International Journal of Safety and Security Engineering
Vol. 15, No. 5, May, 2025, pp. 963-972
Journal homepage: http://iieta.org/journals/ijsse

Risk Management in Sustainable Patchouli Supply Chain

Sofia Keumalasari[1,2], Ahmad Humam Hamid[3,4*], Indra Indra[3,5], Agus Nugroho[6]

[1] Doctor Program in Agricultural Science, Syiah Kuala University, Banda Aceh 23111, Indonesia
[2] Plantation Management Study Program, Politeknik Indonesia Venezuela, Aceh Besar, 23371, Indonesia
[3] Agribusiness Department, Faculty of Agriculture, Syiah Kuala University, Banda Aceh 23111, Indonesia
[4] Center for Sustainable Agriculture and Rural Development, Syiah Kuala University, Banda Aceh 23111, Indonesia
[5] Atsiri Research Center ARC PUI-PT, Nilam Aceh Syiah Kuala University, Banda Aceh 23111, Indonesia
[6] Department of Livestock Socioeconomics, Faculty of Animal Science, Brawijaya University, East Java 65145, Indonesia

Corresponding Author Email: humamhamid@usk.ac.id

https://doi.org/10.18280/ijsse.150510

Received: 25 March 2025
Revised: 30 April 2025
Accepted: 20 May 2025
Available online: 31 May 2025

Keywords:
patchouli, risk management, sustainability, supply chain

ABSTRACT

This study introduces a novel, systematic risk management framework for the patchouli supply chain in Aceh Province, Indonesia, utilizing the House of Risk (HOR) model integrated with the Supply Chain Operations Reference (SCOR) approach. Unlike previous research, which has focused mainly on market dynamics or production techniques, this work applies the HOR methodology—a combination of Quality Function Deployment (QFD) and Failure Modes and Effects Analysis (FMEA)—to comprehensively identify, assess, and prioritize supply chain risks across all actors, from farmers to exporters. Employing a descriptive qualitative design, the research engaged 172 stakeholders through purposive and snowball sampling, in-depth interviews, and participatory observation to ensure robust risk mapping and validation. The HOR analysis enabled the prioritization of risk agents and the formulation of targeted mitigation strategies based on their effectiveness-to-difficulty ratios. Key findings highlight that processing patchouli waste into organic fertilizer, product diversification through research and development, and strengthening access to capital via partnerships with financial institutions are among the most effective and feasible strategies for risk mitigation. These interventions address critical ecological and economic risks, enhancing supply chain sustainability, resilience, and competitiveness. The methodological applicability of the HOR model is demonstrated by its adaptability to other agricultural supply chains, offering a proactive, data-driven approach to risk management that supports sustainable agricultural ecosystems. This research provides actionable recommendations for policymakers, industry stakeholders, and farmers, advancing both the theory and practice of sustainable supply chain risk management in the essential oils sector.

1. INTRODUCTION

Essential oils also known as essential oils are flavored compounds extracted from various parts of plants through a distillation process, and have many uses, ranging from aromatherapy to medicine [1, 2]. Patchouli (*Pogostemon cablin Benth.*) is one of the essential oil producing plants that has high economic value and is widely used in the perfume, cosmetics, and pharmaceutical industries [3, 4]. Indonesia, especially Aceh Province, is known as one of the main producers of high-quality patchouli oil in the world. The special content in patchouli oil is patchouli alcohol which is needed by the world for various disease prevention [5]. Aceh Patchouli is the best variety because its essential oil has Patchouli Alcohol (PA) content and quality reaching 35.86%, alpha-patchoulene 26.05% and delta-Guaiene 18.36% with oil yield of 3.6% [6]. Patchouli crops are exported to the world in the form of crude oil, export standards and prices are determined by the market and buyers, Indonesia is only a pricetaker.

Patchouli crude oil is a renewable resource with a wide range of applications, making it economically very important in the fragrance and herbal sectors. The useful value of patchouli Alcohol has been applied in the world of cosmetics PA acts as a fragrance binder [7], in the pharmaceutical world PA serves as a relaxaxing treatment that has the potential to treat Alzheimer's disease (AD) Clinical use in the treatment of neuritis [8, 9], attenuates depressive behaviors induced by CUMS (chronic unpredictable mild stress), including increased effective sucrose preference and spontaneous exploration, and reduced immobility [10].

Aceh's patchouli industry has great economic potential in international markets, but fluctuating production and prices demand risk mitigation at every stage of the supply chain. The patchouli supply chain involves various actors, such as farmers, collectors, refiners, and exporters, which requires coordination and adequate facilities and infrastructure [11]. The implementation of supply chain management can improve efficiency, transparency and sustainability, while minimizing risks such as price fluctuations, imbalances in production and demand, and low quality of raw materials. A structured supply chain enables logistics optimization, cost efficiency, increased competitiveness, as well as farmers' access to technology, market information, and financing schemes, ultimately improving farmers' welfare and sustainability [12-14].

Supply chain management (SCM) has been applied in various agricultural products to improve the efficiency of production to distribution [12, 15]. The success of SCM is also influenced by the effectiveness of information [16]. In the patchouli supply chain, risks can arise from environmental factors, market fluctuations, infrastructure limitations, and limited access to funding. These risks often lead to production inefficiencies, increased costs, and reduced product quality, exacerbated by traditional farming methods and reliance on middlemen. Without appropriate mitigation strategies, these risks can threaten sustainability [17, 18] supply chain adaptation towards improvement is needed [19].

To address these challenges, the House of Risk (HOR) model can be used as a systematic approach in identifying, assessing, and mitigating risks in the supply chain [20]. This study aims to: (1) identify key risks in the patchouli supply chain in Aceh, (2) assess the severity and frequency of risk occurrence using the HOR approach, and (3) formulate risk mitigation strategies to improve the sustainability of the patchouli supply chain. A SCOR (plan, source, make, deliver, return) approach was used to be more focused [21]. With this approach, the research is expected to provide strategic recommendations for policy makers, industry players, and farmers in improving the resilience and sustainability of the patchouli industry.

Patchouli supply chain management can play an important role in supporting the design of sustainable agricultural ecosystems by integrating ecological principles into every stage of the production and distribution process Agricultural systems face various risks, including climate change, market volatility, and outbreaks Sustainable supply chains encourage the application of environmentally friendly cultivation techniques, such as agroforestry systems, the use of organic fertilizers, and biological pest management, so that patchouli production can run in harmony with the balance of natural ecosystems to true sustainability [22]. Supply chain optimization can also reduce waste of resources, such as water and energy in the patchouli oil refining process, with the application of energy efficiency technologies that provide benefits [23]. Furthermore, waste from the production process, such as distillation residues and biomass, can be reused as organic fertilizer or renewable energy feedstock, thereby reducing environmental impacts [24].

Structured supply chains support diversification of patchouli-based products as well as cropping patterns that improve soil fertility and ecosystem resilience, for example through intercropping with other crops that have ecological benefits to prevent soil erosion and maintain nutrient balance [25]. Adaptive supply chain management also helps farmers anticipate the impacts of climate change, such as fluctuations in temperature and rainfall, with mitigation strategies such as rainwater harvesting and adjusting planting schedules [26-28]. In addition to environmental aspects, the sustainability of agricultural ecosystems also includes the welfare of farmers, where well-managed supply chains enable better access to technology, market information, and funding, thereby improving their competitiveness and welfare economically and socially [29]. Supporting their well-being, farmers already use various risk management techniques, such as crop diversification, insurance, and sustainable practices such as organic farming to improve ecological sustainability.

The House of Risk (HOR) approach is not only relevant for patchouli supply chains, but can also be applied in the design of sustainable supply chains in other agricultural sectors. In other agricultural commodities such as coffee, cocoa, and rubber, HOR can be used to address challenges such as price fluctuations, climate change, limited market access, and imbalances between production and demand [30-32]. The application of HOR in the agricultural sector can optimize supply chain efficiency, improve production sustainability, and strengthen farmers' competitiveness in the global market. In addition, this approach assists stakeholders in developing more appropriate data-driven policies to support resilient and sustainable agriculture.

The House of Risk (HOR) approach to risk management presents an innovative aspect of sustainable supply chain management with a systematic approach to risk identification, assessment and mitigation. In contrast to conventional methods that are often reactive, HOR enables proactive analysis of potential risks along the supply chain, so that preventive measures can be designed more effectively. The model integrates risk probability and impact factors to determine mitigation priorities, resulting in more efficient resource allocation. In addition, HOR can be adapted to various agricultural sectors by considering sustainability factors, such as resource use efficiency, waste reduction, and resilience to climate change. In HOR analysis, risk management has the ability to improve supply chain resilience and efficiency, HOR is an innovative approach that can encourage the sustainability of the agricultural industry while increasing product competitiveness in the global market [20].

Previous research on patchouli commodities has mostly addressed market dynamics, production techniques, and value chain analysis, while studies on the application of a structured risk management framework in relation to improving sustainable agricultural ecology are limited. The application of the HOR model in this context is expected to provide a more comprehensive analysis and strategic solutions for risk mitigation, thereby improving the competitiveness and sustainability of the Aceh patchouli industry [14, 33].

Aceh's patchouli supply chain suffers from fragmented governance, outdated distillation technology, and inadequate logistics. Chehbi-Gamoura et al. emphasize SCOR-based optimization for agricultural supply chains, but existing frameworks rarely address Aceh's unique institutional barriers, such as limited access to international ports or certification programs for organic exports. Moreover, Erratic rainfall and temperature spikes threaten patchouli yields, but conventional risk models HOR Phase 1 fail to incorporate adaptive strategies like drought-resistant cultivars or agroforestry systems. Contrastingly, climate-smart techniques in coffee and cocoa supply chains have improved yield stability by 25–30%, highlighting a gap in patchouli-specific resilience research.

Small holder farmers face systemic barriers, including price volatility, limited access to capital, and gender disparities in decision-making. While studies acknowledge these issues, few propose scalable solutions. For example, Givaudan's partnership with Swisscontact in Sulawesi reduced loan default rates by 40% through financial literacy programs and cooperative strengthening, yet such models remain under-researched in Aceh's context.

2. MATERIALS AND METHODS

The study was conducted in Aceh Province from November 2022 to August 2023, covering three regencies: Aceh Jaya, South Aceh, and Gayo Lues (Figure 1) which are the areas with the highest value of patchouli commodity productivity in Aceh. All actors in the supply chain in the three regencies were involved in the study as respondents.

The method used in the first phase of this research is to identify and analyze the risks in the patchouli supply chain in Aceh Province with the House of Risk (HOR) Analysis which is the development of two methods from the QFD (Quality Function Deployment) and FMEA (Failure Modes and Effects Analysis) methods used to design frameworks for managing risks [20].

This research uses a descriptive qualitative research design involving all patchouli supply chain actors using in-depth interview techniques as the main technique followed by participatory observation to validate the interview results. The research instrument includes all activities in relation to supporting facilities and infrastructure for upstream and downstream patchouli commodities. Determination of research respondents was carried out by Purposive Sampling then continued with Snowball Sampling, methods with different objectives to improve data quality [34, 35].

Snowball sampling is a sampling method obtained by rolling information from one respondent to another, generally this method is used to nest social or communication patterns (sociometrics) of a particular community [36, 37]. The 172 respondents were patchouli supply chain actors, namely: farmers, cooperative officers, refiners, boiler owners, agents, environmental activists, government, forwarding and international companies.

Research using HOR analysis consists of 2 parts, namely: (1) HOR1 was used to determine which risk agents should be prioritized for preventive action; (2) HOR2 was used to prioritize actions that were considered effective but with a reasonable commitment of funds and resources.

The steps in HOR stage 1 are: (1) Identifying risk events that can occur in each process in the supply chain, in this research is done by mapping the supply chain process (plan, source, deliver, make and return) identifying constraints that arise in each process. In Table 1, the risk event is placed in the left column, represented as E_i; (2) Assess the impact severity of the risk event using a scale of 1-10 where 10 indicates a very impact (1 means no impact and a value of 10 means a very critical impact). The severity of each risk event placed in the right column of Table 1 shown as S_i; (3) Identify risk agents and assess the likelihood of occurrence of each risk agent. This study applies, a scale of 1-10 (1 means almost never occurring and a value of 10 means occurring continuously and repeatedly). The risk agent (A_j) is placed in the top row and the corresponding event is in the bottom row, notated as O_j; (4) Development of a relationship matrix, i.e., the relationship between each risk agent and each risk event, R_{ij} (0, 1, 3, 9) where 0 indicates no correlation and 1, 3, and 9 indicate low, medium, and high correlation, respectively; (5) Calculating the potential of each risk agent and each risk event. Aggregate risk of agent j (ARP_j) which is determined as the product of the probability of occurrence of risk agent j and the aggregate impact generated by the risk event caused by risk agent j as in Eq. (1); (6) Rank the risk agents according to their aggregate risk potential in descending order (from high value to low value).

$$ARP_j = O_j \sum_i S_i R_{ij} \quad (1)$$

The results of the calculations in the Risk Agent Prioritization Table are displayed in the form of a pareto diagram. A pareto diagram is a histogram of data sorted from the largest to the smallest frequency, and the cumulative count is also calculated. This diagram helps management quickly identify the most critical areas that require special and immediate attention. Pareto analysis is the process of ranking opportunities to determine which potential opportunities should be pursued first. Pareto analysis should be used at various stages in a quality improvement program to determine which steps to take next.

After the HOR stage 1 analysis is completed, followed by HOR stage 2, HOR2 is used to determine which actions should be taken first, taking into account their different effectiveness as well as the resources involved and the level of difficulty in implementation. The actions selected should be a series of actions that are not too difficult to carry out but can effectively reduce the likelihood of a risk agent occurring. The steps are as follows: (1) Select a number of risk agents with a high priority ranking, resulting from the Pareto analysis of ARPj, to be addressed in the second HOR. The selected agents will be placed on the left side of HOR2 as depicted in Table 1. Place the corresponding $ARPj$ values in the right-hand column; (2) Identify actions deemed relevant to prevent the risk agents. Note that one risk agent can be addressed by more than one action and one action can simultaneously reduce the probability of occurrence of more than one agent risk.

The actions are placed in the top row as "How" for this HOR; (3) Determine the relationship between each countermeasure and each risk agent, E_{jk}. Values can be {0, 1, 3, 9} which represent, respectively, no, low, medium, an3d high relationship between action k and agent j. This relationship (E_{jk}) can be regarded as the degree of effectiveness of action k in reducing the probability of occurrence of risk agent j; (4) Calculate the total effectiveness of each action as follows:

$$TE_k = \sum_j ARPjE_{jk} \quad (2)$$

(5) Assess the degree of difficulty in performing each action, Dk, and place the values in a row below the total effectiveness. The level of difficulty, which can be represented by a scale, reflects the funds and other resources required in performing the action; (6) Calculate the ratio of total effectiveness to the level of difficulty, i.e. $ETD_k = TE_k/D_k$; (7) Assign a priority ranking to each action (Rk) where Rank 1 is given to the action with the highest ETD_k. In the second phase (HOR 2), the study identifies and evaluates preventive actions (P_{Ak}) for the prioritized risk agents. Each action is assessed for its effectiveness (E_{jk}) in reducing the likelihood of each risk agent, using the same 0, 1, 3, 9 scale.

Actions are ranked by ETD_k, with the highest ratios indicating the most efficient and feasible mitigation strategies. For example, processing patchouli waste into organic fertilizer achieved the highest ETD_k (2.33), signifying high impact and low implementation difficulty, while alternative energy solutions like biomass boilers, though environmentally beneficial, scored lower due to higher costs and complexity.

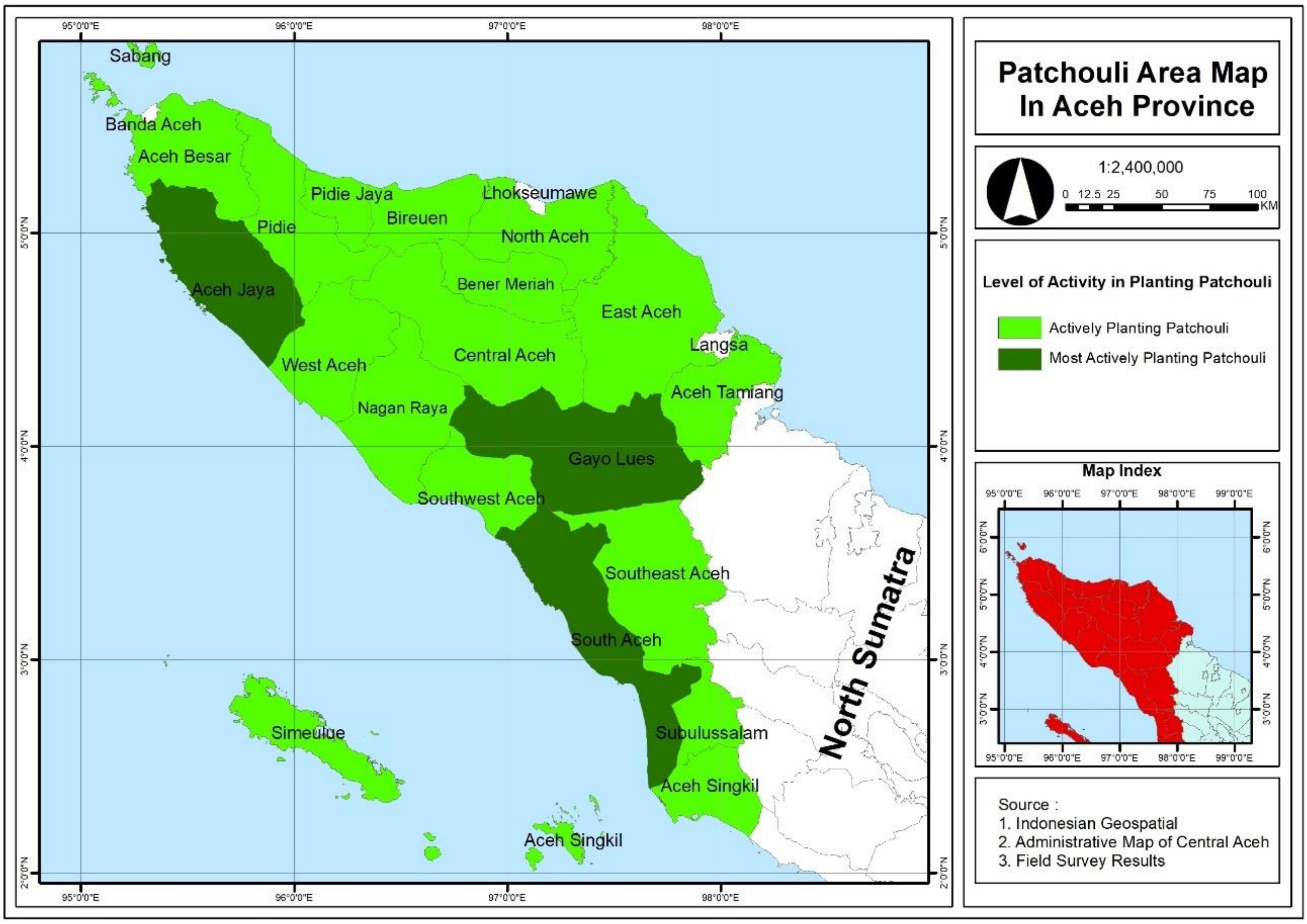

Figure 1. Map of research location

Aceh Province was chosen as the locus for this study due to its status as Indonesia's, and indeed the world's, leading producer of high-quality patchouli oil. The region's patchouli is renowned for its superior patchouli alcohol content, which is highly valued in global fragrance, cosmetic, and pharmaceutical industries. Within Aceh, the regencies of Aceh Jaya, South Aceh, and *Gayo Lues* have consistently demonstrated the highest productivity and concentration of patchouli cultivation and processing activities.

These areas represent the core of the patchouli supply chain, encompassing a diverse range of actors from smallholder farmers and cooperatives to refiners, agents, and exporters-thereby providing a comprehensive and representative context for risk mapping and analysis.

The rationale for focusing on these regencies is further supported by their unique combination of ecological, economic, and social dynamics that typify the broader challenges facing Indonesia's patchouli sector. For instance, Aceh Jaya is characterized by traditional cultivation practices and ecological sensitivities, South Aceh is notable for its historical significance in patchouli trade, and Gayo Lues is recognized for its highland agro-ecological conditions that influence both yield and quality. By selecting these regencies, the study ensures that the risk identification process—central to the HOR methodology captures the full spectrum of sustainability issues, including environmental degradation, market volatility, infrastructure gaps, and institutional constraints.

Methodologically, the HOR approach is particularly well-suited to this context because it allows for the systematic identification, assessment, and prioritization of risks across the entire supply chain, as experienced by all key actors in these regencies. The research employed a descriptive qualitative design, utilizing purposive and snowball sampling to engage 172 respondents representing every segment of the supply chain. In-depth interviews and participatory observation were conducted to ensure that the risk events and agents identified were grounded in the lived realities of those directly involved in patchouli production and trade.

3. RESULTS AND DISCUSION

3.1 House of risk phase 1

The results of the identification of risk events in each process in the supply chain are carried out by mapping the main processes, namely to source, deliver, and make. Major process plans are carried out on each actor in the supply chain so that only the main major risks are assessed (Table 1). Major process returns are not calculated because sales to international buyers already use the flow of crued oil samples to be sent and the risk of mixing oil is not obtained because this is not done because it harms anyone in the long run. Furthermore, risk events in major processes were assessed using a scale of 1-10, where a score of 1 indicates that the risk has no significant impact, while a score of 10 indicates that the risk has a very critical impact on the success of the supply chain. The research results are shown in the following table:

Table 1. Risk event patchouli supply chain aceh province

Major Process	Risk Event	Sev. (Si)
Source	Low land fertility	8
	Low water availability	5
	Limited quality and number of seeds	4
	Pests and diseases that often appear	3
	Limited capital for farming/sales/forwarding business	5
	No family support in patchouli cultivation	7
	No support from village officials	8
	Absence of institutions supporting patchouli farming (for example: farmer groups, cooperatives, etc.)	5
	Conflict (internal farmers/security conditions)	6
	Harvest Failure	6
Make	No managerial process of patchouli oil cultivation (planning, process, sales)	5
	Patchouli farming income is low	6
	No facilities to support patchouli farming (kettle, warehouse, etc.)	6
	Low/poor quality of patchouli oil	6
	Net product weight depreciation	7
	Irregular refining activities	7
Deliver	Fluctuating price of patchouli oil	7
	Limited sales market / Unstable demand for patchouli oil (supply and demand fluctuate)	3
	Absence of price standardization rules	2
	No regulation of patchouli sales market	2
	Lack of government supervision of the patchouli supply chain	2
	Delays in receiving patchouli oil to buyers	2

After obtaining the event, then proceed with the identification of the risk agent in the form of risk occurrence opportunities (occurrence), stating the level of chance of the frequency of occurrence of a risk source so that it occurrence of risk.

The incidence of risks that can cause disruption to the chain process. Applying a score on a scale of 1-10 (1 means it almost never happens and a score of 10 means it happens continuously and repeatedly). The results of the study are shown in the Table 2.

The correlation between a risk source and a risk cause is identified and assigned a value of 0,1,3, or 9 as the sign of each relationship/combination. The correlation between each risk source R_{ij} (0,1,3,9) indicates low, medium, and high correlation, respectively. If a risk source causes a risk to occur, it is said that there is a correlation. The higher the correlation indicates the greater the correlation between the risk event and the risk source that causes it. Table 3 shows the correlation between risk sources and risk causes in Aceh Province.

Based on the calculation of the risk rank of Aceh Province, the results of the Pareto graph are as presented in Figure 2.

The results of the calculation of the Aggregate Risk Potential in HOR 1 illustrated in Pareto Diagram. In accordance with the 80-20 Pareto Diagram principle, the priority problems that must be resolved are problems with percentage to 80% (Table 4).

From the Pareto diagram, 5 risk agents are obtained which are the main causes of risk in the Aceh patchouli supply chain. Based on the risk agents obtained, there are Preventive Actions that can be applied in activities to solve the problems that occur. Next step mapping of the correlation matrix between risk agents and preventive actions in HOR 2 (Table 5).

Table 2. Risk agents of patchouli supply chain Aceh Province

Code	Risk Agents	Frek.(Oj)
A1	High temperature (heat)	5
A2	High rainfall	5
A3	New land clearing (shifting cultivation)	6
A4	No fertilizer application during farming	5
A5	No treatment	6
A6	Harvesting procedures are not appropriate	6
A7	Expensive production facilities (seeds, fertilizers, pesticides)	5
A8	Absence of organic fertilizer manufacturing process	6
A9	Low cultivated land area	6
A10	Land ownership status	6
A11	Limited farm capital	6
A12	Not joining a farmer group	3
A13	Cooperative relationship between farmers is low	4
A14	Absence of supporting institutions (farmer groups, cooperatives)	4
A15	Absence of supporting production facilities	5
A16	Patchouli oil mixed with other ingredients	3
A17	Water used for distilling is not sterile	4
A18	Distilled fuel uses wood (not environmentally friendly)	6
A19	Oil storage/shipping packaging is not appropriate	5
A20	The price of distillation equipment according to the standard (stainless steel) is high	6
A21	High refining operational costs (fuel etc.)	3
A22	High costs (shipping, taxes, packaging)	4
A23	Work procedures are not applied when distilling	5
A24	Distillery operational hours are uncertain	3
A25	Limited human resources/labor in farming/processing/shipping	3
A26	Delay in distillation process	4
A27	No easy access to documents/files (assistance)	6
A28	Limited number of agents that accommodate patchouli	6
A29	Not maintaining hygiene during production, storage and shipping processes	4
A30	Unavailability of international port in Aceh	7
A31	Long travel distance (lading, warehouse, shipping place)	6
A32	Absence of derivative product innovation (manufacturing of finished products for example: dish cleaner made from patchouli oil, perfume etc.)	7

Based on the results of the HOR 2 analysis, five main risks were found in the patchouli supply chain in Aceh Province, each of which has a mitigation strategy with different levels of effectiveness and implementation costs. The calculation of the priority ratio (TE_k/D_k) is used to determine the most efficient mitigation strategy in reducing the impact of risk at a more optimal cost.

The main findings in this analysis are as follows:

1. The mitigation strategy with the highest priority ratio is processing patchouli waste into organic fertilizer (TE_k/D_k= 2.33). This indicates that this approach is effective and requires relatively low implementation costs, making it a very feasible mitigation strategy to prioritize.

Table 3. Risk rank supply chain Aceh province

Rank	Code	ARP	Percentage	Cumulative Percentage
1	A18	3.153,333	7.25%	7.25%
2	A28	2.996,118	6.89%	14.15%
3	A32	2.876,044	6.62%	20.76%
4	A11	2.814,148	6.47%	27.24%
5	A8	2.652,108	6.10%	33.34%
6	A30	2.468,325	5.68%	39.02%
7	A4	2.419,968	5.57%	44.58%
8	A5	2.206,285	5.08%	49.66%
9	A14	2.052,506	4.72%	54.38%
10	A15	2.019,761	4.65%	59.03%
11	A20	1.819,607	4.19%	63.21%
12	A3	1.695,290	3.90%	67.11%
13	A7	1.667,133	3.84%	70.95%
14	A13	1.545,905	3.56%	74.50%
15	A27	1.240,036	2.85%	77.36%
16	A19	1.231,806	2.83%	80.19%
17	A12	1.138,869	2.62%	82.81%
18	A10	1.119,795	2.58%	85.39%
19	A16	957,796	2.20%	87.59%
20	A31	954,047	2.19%	89.79%
21	A9	853,515	1.96%	91.75%
22	A6	711,796	1.64%	93.39%
23	A23	523,409	1.20%	94.59%
24	A29	516,896	1.19%	95.78%
25	A26	478,868	1.10%	96.88%
26	A21	449,099	1.03%	97.91%
27	A25	350,487	0.81%	98.72%
28	A2	273,560	0.63%	99.35%
29	A17	132,792	0.31%	99.66%
30	A1	72,843	0.17%	99.82%
31	A24	51,850	0.12%	99.94%
32	A22	24,947	0.06%	100.00%
Total		43.468,942	100.00%	

Table 4. Risk agent prioritization based on pareto diagram

Code	Risk Agent	ARPj
A18	Distilled fuel uses wood (not environmentally friendly)	3153
A28	Limited number of agents that accommodate patchouli	2996
A32	Absence of derivative product innovation (manufacturing of finished products for example: dish cleaner made from patchouli oil, perfume etc.)	2876
A11	Limited Business Capital	2814
A8	No organic fertilizer manufacturing process.	2652

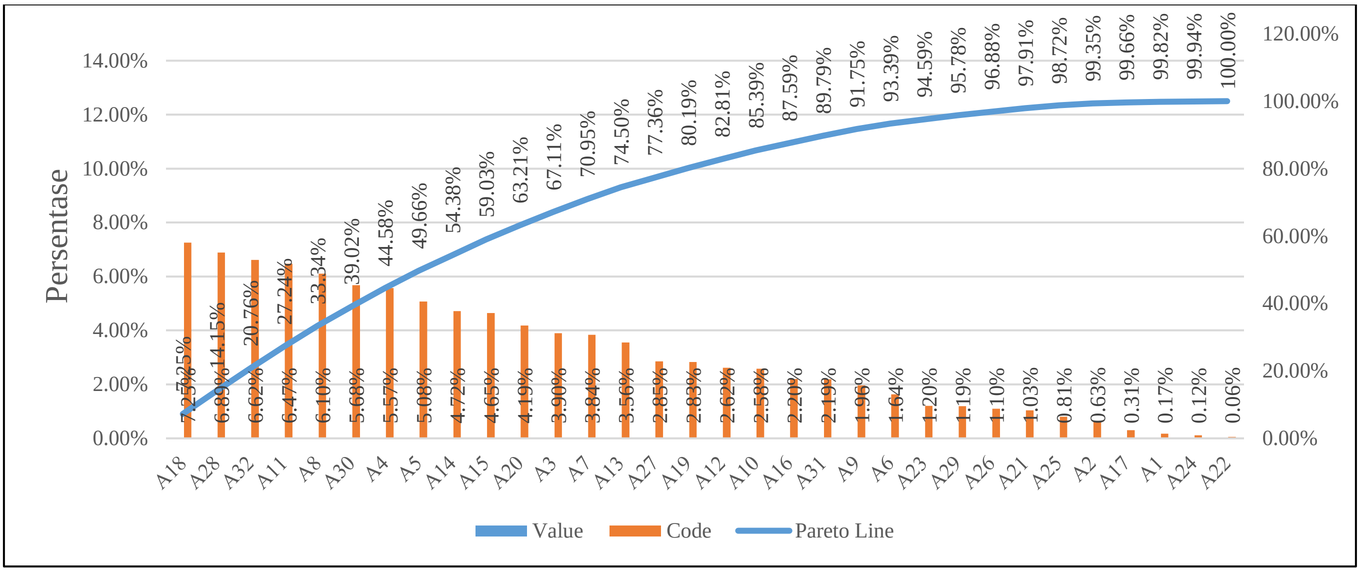

Figure 2. Pareto diagram

2. R&D for patchouli oil-based product diversification also has a high priority ratio ($TE_k/D_k = 2.00$), which means the

development of derivative products such as perfumes and household cleaners can be a value-added solution for the patchouli supply chain.
3. Partnerships with financial institutions for access to capital for small and medium enterprises (*SMEs*) have a high priority ratio (TE_k/D_k= 1.75), which means that data collection and partnership readiness are needed to improve business capital limitations.
4. The establishment of cooperatives and farmer distribution networks as well as partnerships with financial institutions have medium priority ratios (TE_k/D_k = 1.60 and 1.75), indicating that these strategies are quite effective but require greater investment and cooperation of various parties for implementation.
5. The use of alternative energy such as biomass boilers or gasification of agricultural waste has the lowest priority ratio (TE_k/D_k = 1.50). This shows that while these solutions can reduce dependence on firewood and improve environmental sustainability, their implementation costs are still relatively high, requiring careful planning and additional funding support to be realized.

Based on the results of the calculation of the effectiveness to difficulty ratio (ETD_k), the obtained proposed and prioritization of preventive actions in the following order as shown in Table 5 and Table 6.

Table 5. Proposed preventive action

Code	Preventive Action
PA1	Use of biomass boilers or gasification of biomass from agricultural waste.
PA2	Establishment of farmer cooperatives or distribution networks.
PA3	R&D for diversification of patchouli oil-based products (perfume, soap, household cleaners).
PA4	Partnerships with financial institutions for access to capital for small and medium enterprises (SMEs).
PA5	Processing patchouli waste into organic fertilizer through fermentation or bioactivators.

Table 6. Prioritization of preventive action for patchouli supply chain

Prt	Code	Preventive Action
1	PA5	Processing patchouli waste into organic fertilizer through fermentation or bioactivators.
2	PA3	R&D for diversification of patchouli oil-based products (perfume, soap, household cleaners).
3	PA4	Partnerships with financial institutions for access to capital for small and medium enterprises (SMEs).
4	PA2	Establishment of farmer cooperatives or distribution networks.
5	PA1	Use of biomass boilers or gasification of biomass from agricultural waste.

The application of the House of Risk (HOR) methodology in the Aceh patchouli supply chain identified and prioritized key risk agents, providing a data-driven foundation for targeted mitigation strategies. However, to fully appreciate the implications of these risks and the effectiveness of proposed interventions, it is essential to discuss their impacts across the three pillars of sustainability: environmental, economic, and social dimensions.

On environmental impact, the highest-ranked risk agent continued use of wood as fuel for patchouli distillation directly contributes to deforestation and increased carbon emissions, undermining local biodiversity and ecosystem health. This unsustainable practice not only depletes natural resources but also accelerates land degradation, making future cultivation less viable. The absence of organic fertilizer production and poor waste management further exacerbate soil nutrient depletion and pollution, reducing long-term agricultural productivity. Mitigation strategies such as processing patchouli waste into organic fertilizer and transitioning to alternative energy sources like biomass boilers are thus critical for closing nutrient cycles, reducing environmental footprints, and supporting regenerative agricultural practices.

Economically, the patchouli supply chain is hampered by limited access to capital, a lack of product diversification, and dependence on a small number of collection agents or intermediaries, which leads to price volatility and reduced bargaining power for farmers. The absence of innovation in derivative products restricts value addition, keeping farmers and local businesses in a price-taker position in the global market. High operational costs stemming from inefficient production processes, outdated technology, and expensive logistics further erode profit margins. The proposed strategies, such as fostering partnerships with financial institutions, establishing cooperatives, and investing in R&D for new patchouli-based products, directly address these economic vulnerabilities. By enabling access to finance, improving market linkages, and supporting product innovation, these interventions can stabilize incomes, enhance competitiveness, and ensure the economic sustainability of the sector.

Socially, the patchouli supply chain faces challenges including limited institutional support, weak farmer cooperation, and a lack of training or extension services. These factors contribute to low adoption of sustainable practices, limited knowledge transfer, and reduced resilience to shocks such as market downturns or climate variability. The absence of organized farmer groups or cooperatives not only weakens collective bargaining but also hinders access to government programs and external support. Mitigation actions like cooperative development, capacity building, and inclusive financial partnerships are essential for strengthening social capital, empowering smallholders, and promoting equitable growth. Furthermore, community-focused programs as demonstrated by initiatives like IFF's traceable supply chain and reforestation efforts can deliver direct benefits to farmers and broader rural communities, enhancing social well-being and long-term sector resilience.

The risk ranking and prioritization process revealed that the most critical threats to the patchouli supply chain are deeply intertwined with sustainability challenges. Environmental risks, if left unaddressed, will undermine the resource base required for future production. Economic risks limit the ability of farmers and businesses to invest in sustainable improvements, while social risks perpetuate cycles of vulnerability and inefficiency.

The effectiveness to difficulty (ETD) analysis of mitigation strategies underscores the importance of selecting interventions that are not only impactful but also feasible within local resource constraints. For example, processing patchouli waste into organic fertilizer (highest ETD ratio) offers a low-cost, high-impact solution that addresses both environmental and economic goals. Similarly, product diversification and improved access to capital are practical steps toward greater value addition and financial stability. However, strategies such as transitioning to alternative energy sources, while environmentally desirable, may require phased implementation and external support due to higher initial costs.

In brief, a holistic risk management approach grounded in the HOR framework and informed by sustainability principles enables the patchouli supply chain in Aceh to move beyond reactive problem-solving. By proactively addressing the root causes of environmental degradation, economic vulnerability, and social fragmentation, the sector can build resilience, enhance competitiveness, and contribute meaningfully to the well-being of local communities and ecosystem.

To ensure the practical value of the proposed mitigation strategies for the Aceh patchouli supply chain, it is crucial to provide a detailed feasibility analysis and clear implementation pathways for each prioritized action. This approach not only highlights the strategies' effectiveness but also addresses their operational, financial, and institutional realities, ensuring that recommendations are actionable for stakeholders ranging from farmers to policymakers.

The top-ranked strategy processing patchouli waste into organic fertilizer stands out for its high effectiveness-to-difficulty ratio, making it both impactful and readily implementable. This approach leverages existing waste streams from patchouli distillation, requiring only modest investments in training and simple fermentation or bioactivator equipment. Local extension services and cooperatives can facilitate farmer training, while government agricultural programs can support initial funding. The technical requirements are low, and the benefits are immediate: reduced environmental impact, improved soil fertility, and lower input costs for farmers. Barriers such as initial labor or knowledge gaps can be overcome through demonstration plots and peer-to-peer learning, making this a highly feasible intervention for rapid scaling.

The second priority, research and development for patchouli oil-based product diversification, is moderately more complex but remains feasible with targeted support. This strategy involves encouraging SMEs, cooperatives, and research institutions to develop new value-added products such as perfumes, soaps, and household cleaners. Implementation can begin with technical workshops and innovation grants, utilizing the expertise of local universities and research centers. Financial feasibility is supported by potential access to government innovation funds and private sector partnerships, while collective marketing and certification schemes can help overcome market entry barriers. The growing demand for natural products both domestically and internationally further enhances the commercial viability of this approach 1.

Facilitating partnerships with financial institutions for SME capital access is another highly practical strategy. By adapting existing microfinance models and leveraging cooperative structures, this approach can be implemented quickly and at scale. Government-backed credit guarantees and risk-sharing mechanisms can reduce barriers for both lenders and borrowers, while targeted financial literacy training ensures that farmers and small businesses are equipped to manage new capital responsibly. The institutional feasibility is high, given the presence of established microfinance institutions and the positive track record of cooperative-based lending in Indonesia.

The establishment of cooperatives and farmer distribution networks is also a feasible strategy, drawing on Indonesia's long history of successful agricultural cooperatives. Implementation involves legal facilitation, organizational training, and initial seed funding, which can be accessed through rural development programs or donor agencies. The social feasibility is high, particularly if early successes are demonstrated and participatory governance models are adopted. Challenges related to leadership and trust can be addressed through transparent management and ongoing capacity building efforts.

Adoption of alternative energy sources, such as biomass boilers or gasification units, presents greater technical and financial challenges. While these solutions offer significant long-term environmental benefits by reducing deforestation and emissions, they require higher upfront investment and more complex maintenance. As such, implementation should begin with pilot projects targeting larger-scale processors or cooperative-owned facilities, supported by blended finance (government grants, soft loans, and private investment). Demonstration projects can help build local technical capacity and showcase the benefits, paving the way for gradual scaling as costs decrease and technical expertise grows.

In summary, the prioritized mitigation strategies for the Aceh patchouli supply chain are not only theoretically sound but also operationally and financially viable within the local context. The most immediately actionable strategies organic fertilizer production, product diversification, and expanded access to capital can be rapidly deployed using existing resources and institutional frameworks. More complex interventions, such as alternative energy adoption, require phased implementation and external support but are crucial for long-term sustainability. By providing these detailed implementation pathways and feasibility assessments, this study equips policymakers, industry stakeholders, and farmer organizations with a clear roadmap for building a resilient, sustainable, and competitive patchouli industry in Aceh.

4. CONCLUSIONS

This study demonstrates that the sustainability and resilience of the Aceh patchouli supply chain can be significantly enhanced through the systematic application of the House of Risk (HOR) methodology, which enables the identification, prioritization, and mitigation of critical risks across all supply chain stages. The results reveal that the most disruptive risks stem from environmentally unsustainable practices (such as the use of wood as distillation fuel), limited innovation in value-added products, restricted access to business capital, a lack of organized farmer networks, and the absence of organic fertilizer production. Addressing these interconnected risks is essential for ensuring the long-term viability of the patchouli industry from environmental, economic, and social standpoints.

The mitigation strategies formulated in this research are not only theoretically robust but also highly practical and feasible for implementation by local stakeholders. Processing patchouli waste into organic fertilizer emerges as the top-priority strategy, offering a dual benefit: it reduces environmental impact by recycling waste and improves soil fertility at a relatively low cost and technical barrier. This approach is immediately actionable for farmers and processors, requiring only modest investments in training and simple equipment. Similarly, the diversification of patchouli-based products through targeted research and development can open new market opportunities, stabilize farmer incomes, and reduce the sector's vulnerability to price fluctuations. This strategy leverages local knowledge and resources, making it accessible for small and medium enterprises with support from cooperatives or local government programs.

Improving access to capital through partnerships with financial institutions is another highly feasible strategy. By leveraging existing microfinance schemes and fostering cooperative structures, this approach can be rapidly scaled to reach a broad base of patchouli farmers, empowering them to invest in productivity improvements and risk-reducing technologies. The establishment of farmer cooperatives and distribution networks, while requiring a higher degree of coordination and initial investment, has proven effective in other agricultural sectors and can be facilitated through targeted policy support and capacity-building initiatives.

Although the adoption of alternative energy sources such as biomass boilers presents a greater challenge due to higher upfront costs and technical complexity, it remains a valuable long-term goal for reducing the environmental footprint of patchouli processing. This strategy is best pursued incrementally, starting with pilot projects and external funding support, before wider rollout.

In summary, the mitigation strategies prioritized in this study especially those with high effectiveness-to-difficulty ratios are both impactful and realistically achievable within the local context. Their implementation will not only address immediate risks but also lay the groundwork for a more sustainable, competitive, and socially inclusive patchouli industry in Aceh. These findings provide clear, actionable guidance for policymakers, industry leaders, and farmer organizations seeking to build a resilient supply chain that balances economic growth with environmental stewardship and community welfare.

ACKNOWLEDGEMENT

The authors would like to *Atsiri Research Center PUI PT Nilam Aceh* - USK, All stakeholders in the Aceh patchouli supply chain.

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