Seaweed Supply Chain Risk Identification in Sabah Using Fuzzy Failure Mode and Effect Analysis

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Abstract. Kappaphycus sp. and Eucheuma sp. were cultivated in Sabah, Malaysia, mainly to extract a compound called carrageenan which used in various industries including human food, pet food, fertiliser, and pharmaceutical. As any agricultural activities, seaweed industry also full with risks and uncertainties. This study hence was conducted to identify risk sources along the supply chain (SC) of seaweed cultivated in Sabah, Malaysia. Data were collected using face-to-face, in-depth interview with Key Informants (KIs) (n = 33). Interviews were transcribed and analysed using thematic analysis using ATLAS.ti. The analysed data then were further analysed using FMEA (Failure Mode and Effect Analysis) in integration with Fuzzy set theory for risk prioritisation. The result has shown that farmers faced 19 unique risks, while intermediaries 13 risks, and 16 risks on the customers part. The analysis also showed that the three most critical risks for with the highest fuzzy RPN number is exchange rate fluctuations, highly volatile global seaweed price and followed by changes in government policy. This research has successfully identified, categorised and assessed 18 most important risk sources that have the probability of disrupting the seaweed supply chain in Sabah. Should stakeholders or policymakers like to ensure the sustainability of the industry, those are the risks that should be paid more attention to increase the resilience of the SC.

1. Introduction
Seaweed, both macro- and macroalgae, can be divided into three main groups according to the colour of their pigments. Those which contained red pigment were grouped into Rhodophyta, while taxonomists classified seaweed with green pigment as Chlorophyta, and lastly, Phaeophyta is a group belonged to seaweed with brown pigment [1]. Other than its ecological importance, community living by coastal regions has been exploiting seaweed for centuries as a food source [1] which rich in calcium, iron, iodine, vitamins, natural antioxidants and proteins. Since last a few decades, many pharmaceutical firms also started to look toward seaweed as a new source for new drugs [2] such as antiviral agents against human immune deficiency virus (HIV) [3] thyroid goitre [4], cardiovascular diseases, osteoarthritis, and diabetes, and anti-ageing and anaemia [1].

Another type of red seaweed, Kappaphycus, and Eucheuma is the primary source of a phycocolloid called carrageenan [5]. The phycocolloid is mostly used because of its gelling capability, especially in the dairy industry since ancient times in China, Ireland, Britain and Europe. Carrageenan has been used as a stabilizer in dairy-based products such as cheese, ice cream, pudding, and milk [5], sausages, cheaper and processed meat [6]. Kappaphycus and Eucheuma are abundantly cultivated in Indonesia, the Philippines and Malaysia [7].

Most of the market for seaweed cultivated in South East Asia is for the carrageenan industry [8]. Hence the majority of farmers prefer to plant K. alvarezii than any other species such as Eucheuma because the former contained a higher percentage of κ-carrageenan [6] thus securing better price in the market. Kappaphycus and Eucheuma made up to the list of seven most cultivated seaweed taxa in the world [9].
Since the 1960s, due to the development of new food products [10] and more processed food, demand for seaweed especially carrageenophytes is expected to increase substantially [11, 12]. For example, more research has been done on the potential of seaweed for industrial uses which open up a new market for seaweed, beyond regular commodity for food and feed [13,14], and source of polysaccharides [15] into biomass and bioenergy [16], biofertilizers [17], cosmeceuticals, nutraceuticals, and pharmaceuticals [18,19,20].

It is estimated that the market value of seaweed cultivation to be worth around USD4.2 billion, constituting almost half of all marine aquaculture products [21]. Moreover, the fact that this industry employs close to half a million workers around the world [11] give it more reason to be sustainably managed.

The first objective of this study is to map the structure of seaweed supply chain in Sabah; secondly to identify every possible risk source that might exist along the supply chain, and the third objective is to prioritize those risks based on its fuzzy integrated value.

2. Literature Review

2.1 Definition of Risk
Like any other agricultural activities, seaweed and its by-products are not shy of risks. Risk itself can be defined in various ways, depends to which perspective it is looked from [22,23,24]. For example, according to Zsídís [25], risk can be defined scientifically as a function of a probability of occurrence and the severity of its adverse effect. Meanwhile, van Mieghem [26] defined risk as “a possible undesirable consequence of uncertainty”. Some authors also agreed that risk cause undesirable deviation from the original objective [27] or when the measured outcome is lower than the expected value [28,29].

In contrast to the definition of risk; however, researchers are still having a problem to come with a concession regarding the most precise definition of supply chain risk [22]. The paper from Ho et al. [29] defined supply chain risk as “the likelihood and impact of unexpected macro and/or micro-level events or conditions that adversely influence any part of a supply chain, leading to operational, tactical or strategic level failures or irregularities”. It emphasises on two criteria; unexpected events and the adverse impact of the said event towards a supply chain, in agreement with many other prior authors.

2.2 Supply Chain Risk
Risks in a supply chain can be divided into two broad categories namely macro and micro [29] or may also referred as catastrophic and operational [30]. Macro risks or disruptions are one that exists outside of the supply chain and still has a significant impact on the member of the chain such as climate change, natural disaster, political instability, and economic uncertainty. Meanwhile, micro factors refer to risks that might exist or cause by the activities performed directly by the players in the said supply chain which can be further divided into five subcategories; demand, manufacturing, supply, information, transportation, and financial.

Disruption risk such as climate can play a vital role as a risk source in agriculture. For example, the geographical location of East Sabah exposed the industry to a strong wind blowing starting from October until February during the northeast monsoon season [31]. During this period, wind motion in the atmosphere are capable of influencing sea current which will adversely affect the physicochemical complex of the environment such as seawater temperature, salinity, and light attenuation as shown in a study by Trung [32]. The unfavourable underwater condition is taxing to the seaweed growth performance, which can be observed from lower biomass gain and smaller thalli. The size of the thalli and roughness of the sea is directly related and can reach more than 10% [33,34]. The location of seaweed farms which usually located in open sea increase its vulnerability to storms and possibly typhoon which has been reported in the Philippines [35] and Gilbert Island [36].

On the other hand, another risk source, for example, demand risk can exist in a few forms; positive and negative. Sodhi [37] discussed demand risk as a last-minute change in order quantity which prompts a company to either decrease or lowers their inventory. Negative demand risk occurs when final quantity which ordered by the end customer is lower than inventory, which in the end will create surplus while on the other hand, positive demand is when final quantity ordered is higher than inventory available.
2.3 Fuzzy Failure Mode and Effect Analysis (Fuzzy FMEA)

This research attempted to apply fuzzy Failure Mode and Effect Analysis (FMEA) on the first two processes of SCRM; identification and evaluation of risks by using seaweed industry in Sabah as a case study. Introduced in the 1960s, Failure Mode and Effect Analysis (FMEA) is one of the tools widely used in manufacturing, engineering, and aerospace [38]. The method called for the derivation of Risk Priority Number (RPN) by calculating the severity (S) of risk, its occurrence (O), and also the ability to detect (D) a risk before it materialised [39]. However, this method is not without its weaknesses. Risk Priority Number (RPN) has been criticised by many researchers [40,41,42] mainly due to its assumption that every element; S, O, and D are equally important. Other than that, classical FMEA also requires linguistic input to describe risks from domain experts who are considered too subjective and are not quantitatively precise [43].

The integration of fuzzy set theory to FMEA was introduced by Zadeh [44]. Fuzzy can assign membership values expressing the degree to which a certain value of a variable fits a linguistic concept. Accordingly, a gradual transition between different states of a variable can be achieved through the use of membership functions (MFs). Moreover, the fuzzy set theory also capable of managing situations in which accurate data are scarce or hard to collect, or circumstances where information are explained in linguistic and subjective terms [38].

3. Research Method

This study was conducted using primary qualitative data gathered using face to face interview and structured questionnaire instrument. For the purpose of simplification, the methodology was summarised in a diagram below.

![Diagram](image)

**Figure 1.** Flow chart summarising methodologies used in this study.

3.1 Study Area and Data Collection

Data collection was conducted at the largest producer of fresh eucheumatoid seaweed by area; Semporna, Sabah. In the area, most of the production was centred at Sebangkat Island, Bum-Bum Island and Manampilik Island which made of 83% of total production [45]. The interview was conducted in two phases to 33 respondents who are directly involved in the industry where 27 of them were owner or manager of seaweed farms, four collectors, and processors. All respondents were selected using non-probability sampling through purposive sampling, and snowball technique was used to identify a key player in the industry. These respondents or Key Informants (KIs) were considered as a domain expert on their respective role in the seaweed supply chain.

A semi-structured questionnaire was adopted and modified based on a framework by Jaffee et al. [46]. Recorded interviews were immediately transcribed verbatim and analysed using Atlas.ti version 8.2.4 for Mac. Transcribed interviews were then subjected to thematic analysis [47]. The second stage of data collection was held guided by a failure mode and effects analysis (FMEA) based on Stamatis [48].

3.2 Data Analysis.
Failure Mode and Effect Analysis (FMEA) required respondents to rate risks identified during the first phase of data collection according to its severity (S), detection (D), and occurrence (O) between 1 to 10 as detailed in Table 1 to 3. Severity refers to the magnitude of a risk, while detection is the capability of a system or procedure to discover risk potential before it happens. Lastly, the occurrence is the frequency of a particular risk factor to occur [48]. Consequently, for every risk identified \((i)\), a risk priority number (RPN) was calculated using the following equation (1) below.

\[
RPN_i = \text{Severity} \times \text{Occurrence} \times \text{Detection}
\]

However, the value obtained from calculating RPN resulted in a vague and imprecise value. Besides, the rating by domain experts which used linguistic terms is not very objective [49]. Moreover, RPN also could not differentiate the importance of every factor \((S, O, \text{ and } D)\) weight [50]. Hence, to overcome the issue, this study integrated FMEA with fuzzy membership function. Fuzzy set theory has the capability to provide objective values from the vague linguistic variables. It also could assign a different weight to every factor.

### 3.2.1 Risk Assessment with Fuzzy Membership Function

To simplify the process of fuzzification for severity, occurrence, and RPN, this study used a triangular membership function as shown in Equation (2) where \(a\) and \(b\) are respective top and bottom ends while \(\mu\) is the vertex triangle.

\[
\mu_A(x) = \begin{cases} 
\frac{(x - a)}{(b - a)}, & \text{for } a \leq x \leq b \\
\frac{(c - x)}{(c - b)}, & \text{for } b \leq x \leq c \\
0, & \text{otherwise}
\end{cases}
\]

On the other hand, a trapezoidal membership function was used and is shown in Equation (3).

\[
\mu_A(x) = \begin{cases} 
\frac{(x - a)}{(b - a)}, & \text{for } a \leq x \leq b \\
1, & \text{for } b \leq x \leq c \\
\frac{(d - x)}{(d - c)}, & \text{for } c \leq x \leq d \\
0, & \text{otherwise}
\end{cases}
\]

Finally, a method of “left and right rating of fuzzy number” was used to defuzzify and prioritized the result into concrete value. All three parameters of FMEA were multiplied as fuzzy numbers to obtain fuzzy RPN, and the result is measured as a triangular fuzzy number. The Fuzzy RPN then defuzzified using “left and right rating of fuzzy number” followed by risk prioritization.

| Criteria | Effect | Triangular Fuzzy number | Rank |
|----------|--------|-------------------------|------|
| No effect | None (NO) | \((0 , 0.1 , 0.2)\) | 1 |
| Very minor effect on product or system performance. | Very minor (VM) | \((0.1 , 0.2 , 0.3)\) | 2 |
| Minor effect on product or system performance. | Minor (MI) | \((0.2 , 0.3 , 0.4)\) | 3 |
| Small effect on product performance. | Low (LO) | \((0.3 , 0.4 , 0.5)\) | 4 |
| The product does not require repair. | Moderate (MO) | \((0.4 , 0.5 , 0.6)\) | 5 |
| Moderate effect on product performance. | Significant (SI) | \((0.5 , 0.6 , 0.7)\) | 6 |
| The product requires repair. | Product performance is degraded. | \((0.6 , 0.7 , 0.8)\) | 7 |
| Comfort or convince functions may not operate. | Product performance is severely affected but functions. | \((0.7 , 0.8 , 0.9)\) | 8 |
| The system may not operate. | Failure is hazardous and occurs without warning. | \((0.8 , 0.9 , 1)\) | 9 |
| Its system is inoperable. | Failure involves hazardous outcomes and/or noncompliance with government regulations or standards. | \((0.9 , 1 , 1)\) | 10 |
| Failure is hazardous and occurs without warning. | Hazardous (HA) | \((0.9 , 1 , 1)\) | 10 |
It suspends the operation of the system and/or involves noncompliance with government regulations.

| Criteria | Effect | Triangular Fuzzy number | Rank |
|----------|--------|-------------------------|------|
| Failure unlikely. History shows no failures. | Remote (R) | (0, 0.1, 0.2) | 1 |
| A rare number of failures likely. | Low B (LB) | (0.1, 0.2, 0.3) | 2 |
| Very few failures likely. | Low A (LA) | (0.2, 0.3, 0.4) | 3 |
| Few failures likely. | Moderate C (MC) | (0.3, 0.4, 0.5) | 4 |
| Occasional number of failures likely. | Moderate B (MB) | (0.4, 0.5, 0.6) | 5 |
| Moderate number of failures likely. | Moderate A (MA) | (0.5, 0.6, 0.7) | 6 |
| Frequent high number of failures likely. | High B (HB) | (0.6, 0.7, 0.8) | 7 |
| High number of failures likely. | High A (HA) | (0.7, 0.8, 0.9) | 8 |
| Very high number of failures likely. | Very high B (VHB) | (0.8, 0.9, 1) | 9 |
| Failure almost certain. History of failures exists from previous or similar designs. | Very high A (VHA) | (0.9, 1, 1) | 10 |

| Criteria | Detection | Triangular Fuzzy number | Rank |
|----------|-----------|-------------------------|------|
| Current controls almost always will detect the failure. Reliable detection controls are known and used in similar processes. | Almost certain (AC) | (0, 0.1, 0.2) | 1 |
| Very high likelihood current controls will detect the failure. | Very high (VH) | (0.1, 0.2, 0.3) | 2 |
| Good likelihood current controls will detect the failure. | High (H) | (0.2, 0.3, 0.4) | 3 |
| Moderately high likelihood current controls will detect the failure. | Moderately high (MH) | (0.3, 0.4, 0.5) | 4 |
| Medium likelihood current controls will detect the failure. | Medium (M) | (0.4, 0.5, 0.6) | 5 |
| Low likelihood current controls will detect the failure. | Low (L) | (0.6, 0.7, 0.8) | 6 |
| Slight likelihood current controls will detect the failure. | Slight (S) | (0.7, 0.8, 0.9) | 7 |
| Very slight likelihood current controls will detect the failure. | Very slight (VS) | (0.8, 0.9, 1) | 8 |
| Remote likelihood current controls will detect the failure. | Remote (R) | (0.9, 1, 1) | 9 |
| No known controls available to detect the failure. | Almost impossible (AI) | (0.9, 1, 1) | 10 |

4. Results and Discussion

4.1 Seaweed Supply Chain in Sabah
As presented in Figure 2, the seaweed supply chain in Sabah can be modelled as a network of three subsystems; supplier of fresh and dried seaweed, multilevel of middlemen, and customers. These subsystems were designed based on their nature of activity in the supply chain. The supply chain is integrated under a push paradigm where production is running almost the whole year without any forecasting on demand done by farmers since 90% of them are small farmers, non-citizen [51] without much access to market intelligence or information.
Main activities of seaweed farmers were planting, harvesting, drying, and short-term storage. Since the cultivation activity doesn’t need any input of fertilizer, the only recurring resources are the planting materials such as seed or *bibit*. Every four (4) cycles which took 45 days each, the seed will be exchanged between farmers from a different area as the genetic quality will become intolerable after the fifth generation. They will produce as many dried seaweeds as possible to be sold to a minor collector or *agents at sea*. These agents will collect and evaluate the quality of the dried seaweed on individual farmers small sea platforms, scattered across the sea. The quality of dried seaweed is determined by the Moisture Content (MC) where 35% to 40% are deemed acceptable [52]. If the MC is higher than 40%, the agent will penalize the farmer by offering a lower price. Other than that, this member of the supply chain also acts as a marine logistics provider by arranging boats and labour to collect the dried seaweed on each sea platforms. Agents at sea and farmers share a special relationship as they work on trust, where a similar situation can also be found in Indonesia [8]. Sometimes, agents at sea act as a credit provider or food supplier to these farmers as a duration for payment from more significant collectors were not consistent, and it could take up to three months. These agents also work like a mafia, in a way that each agent is taking care a group of farmers of a specific area on the sea and the farmers won’t sell their harvest to any other agents.

According to Sade et al. [53], there can be as many as five layers of agents before the harvested seaweed reached processors. Major collectors play a very crucial role in the supply chain as they provide ground logistics, storage facility, and marketing. A final subsystem in the network is customers, which composed of a few groups. The first and largest group customer is Tacara, a local private limited company which located in Tawau. This company processed dried seaweed into semi-refined, food-grade carrageenan for the international market, mostly to China and European countries. The second group of customers is from food and beverage company which bought seaweed in a much smaller amount to be used as an ingredient in their products. The third group is overseas buyers, mostly from the Philippines, and China.

4.2 Risk Identification, Categorization, and Assessment using Fuzzy FMEA
Risk identification along the supply chain was conducted to assess the most influential risks towards every member of the chain. As in Table 4, risks were assigned based on each member of the supply chain; farmers, middlemen, and customers. Farmers faced 19 unique risks, while intermediaries 13 risks, and 16 risks on the customers part. The risks on each member were categorized into seven risk types, based on the definition by Ho et al. [29], and were then assigned a risk rating by domain experts. Afterwards, its respective RPN was calculated by using Equation (1). The rate of each FMEA components (S, O, and D) was presented in Table 4 as the mean value. The higher the RPN, the more critical the risk is towards the system. To enable priority ranking to those identified risks, a criticality analysis was conducted.

Based on Table 4, the three most critical risks for with highest fuzzy RPN number is exchange rate fluctuations, highly volatile global seaweed price and followed by changes in government policy. Most of the largest customer for major middlemen and dried seaweed processor in Sabah is from overseas such as China, the Philippines, and eastern European countries. The business transaction which was conducted in US dollars makes profits and losses heavily dependent on the movements of exchange rates [54]. Radical changes in exchange rates might happen in a
short period, causing companies dealing internationally to lose a significant amount of profit. The economist has listed this risk as one of the top concern among executives [55].

Table 4. Risk assessment of seaweed supply chain in Sabah using FMEA

| Supply chain member | Risk type | Code | Risk factors | Severity (S) | Occurrence (O) | Detection (D) | RPN | Defuzzy RPN | Rank |
|---------------------|-----------|------|--------------|--------------|----------------|--------------|-----|-------------|------|
| Disruption          | FD1       | Security (ESSZONE) | 4 | 5 | 7 | 140 | 0.1395 | 4 |
|                     | FD2       | Climate | 7 | 3 | 7 | 147 | 0.1479 | 3 |
|                     | FD3       | Government policy | 8 | 2 | 9 | 144 | 0.1516 | 2 |
|                     | FD4       | Fuel price fluctuation | 2 | 5 | 10 | 100 | 0.1129 | 6 |
| Demand              | FDe1      | Too many middlemen | 3 | 10 | 1 | 30 | 0.043 | 14 |
| Manufacturing       | FM1       | Uncertain of seaweed yield | 7 | 5 | 4 | 140 | 0.1395 | 4 |
|                     | FM2       | Labour supply shortage | 8 | 7 | 2 | 112 | 0.1197 | 5 |
| Supply              | FM3       | Hard to get seeds | 5 | 5 | 2 | 50 | 0.0568 | 10 |
| Farmers             | FI1       | No information on current price of dried seaweed | 4 | 10 | 1 | 40 | 0.0553 | 11 |
| Transportation      | FT1       | Jetty is too far from farm | 6 | 7 | 1 | 42 | 0.0548 | 12 |
|                     | FF1       | Fluctuating seed price | 5 | 5 | 3 | 75 | 0.0795 | 7 |
|                     | FF2       | Fluctuating dried seaweed price | 6 | 3 | 9 | 162 | 0.1624 | 1 |
| Financial           | FF3       | No control over factory price | 5 | 10 | 1 | 50 | 0.0677 | 8 |
|                     | FF4       | High planting cost | 7 | 3 | 2 | 42 | 0.0492 | 13 |
|                     | FF5       | Payment from buyer delayed | 7 | 7 | 1 | 49 | 0.0633 | 9 |
| Disruption          | MD1       | Government policy | 5 | 2 | 9 | 90 | 0.0981 | 5 |
|                     | MD2       | Fuel price fluctuation | 4 | 3 | 10 | 120 | 0.1294 | 2 |
|                     | MD3       | Exchange rate fluctuation Not enough inventory to cater demand | 4 | 4 | 10 | 160 | 0.1664 | 1 |
| Demand              | MDe1      | Not enough inventory to cater demand | 6 | 2 | 2 | 24 | 0.0305 | 8 |
| Middlemen           | MDe2      | Sudden change of orders | 3 | 2 | 10 | 60 | 0.0305 | 8 |
| Manufacturing       | MM1       | Product damaged during storage Unstable raw dried seaweed supply | 5 | 2 | 2 | 20 | 0.0258 | 9 |
| Supply              | MS1       | Error in forecasting of supply and demand | 5 | 5 | 4 | 100 | 0.1023 | 4 |
| Information         | MH1       | Error in forecasting of supply and demand | 3 | 2 | 5 | 30 | 0.0361 | 7 |
| Transportation      | MT1       | Poor jetty infrastructure | 2 | 2 | 1 | 4 | 0.007 | 11 |
|                     | MT2       | Transport broke down | 6 | 3 | 3 | 54 | 0.0598 | 6 |
The uncertainty in the price of dried seaweed marked by “price boom”. It is a situation where a rapid increase in price in several cycles and followed by a crash. Usually, this happens when the market is flooded with money from China. The impact of the risk also felt by customers as they now will have to compete with a higher price, but with little capital. This phenomenal usually will be followed by a seaweed market crash. However, it is also common for individual involved in the agriculture sector or food system to perceived price volatility as one of the most critical risk factor [56]. One of the management strategies to handle price risk is by having forward contracts [57,58,59] but in Sabah seaweed industry the practice is non-existence. Price risk, as can be seen in this study affect producers and processors, but not so much on the middlemen.

The third risk that was regarded as high in the supply chain is government policy. As presented in Table 4, the reason for this situation is due to the unpredictability of government policy. As an example, the Malaysian government has included seaweed cultivation as one of its entry point projects for NKEA in 2012. This introduction of the new programme came with many changes in policy and implementation and caught both executive agencies and farmers by surprise. As a result, in 2012 the production of seaweed decreased for the first time since 2006 as reported by the Department of Fisheries [60].

5. Conclusion
From this study, it can be concluded that there were three subsystems identified in the seaweed supply chain in Sabah with a unique characteristic of specialized multi-level agents. Besides, this study also successfully attempted to implement fuzzy FMEA in risk identification and assessment of seaweed supply chain in Sabah. The result from the analysis shown that there is the member of the supply chain is interrelated by two types of risks. Farmers and processors were experiencing uncertainty in price risk while at the same time processors and middlemen also facing similar risk in term of fluctuating exchange rate due to their major market are overseas. Future research should expand this study by quantitatively analyse the best risk mitigation strategy to overcome the most critical risks which have been identified in this study.

Acknowledgements
The authors would like to thank Universiti Malaysia Kelantan. This work was supported and made possible by the Short Term Grant Scheme [R/SGJP/A07/00/01406A/002/2018/000526].

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