots & a_{nn} \end{bmatrix}, \quad a_{ij} = 1/a_{ji}, \quad a_{ii} = 1 \quad (i, j = 1, 2, \dots, n). \quad (1)$$

Then, matrix  $A$  is converted into a normalized matrix in order to calculate the relative weights from the same level of criteria that reflect the preference scores as provided by the experts. Matrix  $W$  is a normalized pairwise matrix of matrix  $A$ , produced by dividing each value in the same column by a sum of the factors in the respective column. The step of normalization is the calculation of the results of the relative weights, where all the elements add up to 1.

$$w_i = \frac{\sum_{j=1}^n a_{ij}}{n} \quad (i, j = 1, 2, \dots, n), \quad (2)$$

$$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} \quad (3)$$

where  $W$  refers to the eigenvectors.

$$\bar{W} = \frac{W_i}{\sum_{j=1}^n W_j} \quad (j = 1, 2, \dots, n). \quad (4)$$

The weighted sum vector ( $\bar{W}$ ) can be quantified by calculating the eigenvector as shown in Eq. 4. The derived values of each element from the same column indicate the relative weights of the criteria included in the matrix. The steps for calculating the normalized matrix can be

referred to in previous studies [129, 130].

In addition to calculating relative weights, the calculated results need to be examined for consistency to verify the reliability of the data. The following steps verify the AHP consistency.

$$\lambda_{\max} = \sum_{j=1}^n \frac{A \bar{W}_j}{\bar{W}_i}, \quad (5)$$

whereby  $\lambda_{\max}$  is the maximum eigenvalue that can be obtained from the average values in vector  $\bar{W}$  of matrix  $A$ :

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)}, \quad (6)$$

$$CR = \frac{CI}{RI}. \quad (7)$$

When  $n$  indicates the size of the matrix, then in this study,  $n=4$  for the main criteria and  $n=3$  for the sub-criteria. Consistency index (CI) and consistency ratio (CR) can be determined by Eqs. 6 and 7, respectively. The latter value can be calculated using the random index (RI) as described in Table 3, which was identified by Saaty and is based on the matrix size ( $n$ ). An acceptable CR for rational decision-making should be lower than or equal to 0.1 [72]. Even though the consistency can identify the reliability, due to human-based judgement, it is highly possible for the data to become inconsistent. In particular, larger numbers of criteria can result in inconsistency. As a result, in some cases, such as in a group evaluation, a CR between 0.1 and 0.2 is also acceptable [131]. Otherwise, exceeding the CR suggests the criteria comparison should be performed again.

After the CI and CR have been shown to prove the validity of matrix A, the local weights and global weights can be derived by calculating the weighted sum vector as described in Eq. 4. Firstly, the local weights are determined from the criteria in the same hierarchical level, meaning that the main criteria and sub-criteria which fall under the same category of main criteria are calculated in terms of their local weights. Next, the local weights derived from the main criteria are multiplied by the local weights of the sub-criteria that belong to the same category in order to produce the global weights. The global weights are the final weighting scores, which are crucial for an overall comparison of cross-dimensional sub-criteria.

Because the allocated number of panelists in each group was not equal for all sectors, an arithmetic average was calculated for the individual responses. This step was conducted within each organization group before

calculating the overall mean values for all participants, as previously shown in the studies of expert participatory evaluations [129, 132].

In addition to the set of criteria indicated in the pairwise comparison matrix, this study provided more opportunities for experts to select additional points of concern and to suggest supplementary criteria that are considered important in the respective context.

## Results

### Expert panel

In the first round of the survey, a total of 20 respondents from 29 contacted targets consented to participate in the survey. After informing the participants of the results of round one, the surveys were sent to the participants in round two, with 16 respondents (80%) returning their responses. In the second round of the survey, three participants opted to modify their answers from the first round based on the overall results presented to them. Due to the marginal number of re-evaluations in the second round, we decided not to conduct further rounds of the survey. The number of survey rounds tend to vary, but are on average two to three rounds [133]. Many studies stop at the second round [128, 134]. The ratio of respondents who modified their responses in the second round of our survey is comparable to previous Delphi-AHP ratios [135].

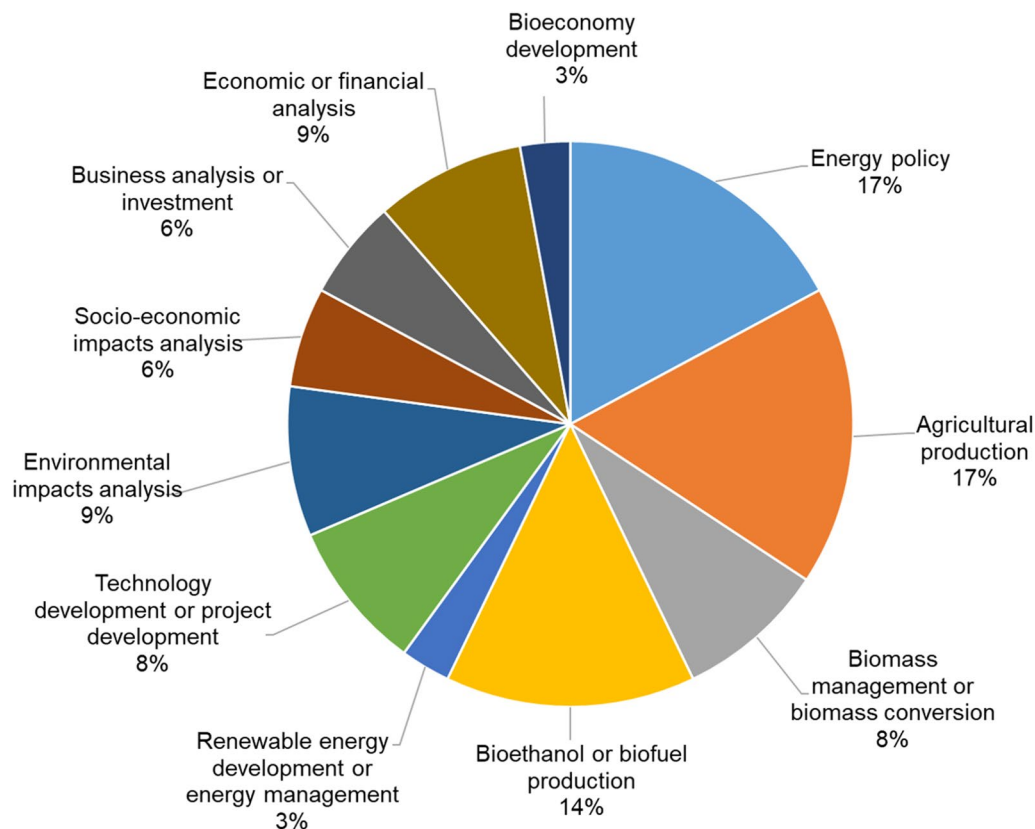
Even though the results of the survey did not differ significantly between round one and round two, further comments and topics were suggested. The participating organizations and the number of the respondents are summarized in Table 4. The proportions of participants broken down by area of expertise are shown in Fig. 3. The expert panel comprised 6 experts from the governmental

**Table 3** Scales of random index as investigated by Saaty [72]

Matrix size (n)	1	2	3	4	4	6	7	8	9	10
Random index (RI)	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

**Table 4** Number of respondents broken down by type of organization

Type of organization	Contacted numbers	Number of responders (round one)	Number of respondent (round two)	Proportion of type of organization in [%]
Government/ministry/policymakers	8	6	4	30
Industry/business sector	10	5	4	25
Non-profit organization (NPO)/non-governmental organization (NGO)	3	3	2	15
Academic/research institute	4	3	3	15
Financial institution/bank	4	3	3	15
Total	29	20	16	100



**Fig. 3** Proportions of the areas of expertise in the group of participants

sector, 5 experts from the private sector, and 3 experts each from NPO/NGOs, academic institutes, and financial institutions.

Data about the participants' expertise were gathered in order to understand the underlying reasons behind the results. The empirical factors of the different backgrounds would assist in interpreting the AHP. Figure 3 illustrates the proportions of topics which the panelists are knowledgeable in. It is notable that the highest number of participants are proficient in the topics of energy policy (17%) and agricultural production (17%). The second most frequent background was in bioethanol or biofuel production (14%).

### Results of the AHP analysis

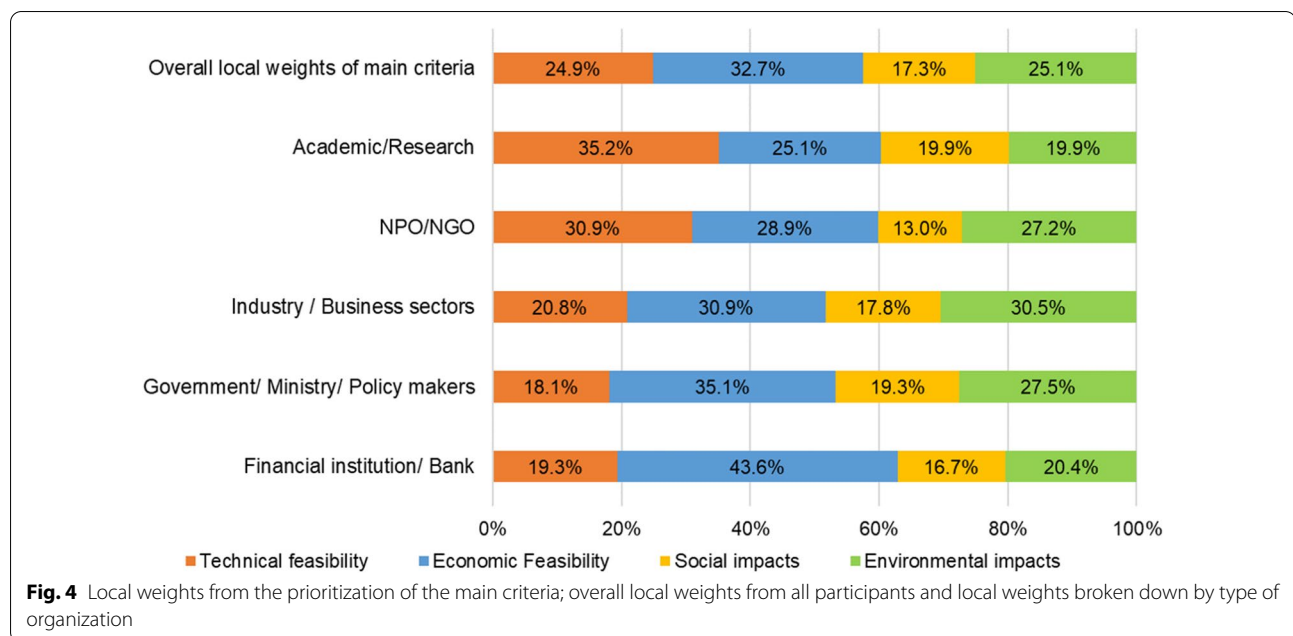
#### Prioritization of the main criteria

The results of the local weights of the main criteria from round one to round two showed slight changes in terms of importance level scores although the ranking of the main criteria remained the same. The results of the local weights of the main criteria from the second round are shown in Fig. 4. Based on the scores of the pairwise comparison from every respondent, the consistency index (CI) ranged from 0.000 to 0.090, whereas

the consistency ratio (CR) was between 0.000 and 0.097. According to Saaty, if the CR is  $< 0.1$ , the survey answers of all participants are considered to be consistent. According to the overall local weights presented in Fig. 4, of the four main criteria, 'economic feasibility' were of the highest priority (32.7%), followed by 'environmental impacts' (25.1%) and 'technical feasibility' (24.9%). Lastly, the criteria weights for 'social impacts' were the lowest (17.3%).

When comparing the experts' scores for the main criteria, as listed in Fig. 4, it is notable that the results can be divided into two groups. First, the groups from governmental organizations, industry/businesses, and financial institutes gave 'economic feasibility' a high score. The other expert groups—NPO/NGOs and academic or research institutes—prioritized 'technical feasibility'.

Comparing 'environmental impacts' and 'social impacts', most of the experts rated the former as more important than the latter, except for the group academic/research institutes. Interestingly, academic or research institutes and NPO/NGOs paid more attention to the technical aspects, which received a higher score than economic and environmental criteria. On the other hand,



the industry and business sectors placed a higher priority on economic and environmental aspects, compared to technical and social aspects.

#### Prioritization of sub-criteria

The sub-criteria were assessed according to local weights and global weights. “Local weights” refer to the relative weights among the sub-criteria of a main criterion, while “global weights” indicate the overall ranking of sub-criteria across the main criteria. The average local weights of sub-criteria were obtained from the criteria evaluation of the first round and adjustments in the second round. As a result of the consistency analysis, the average CI values were calculated from sub-criteria under the four main criteria: technical, economic, social and environmental aspects, resulting in 0.011, 0.017, 0.008, and 0.007, respectively. Meanwhile, the average values of CR were calculated to be 0.019, 0.030, 0.014, and 0.014, respectively. The CR for all participants in the evaluation of the sub-criteria has proved to be consistent ( $CR < 0.1$ ) in the study.

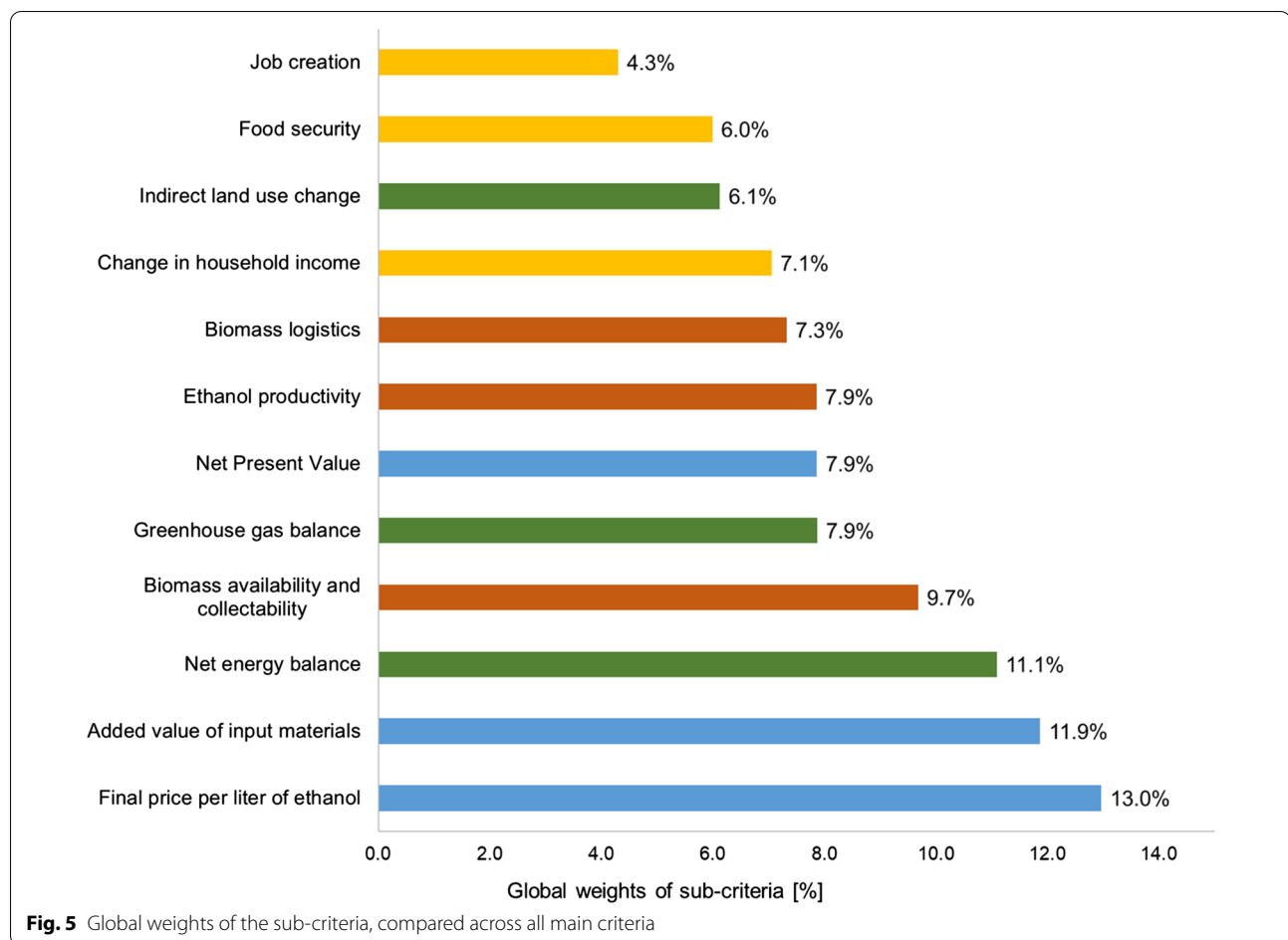
The results of the global weights for all sub-criteria are shown in Fig. 5. The top three priorities were the sub-criteria ‘final price per liter of ethanol’ (13.0%) followed by ‘added value of input materials’ (11.9%) and ‘net energy balance’ (11.1%). These top three most important sub-criteria fall under the main criteria ‘economic feasibility’ and ‘environmental impacts’. On the other hand, the sub-criteria ‘food security’ (6.0%) and ‘job creation’ (4.3%), under the main criteria ‘social impacts’ received the lowest rankings.

Table 5 presents the local weights of the main criteria, the local weights of the sub-criteria with respect to the main criteria, and the overall global weights of the sub-criteria. The minimum and maximum weights were clarified with the values of standard deviations in order to indicate the range of scores given by the experts. When comparing the criteria under the aspect of ‘technical feasibility’, ‘biomass availability and collectability’ had the highest local weights score (38.9%). This result could be related to the fact that second-generation bioethanol heavily depends on the quantity of agricultural residues, which is considered to have a scattered availability. The result was identical to the weight for technical factors evaluated in a study by Kheybari et al. [129]. Kheybari described reasons for prioritizing biomass availability in that the factor of availability is associated with the logistic feasibility of biomass sources on the demand side.

Under the dimension of economic feasibility, the experts prioritized the sub-criteria ‘final price per liter of ethanol’, giving it a local score of 39.6%. This outcome identified the concern regarding the production cost of biofuels from agricultural residues. The concern was considered to be logical from today’s standpoint due to the fact that it is an under-commercialized technology in Thailand, implying the lack of reference market prices.

Next, ‘change in household income’ was the highest rated sub-criterion under the main criteria ‘social impacts’, with a local weight of 40.7%. According to a study by von Doderer et al., the socio-economic factor of employment income can be determined based on the sale of products, or from the sale of power generation [97].





Payments to households could be an intriguing way to get local people to accept a novel technology in that the project can be related to the thriving economy in that local area [136].

Lastly, the sub-criterion ‘net energy balance’ was voted as the most important consideration under the main criteria ‘environmental impacts.’ The local weight for this sub-criterion was 44.2% in terms of importance. This factor indicates the efficiency and effectiveness of energy conversion from biomass in influencing carbon emissions [137]. The process of biofuel production affects the ratio between the input and output of energy. This energy indicator allows the sustainability level between renewable biofuels and conventional fuels to be judged [138].

In addition to the overall prioritization of the sub-criteria by all reviewers, the global weights of the sub-criteria were categorized separately based on organization. Figure 6 presents the global weights of the 12 sub-criteria as classified into five groups of organizations.

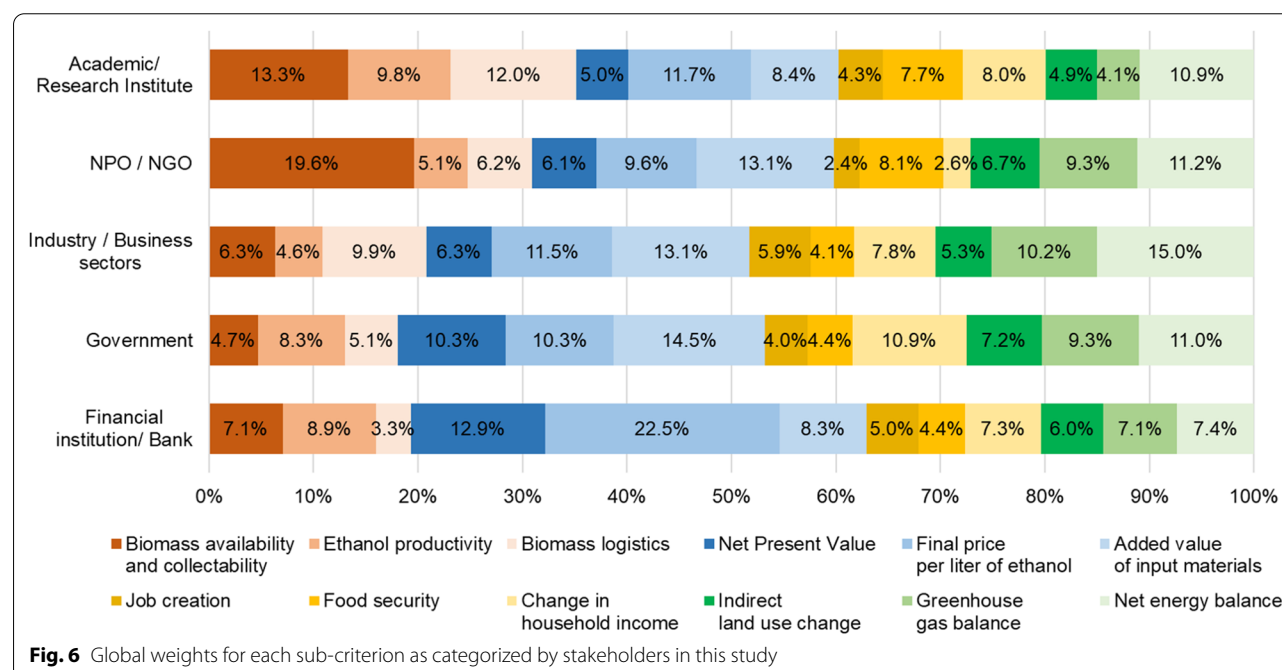
For the academic and research institutes, the factor ‘biomass availability and collectability’ was voted as having the highest priority (13.3%). Surprisingly, even

though the representatives from academic institutes had an environmental background, concerns about environment-related topics were relatively lower than expected. Similarly, the highest priorities as evaluated by the NPOs and NGOs also emphasized the importance of ‘biomass availability and collectability’ as a technical aspect (19.6%). In terms of the results of the industry and business sector participants, although the main criteria were dominated by ‘economic feasibility,’ the largest percentage of the sub-criteria was ‘net energy balance’ (15.0%) under the category of environmental impacts. The possible reason behind this result is the fact that the net energy balance can indicate the costs and efficiency of ethanol production.

Meanwhile, the governmental sector demonstrated similar proportions for each criterion in terms of global weights allocation. There was no significantly high prioritization given to any of the 12 aspects; however, ‘added value of input materials’ (14.5%) received the highest score. The energy sector is considered an important market for conventional agricultural crops to increase the selling price of feedstocks in addition to food-oriented

**Table 5** Summary of local weights of main criteria, sub-criteria and global weights of overall sub-criteria as analyzed in this study

Main criteria	Local weights of main criteria (%)	Sub-criteria	Local weights of sub-criteria (%)	Global weights of sub-criteria (%)	Min. weights (%)	Max. weights (%)	Standard deviation (SD) (%)
Technical feasibility	24.9	Biomass availability and collectability	38.9	9.7	1.8	18.0	5.58
		Ethanol productivity	31.6	7.9	1.7	17.2	5.83
		Biomass logistics	29.5	7.3	1.7	18.6	6.29
		Subtotal	100.0				
Economic feasibility	32.7	Net present value	24.1	7.9	2.3	22.6	6.95
		Final price per liter of ethanol	39.6	13.0	3.0	25.4	7.06
		Added value of input materials	36.3	11.9	2.2	26.8	8.49
		Subtotal	100.0				
Social impacts	17.3	Job creation	24.8	4.3	1.3	11.9	3.32
		Food security	34.5	6.0	1.2	12.6	3.86
		Change in household income	40.7	7.1	3.2	12.6	3.51
		Subtotal	100.0				
Environmental impacts	25.1	Indirect land use change	24.4	6.1	1.9	15.9	5.01
		Greenhouse gas balance	31.4	7.9	2.7	17.4	5.0
		Net energy balance	44.2	11.1	1.7	17.9	5.74
		Subtotal	100.0				
Total	100.0			100.0			



products. Likewise, for the scenario of advanced bioenergy production from agricultural residues, it is crucial to consider the biofuels market that supports the values of the input feedstocks [7]. Therefore, this criterion was important for policymakers in terms of a macroeconomic analysis at the national level.

The experts from the financial institutes/banks placed the highest priority on the sub-criterion ‘final price per liter of ethanol’ (22.5%). This result reflected the viewpoint that biofuel prices must be considered when implementing second-generation bioethanol. In general, banks consider the project potential from an NPV and IRR perspective, which influences decisions about financial loans to the investors for newly constructed projects or factories [139].

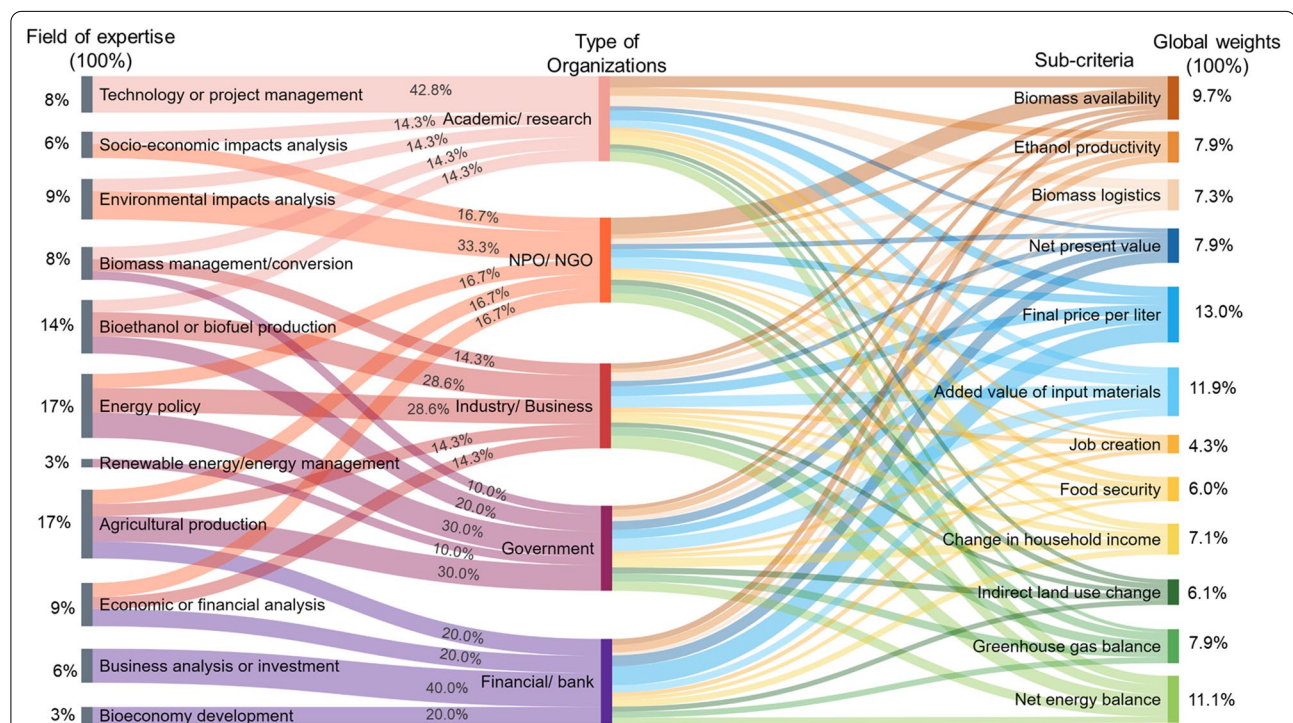
### Connection between the expertise, organizations and prioritized criteria

To obtain a better understanding of the results with respect to the experts’ judgement, information on the participants’ backgrounds was collected on the questionnaire form. Figure 7 shows the connection between the participants’ expertise, their affiliations, and the prioritization outcomes, constructed as a Sankey diagram. As a result of the illustration, it was not possible for one participant from an organization to hold expertise in every

subject. Nonetheless, all survey respondents in this study had the combined expertise needed to cover the elements of the value chain. According to the survey results, the participants’ primary fields of expertise were in ‘energy policy’ (17%) and ‘agricultural production’ (17%), followed by ‘bioethanol or biofuel production’ (14%). The participants were least familiar with the topics of ‘renewable energy/energy management’ (3%) and ‘bioeconomy development’ (3%).

Interestingly, even though the respondents from the governmental and academic sectors did not have expertise in financial or business analysis, the criterion receiving the most weight was ‘final price per liter’. Based on this preference, it can be assumed that the participants viewed the criterion ‘final price per liter’ from different angles of pain points or requirements. For instance, this parameter could be interpreted as the profitable rate for ethanol manufacturers, whereas the ethanol price could also represent the incentive needed to persuade consumers from a governmental perspective.

Looking at the connection between the most prioritized criteria for each organization (Fig. 6) and the experts’ backgrounds (Fig. 7), most of the participants from an academic/research background with expertise in ‘technology and project management’ deemed ‘biomass availability and collectability’ to be the most important.



**Fig. 7** Sankey diagram for illustrating the relationship between the categories “field of expertise”, “type of organization” and “global weights of sub-criteria” as derived from the Delphi-AHP results

This criterion was also prioritized by NPO/NGOs, where the majority of the backgrounds were in 'environmental impacts analysis'. The NPO/NGOs were the organizations that engaged significantly with a broad range of topics, including environmental, bioethanol, energy policy, agriculture, and socio-economic aspects. The results from the NPO/NGO group demonstrates the benefits of involving their views in the early stage of the policy-making process in order to avoid a possible disagreement about public policy implementation.

Meanwhile, the experts from the industry and business sectors were mostly concerned with 'bioethanol and biofuel production' as well as 'energy policy'. Their prioritized criteria are connected to the environmental aspect 'net energy balance'. Following that, the most voted on variable from the experts in the governmental sector was 'added value of input materials', even though the experts' backgrounds were mainly in 'energy policy' and 'agricultural production', which are not directly related to the economic aspect. In comparison to the results from other organizations, the stakeholders from the financial/banking sector emphasized the importance of 'final price per liter of ethanol', which was also the criterion prioritized most by all participants.

#### **Additional criteria and supplementary comments**

In addition to the pairwise comparison of the provided criteria, the participants were asked to select relevant criteria from several lists of topics. The aim of compiling additional criteria is to explore other possible sentiments of the stakeholders. The additional criteria are expected to contribute to figuring out the implications of scenarios in further steps.

Additional remarks are summarized in Additional file 2: Supplementary Table 1. It is notable that the most frequently selected criterion by all participants was 'Governmental subsidy' at 14 points. The most selected factor highlighted the perceptions about the role of government in the policy recommendations. Unsurprisingly, 'technology readiness level' received the second highest number of votes, achieving 12 points. In terms of the idea that second-generation bioethanol should progress at pilot-scale production levels, the results suggest that it might still be too early to make a projection from their perceptions.

Additional criteria that came in at third and fourth place related to technological feasibility, namely 'co-products' and 'air pollution level' receiving 10 points each. It is noteworthy that the criteria related to the environment had a rather limited priority, such as output waste, forest areas, and fertilizers/pesticides. In addition, the social aspect 'job quality' received only one point. The results of the additional criteria in this part demonstrate

overlapping results to the sub-criteria evaluation. Meanwhile, 'land prices' do not seem to concern the experts thus far.

Supplementary comments were compiled from the participants' opinions during the surveying process. The comments were summarized and elaborated on by groups of experts in Additional file 3: Supplementary Table 2. It is noticeable that these viewpoints reflect their own experiences. Some comments hint at underlying issues that should be properly discussed across multiple sectors. As the comments show, the government's role is crucial for endorsing the strategic development of bioenergy. This involves policy-related elements, including laws and regulations, that can support the upcoming advanced technology and, more importantly, the incentivized system structure. Meanwhile, the participants also highlighted the importance of competitiveness in the biofuel market from an economic perspective, which needs to be addressed by biofuel producers and market expansion for bioenergy.

Several experts mentioned factors that were not included in the current study. Interesting topics were addressed, such as risk management and the uncertainty surrounding disruptive electric vehicle technology in the future. Important criteria regarding the technical feasibility of second-generation bioethanol were mentioned by participants from industry and the academic sector which must be verified as a transformation threshold due to the concerns of technological readiness. However, some additional feedback demonstrated the positive signs supporting the utilization of agricultural residues not only in biofuel production. In addition to technical viability, the issues involving environmental and social benefits, as proposed by the stakeholders, brought up crucial points that policymakers cannot overlook when providing recommendations for future scenarios.

#### **Discussion**

Engagement with the organizations was the most challenging aspect when recruiting the panel. The normal bureaucratic organizations limited direct access to the experts and the questionnaire had to be delegated at the executive level to the person responsible for responding to the survey. This resulted at first in people neglecting to reply since they did not see themselves as playing a prominent role as a decision-maker about the topic. To deal with the limited participation, we constantly revised our approach by attempting to communicate more frequently, providing insightful information, and searching for alternative ways to personally connect with participants. Communication other than through written documents, such as phone calls, clarified the objectives of the survey. Through telephone communication, we were able



to convince participants of the importance of their roles in the policy launching process, as can be seen in the supplementary reflections.

One advantage of the institutional system was that this delegation process guaranteed that the indicated participants were well qualified to carry out the task. In some cases, especially in the private firms, the decision to participate in the survey was based on their core business. Hence, the expert panel of the survey was verifiably made up of participants with knowledge of or familiarity with the topic. This helped strengthen the reliability of their responses in the survey rounds.

Feedback in the form of supplementary comments and additional criteria raised by the participants, identified the experts' understanding and concerns with regard to the topic. Comments reflecting a range of attitudes demonstrate that the supplementary comments effectively persuaded the participants to freely contribute their perspectives on the survey questions based on their job functions and within the context of their organization.

With regard to the most prioritized aspect, that of economic feasibility, the reflections from the respondents to economic viability could be considered from the supply and demand side. The supply side was likely linked to concerns about investment cost and financial incentives due to newly emerging technology. A study of the literature also found that investment cost is the most critical criterion from an economic perspective [42]. On the demand side, fuel price instability could be a matter of concern for consumers. The economic aspect of biofuel price was the most focused on factor in terms of the overall relative weights.

When considering the cost structure of bioethanol, the raw material price can influence 40–60% of the minimum selling price [140]. Thus, altering biomass prices could cause major fluctuations in biofuel selling prices. In addition, the decline in crude oil prices since 2015 could lead to a competitiveness with the final price per liter of bioethanol. In this sense, the selling price is a crucial driver for biofuel policy to encourage consumers to choose renewable energy over fossil fuels. Similar outcomes were identified in the SWOT analysis by Chanthawong et al. as part of a case study of first-generation bioethanol production. Price fluctuations of input materials were indicated as a weakness in the development of a bioethanol policy [9].

One of the economic mechanisms for supporting the market of low carbon fuels is to initiate a carbon pricing system for fossil fuels [141]. In many countries, this strategy has successfully stimulated the consumption of biofuels and contributed to the achievement of the CO<sub>2</sub> reduction goal for fossil-based fuel consumption [141]. However, it was determined that the carbon tax imposed

on fossil fuels should be introduced as a way to finance biofuel consumption in order to stimulate biofuel penetration of the market [142]. Thailand is one of the countries where the enforcement of carbon taxation has been under consideration. Thailand's Ministry of Natural Resources and Environment has proposed instruments, such as the carbon taxation or carbon pricing system, in its Climate Change Master Plan 2015–2050 [143]. Until now, Thailand has embarked on the experiment as a pilot project, which has been launched as a carbon trading scheme among industries and the public and private sectors [144].

The concepts of levying carbon pricing and taxation on fossil fuels have been found to increase product prices; hence it would also mean higher expenditure for households [145]. The conceptual idea of carbon pricing for fossil fuels and a tax on such vehicles has been proposed to the Ministry of Energy; however, it has not been approved at the decision-making level as it could increase gasoline prices. The controversy was due to a concern that increasing commodity prices would become a burden for consumers. This has been a significant roadblock in promoting economic instruments for GHG mitigation [146].

With the second-highest global weight, the factor of 'added value in biomass' highlighted the stakeholders' perceptions about increasing the value of agro-materials. More effort has been placed on valorizing residual biomass for higher valuable production systems in Thailand; however, the current technologies have mainly been implemented only with primary products, such as animal feed, fertilizers [29], and fuel for combustion in electricity generation [147, 148]. Until now, there has been doubt about the competitiveness of the commercialization of lignocellulosic ethanol over fossil fuels due to production costs. Nevertheless, a feasible commercialization model has been proposed that includes developing ethanol production along with biorefinery products [28], which would be a motivation to extend the value chain of agricultural products and promote agricultural residues as part of the development of the bioeconomy [22].

Next, the main criterion 'environmental impacts' was the second most significant dimension, with one of its sub-criteria, 'net energy balance', rated the third-highest criterion in terms of overall global weights. Not only does the definition of this criterion have a boundary in environmental terms, but it is also linked to technical feasibility, which can guarantee energy gains from the entire process [101, 149]. As there is a positive net energy ratio for agricultural residues in cellulosic ethanol production, there are potentials for production technology and an indication of environmental benefits. Different types of raw materials are associated with different net energy



balances and CO<sub>2</sub> emissions. Subsequently, an analysis of the optimal types of input materials would be beneficial to lower the level of life cycle greenhouse gases [101, 149].

Even though environmental impacts were ranked second in order of priority, the factors of land use change and GHG balance were not ranked highly in terms of overall sub-criteria scores. Significantly, the criterion 'indirect land use change' gained relatively low recognition from the governmental sectors, which are the key players in the policymaking process. Deforestation remains a constant issue [150]. Despite the fact that there is a forest preservation law in Thailand, namely Forest Act, B.E. 2484 [151], the land use for the agricultural industry still affects food crop cultivation areas [150]. Moreover, burning is still practiced on sugarcane and rice plantations, causing severe air pollution [152]. It can be assumed from the results of our study that the aspect of indirect land use and GHG emissions from plantations are unfamiliar fields for policymakers. As the study by Chanthawong et al. has pointed out, the expansion of cultivation land could be one was to improve agriculture in future scenarios [9]. Nonetheless, land expansion and appropriate land use for cultivating energy crops remains an issue that needs to be clarified at the policy level.

Meanwhile, technical feasibility received the third highest ranking. The scores for this criterion were mostly given by experts from academic/research institutes with knowledge mainly in technology and project management, and experts from NGO/NPOs with backgrounds in energy policy and agricultural production. Among the studied criteria, biomass availability was ranked fourth in terms of overall global weights. However, this criterion is also a critical factor for bioenergy promotion in Thailand, along with the importance of economic feasibility and environmental impacts because it refers to the capacity and potential to develop production from a stable supply [153]. Spatial data with the density of the available biomass would indicate the potential areas and optimal production scales [154], which also influences the economic analysis. This factor is considered to be a key driver in decision-making for project implementation [155].

A surprising outcome was that the weight of social impact was ranked fourth. This illustrates that the awareness of local benefits has not yet risen enough in the stakeholder's minds. A study of conventional ethanol production from sugarcane identified the socio-economic advantages based on a thriving local economy on account of employment and higher rural incomes [136]. However, an evaluation of the criteria in this study found that job creation was the least concerning factor. This is considered to be due to the fact that jobs in the agricultural sector have become less popular in recent

years because of lower incomes in agriculture compared to non-agricultural work [156]. One reason is that sugarcane and cassava cultivation is heavily influenced by weather conditions and the traditional agricultural system (e.g., monoculture system) [156]; hence incomes from farming fluctuate due to unpredictable productivity.

Not only the issue of fewer farmers working in agriculture, but unimproved production yields of sugarcane and cassavas could also be reflective feedback from the bottom-up assessment, which could draw awareness from policymakers. Long-term, sustainable development requires investment in infrastructure, adequate irrigation systems, and technology for mechanizing agriculture to achieve higher value-added products. These are essential elements for transforming the agricultural sector to a higher-level industry as advised by the stakeholders in the supplementary remarks, and could also, in turn, foster employment in this sector.

Of the additional indicators voted on in this study, government subsidies were selected most often. This implies that energy policies or energy-related initiatives rely heavily on economic aspects, as subsidies and price incentives are drivers to be launched on a national scale. In a sense, this result emphasizes the essential role of government in incentivizing biofuel system promotion. Thus far, government incentives have only been at the retail level through the launch of the cross-subsidization scheme which subsidizes the biofuel selling price over non-blended fossil fuels [157, 158]. Nevertheless, in terms of benefits to farmers, the price guarantee system for feedstock providers or crop growers has remained a concern [153].

Utilizing cellulosic residues in biorefineries for further products is a possible option to increase alternative incomes for the farmers and more channels to develop higher-skilled labor in the agricultural sector [159]. One of the potential scenarios is promoting the utilization of regional biomass, which could encourage mixed feedstocks and provide opportunities to facilitate biomass handling and logistics [108]. Furthermore, in terms of the technological development corresponding to added value and co-products, the end products could be extensively recommended for biochemical production. One of the reasons is that the bioeconomy market is transforming over time, encouraging the establishment of biomass conversion technology for a broad range of biorefinery products. This allows industries to have more flexibility [160].

Even though the commercialization of second-generation bioethanol as an emerging technology still needs to be advanced by the private and research sectors, survey participants agreed that policy mechanisms and regulations by the government are essential tools for long-term

policy promotion. Especially from the point of view of governments and policymakers, concerns focused on economic feasibility and environmental impacts. In summary, in addition to verifying technological feasibility, mechanisms of government policy, as well as legislation and regulations, are key to helping technology developers and other relevant stakeholders achieve profitable investment and to enhancing competitiveness on the market.

The findings highlight the importance of financial feasibility and environmental impacts in terms of overall prioritization. However, with respect to the results, there are no significant differences between the four main criteria. Although equal priority need not be given to all criteria, the evaluation should not focus on only one dimension. Keeping in mind that there is no perfect bio-energy strategy that would fit all requirements [60], the results obtained from this study can be used as an initial step in developing second-generation bioethanol. Due to the severity of long-standing field burning in Thailand, focus should first be placed on tackling pollution from field burning, which could be promoted as a way to deploy unutilized agricultural residues. This prospective scenario is believed to be an opportunity for developing lignocellulosic biomass to promote the bioeconomy and mitigate environmental impacts.

## Conclusions

A development plan for bioethanol in Thailand was initially promoted as a way to replace imported fossil fuels and to encourage agricultural crop production in the energy sector. However, biofuel production has focused very little on socio-economic impacts and environmental side-effects. In order to create a sustainable framework to meet the goal of bioethanol production and ensure long-term benefits for stakeholders, it has become more necessary to incorporate multi-disciplinary dimensions and criteria in the policymaking.

In this study, the Delphi-AHP method was deployed to prioritize the important aspects and criteria regarding the commercialization and policy implications of second-generation bioethanol in Thailand. A participatory evaluation using the Delphi-AHP approach accomplished the main objective of the study of prioritizing the criteria for second-generation bioethanol development. The Delphi-AHP tool has been able to verify that the qualitative perceptions of 20 stakeholders could be transformed into quantifiable criteria as demonstrated by the current research. The Delphi approach provides the advantage of survey anonymity. This encourages respondents to share their opinions openly. At the same time, the AHP technique is able to transform the subjective opinions into a multi-criteria prioritization, which enables our study to

obtain the most reflective indicators that represent the transdisciplinary perceptions of the experts. Even though scattered perceptions from different backgrounds are common, the Delphi-AHP method could reduce conflicts and provide agreed on results through the consenting process.

Although the study produced reasonable outputs from two rounds of evaluation, some limitations could have been dealt with in order to improve the implications. The remaining challenges involved a moderate dropout rate in the second round due to limited ways of incentivizing iterative participation. It was found that, between survey rounds, telephone communication with the respondents helped them commit to providing feedback. However, in order to achieve stronger engagement with larger numbers of participants, simpler tools should be adopted for facilitating responses to the questionnaire, which could possibly increase the participation rate. Despite the lower numbers, the overall scores demonstrate the reasonable consistency ratio which supports the ranking based on the calculation. Furthermore, the compilation of supplementary comments also enables possible scenarios for future decision-making analysis.

The research questions as posited in the study were answered. The findings from the study on criteria prioritization demonstrate the stakeholders' priorities with respect to second-generation bioethanol, suggesting the key indicators that need to be taken into consideration when putting the advanced technology forward for policy implementation. As a result, it has been confirmed that economic feasibility is an essential aspect of project analysis. Focus should especially be placed on the final selling price of bioethanol and improvement of the added value of raw materials with respect to commercialization and policy recommendations. Even though the second-generation bioethanol technology is currently only at the demonstration level, indicating that a comprehensive understanding of the technology is still required, environmental and economic benefits have been identified as being concerning factors along with demonstrating technical feasibility.

The application of Delphi-AHP helped to reflect the current concerns and the prospect of scenario suggestions that are compatible with the future biofuel development in Thailand. The outcomes from the current analysis are believed to minimize potential trade-offs, which often occur when implementing policy, and provide the most benefits to the actual stakeholders. The outcomes from the stakeholder survey conducted in this study can be viewed as a steppingstone in creating a sustainable second-generation bioethanol framework and a transparent policymaking process in Thailand.

## Abbreviations

GHG: Greenhouse gas emissions; COP21: The twenty-first session of the Conference of the Parties; AEDP: Alternative Energy Development Plan; SDGs: United Nation's Sustainable Development Goals; EU: European Union; MCDA: Multi-criteria decision analysis; AHP: Analytic hierarchy process; NPV: Net present value; IRR: Internal rate of return; iLUC: Indirect land use; NER: Net energy ratio; CI: Consistency index; CR: Consistency ratio; RI: Random index; NPO: Non-profit organization; NGO: Non-governmental organization; SD: Standard deviation.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13705-021-00313-5>.

**Additional file 1:** Delphi survey questionnaire - the prioritization of criteria.

**Additional file 2: Supplementary Table 1.** Frequency of mentioned topics as additional criteria.

**Additional file 3: Supplementary Table 2.** Supplementary remarks from the participants broken down by sector.

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## Authors' contributions

PJ and AB conceived the presented ideas. PJ contacted the experts, conducted the survey, and performed the data analysis. AB and DT supervised and edited the manuscript. All authors read and approved the final manuscript.

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## Availability of data and materials

The datasets generated and analyzed in this study are not publicly available due to agreement of anonymity with the respondents and to privacy concerns. However, they are available from the corresponding author upon reasonable request.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

All authors consent to this paper being published.

### Competing interests

The authors declare no competing interest.

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