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Production Chain of Commercial Alginate from Sargassum (*Macrocystis pyrifera)* in Peru

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***Abstract*—Peru is a privileged country regarding marine hydrobiological resources due to the vast variety of algae and the biomass they possess. This advantage allows Peru to develop an industrial sector to produce hydrocolloids, a group of natural polymers, chemically known as polysaccharides, derived from marine algae. Among the most widely used hydrocolloids is commercial alginate, an input used in different industries such as food, cosmetics, chemicals, and textiles. This study aimed to identify and characterize the strategic variables that integrate the commercial alginate production chain from sargassum (*Macrocystis pyrifera*) in Peru and the social stakeholders that lead it. Based on an exploratory and descriptive scope, a structural analysis was conducted (using the theoretical bases of French Strategic Foresight as a methodological design) with the support of a panel of seven experts knowledgeable about the system studied and the MICMAC tool (Matrix of Cross Impacts and a Multiplication Applied to a Classification). The outcome shows that the key variables of the production chain are competitive prices, sales levels, potential markets, and quality control. Simultaneously, identifying the most influential social stakeholders made it possible to propose strategies to control the variables to shape and control the chain adequately. This study lays the foundations for the strategic planning of future scenarios for the system in the long term.**

***Keywords*— Commercial alginate; sargassum; production chain; structural analysis; Peru.**

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I. INTRODUCTION

The extraction and collection of brown macroalgae in different regions of the world are considered an economic activity of high commercial value due to the increased demand for algal biomass to obtain valuable products. In the central and southern coasts of the extensive Peruvian coast, one of the commercial brown algae genera with the greatest presence in the regions is *Macrocystis pyrifera*, also known as *sargassum*, which belongs to the *Laminariaceae* family and is considered the largest seaweed in the world.

Concerning its morphological structure, the cell wall of sargassum consists of cellulose microfibrils containing two hydrocolloids: alginic acid (alginate) and sulfated fucans [1]. Their function is to give strength and flexibility to the algae so that they can adapt to the variability of movements of the waters in which they develop. In addition, it is an excellent biodegradable and renewable material that, under its properties, can be used in various industrial applications [2].

In the current context, thanks to the booming global demand for algal biomass, *Macrocystis pyrifera* is considered an attractive raw material with potential use in the hydrocolloid industry. This is due to the presence of alginate in its cell wall, which is of great commercial importance for the manufacture of products in various industries such as food, cosmetics, agrochemical, pharmaceutical, and textile. According to Bixler and Porse [3], the processed food industry remains the main market for hydrocolloids obtained from brown algae, which serve as stabilizing agents and texture regulators in food production. It is considered a popular ingredient, a food additive, and a carrier of essential components in the encapsulation of alginate gels [4].

Similarly, alginates are potentially used in various industrial applications such as textile printing, paper coating, or personal care and pharmaceutical products, which could become a profitable niche market. Thus, alginate has been found to be of great utility for potential biomedical applications, as alginate-based materials have been shown to inhibit a wide variety of viruses affecting different organisms, which is presumed to hold great promise for COVID-19 [5].

Therefore, the design and development of a sustainable biorefinery that generates food, fuel, and chemical products should be promoted, which is largely influenced by the supply of raw materials, technological advances, and socioeconomic conditions [6], overcoming the existing barriers for the development of a viable algae industry.

A. Production Chain

The production chain is a system made up of interrelated stakeholders and a succession of operations for the production, processing, and marketing of a product or group of products in each environment (see Fig. 1). The links from the producer's perspective establish *backward linkages* with suppliers of productive inputs and technical services and *forward linkages* with marketers, processors, and consumers; in other words, with the market itself. The links interact within a relationship constituted by suppliers, producers, and other activities in producing goods and services [7].

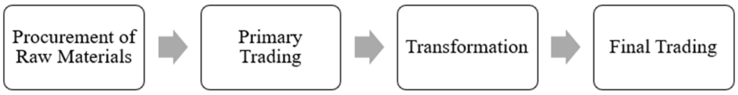


Fig. 1 Diagram of the commercial sargassum-alginate production chain in Peru

The chain can be broken down into a certain number of links or segments depending on geographical, social, political, technological, and economic factors. These are composed of a group of economic stakeholders that conduct similar activities, have proprietary rights over a product or service in a defined state of value, transfer this product to the same clients and receive inputs from suppliers [8]. Within a link, there are value generation processes, which are constantly changing and transforming through innovation. Each segment has specific technical and transaction costs, as well as risks and benefits.

Two types of stakeholders can be identified: direct and indirect. Direct stakeholders participate in the different links and interact within the chain, have direct contact, and own the goods at some point, such as the producer, rural collector, wholesaler, retailer, transformers, processors and exporters, and consumers. Indirect stakeholders provide support as suppliers of productive inputs or services (technical assistance, research, credit, transportation, communications, etc.) for the development of the chain [8].

B. Studies in South America: The Case of Chile

Brown algae (*Chromista, Phaeophyceae*) are the most abundant photosynthetic inhabitants of the intertidal zone in the northern and southern hemispheres. Among the algal species, *Macrocystis pyrifera* is widespread, ravaging the entire Pacific coast from North America to South America, wherein the latter region extends from Peru to Chile [1]. Within the South American region, Chile has a wealth of algal species, some of which have traditionally been extracted from natural beds to produce hydrocolloids (e.g., agar, carrageenan, and alginates). However, a high proportion of the extracted biomass is exported as dried material to processors in Asia and Europe [9].

The harvesting and collection of natural Chilean brown seaweed populations for alginate extraction represent 10% of the world supply, up to 300,000 dry tons per year, and an industrial valuation of US$60 million [10]. Until 2000, the Chilean brown algae fishery was based on natural mortality, whereby artisanal fishers collected all the algae that had been washed ashore.

Since then, driven by international demand for raw material, three economically important seaweed species (*Lessonia nigrescens, Lessonia trabeculata,* and *Macrocystis pyrifera*) have been intensively harvested in coastal areas between latitudes 18° and 42° S [11]. The influence of the Humboldt current promotes a strong upwelling of chilly waters rich in nutrients towards these coastal ecosystems in the central and northern parts of the Chilean coast, becoming one of the most productive marine ecosystems on the planet. Due to these environmental conditions, this region supports the world's largest industry for harvesting seaweed from natural beds [10]. Above all, *Macrocystis pyrifera* has shown the highest overall growth rate (47%) [12]

In terms of economic income, Chile exports algae as raw material without processing, as well as other natural resources (e.g., copper or wood). Most are dried, packaged, and exported to China, Japan, Norway, France (brown algae) and Canada, France, Denmark, and Taiwan (mainly red algae) [13]. Considering the large-scale seaweed fisheries exploiting natural beds in Chile and the susceptibility of brown seaweeds to oceanographic events such as El Niño [14], seaweed farming appears as a logical development initiative.

The production of algal sporophytes, both in laboratory conditions and the natural environment, may help the natural recovery of rocky coastal areas after mass mortality. Additionally, it could allow the development of a sustainable biomass resource for various applications [6]. Therefore, due to the need to develop the economies of Chilean coastal communities, several government agencies are supporting research projects that seek alternative uses and ways to add value to the brown algae currently harvested [14].

C. Analysis of the Peruvian Commercial Alginate Production Chain

PEST (Political, Economic, Social, and Technological) analysis mainly identifies the environment in which a company or sector operates and provides information that allows predictions to be made about new situations and circumstances [15]. The present study used it to conduct a competitive diagnosis of the current production chain of commercial alginate from sargassum (*Macrocystis pyrifera*).

Political and legal factors, state support, and government legislation are the most influential factors in the production chain. Within the legislation in force in Peru, there is Supreme Decree N° 007-2016-PRODUCE that modifies articles of the Regulation of Fishing Management of Marine Macroalgae. The modifications indicate that the dependencies grant the permit to extract or collect and the stockpile with the fishing competence of the Regional Governments or by the Ministry of Production of Peru. It is according to their competencies and as long as the transfer of sectoral functions is completed by the provisions of Law No. 27783, Law of Bases of Decentralization, and Law No. 27867, Organic Law of Regional Governments. The permit to collect and stockpile may be valid for up to two years, renewable for an equal period at the holder's request. Both provisions aim to establish a formal seaweed harvesting process and avoid indiscriminate and unregulated fishing, which could endanger the raw material of this productive chain.

Regarding government support, the Peruvian government promotes studying and preserving brown algae. Innóvate Perú reports that, with state funding, the private sector conducted research to safeguard marine species. This is an example of what the private sector can do with the support of the State: studies using a valid methodology to ensure the preservation of algae in the open sea, especially because it is a marine species that can provide work for many [16].

Regarding economic factors, Peru has been progressively recovering from the negative results of 2020 due to the Covid-19 pandemic. The GDP increased by 13.8% from January to April 2021 concerning the previous year, where the fisheries sector grew 114.1% in April 2020 [17]. Seaweed exports belong to the fishing sector and other marine derivatives, representing 2% of the sector's exports [18]. On the other hand, seaweed prices have maintained an upward trend during the last eight years due to the vast variety of derivative products [19]. Finally, due to Peru's brief history of the algae industry attracting capital investment continues to be a limiting factor due to a lack of knowledge and evidence of successful results [20].

Concerning sociocultural factors, Peru has been one of the countries with the least promotion of professional careers linked to science in the Latin American region. The main reason for this limitation is the lack of intellectual capital due to migration to other countries because of the lack of promotion and development of these professions at the national level [21].

Sustainable development is a worldwide topic with much support from local and regional governments and manufacturing companies seeking to generate green economies without carbon emissions, use resources efficiently, and are socially inclusive [22]. Finally, the Peruvian population is characterized by being loyal to the goods and products it consumes (see Fig. 2). Even though the product has better benefits, the Peruvian consumer opts for the best known. This lack of consumer culture impedes eco-friendly products from being considered substitute input in a productive process, where cost is often prioritized [23].

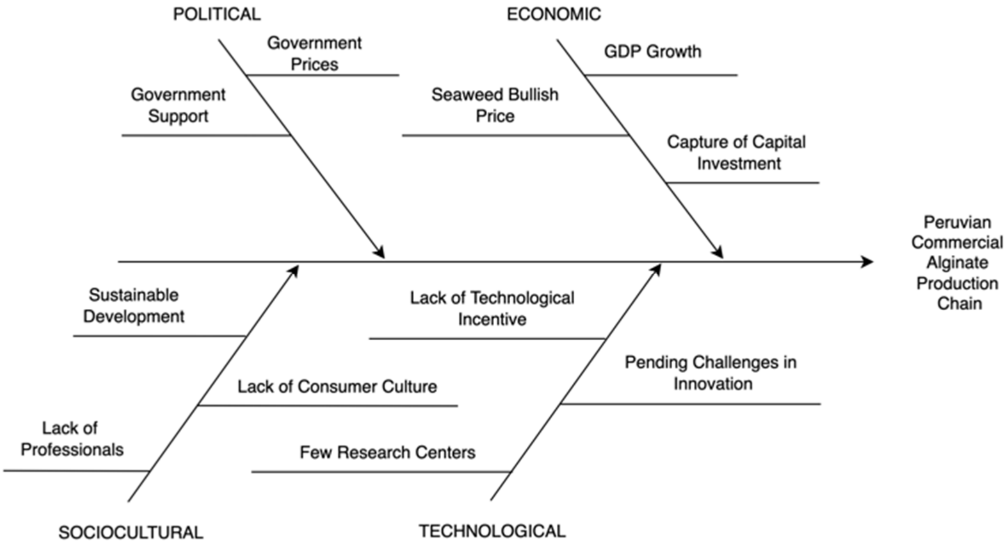


Fig. 2 PEST analysis of the Peruvian commercial alginate production chain

Science and technology have a theoretical and practical relationship that are key to national development, economic growth and sustainability, the training of professionals, and the generation of competencies, according to market needs [24]. In Peru, science and technology concepts do not complement the reality of student training. There are insufficient incentives for science and technology, few sources of financing, limited promotion instruments for technology absorption, transfer, and dissemination, inadequate sources of financing, and inadequate support for technological entrepreneurship [25].

From a regional perspective, there are still pending challenges in Latin America in terms of research and innovation since these challenges would be considered fundamental instruments for fighting poverty, improving health indices, and achieving sustainable, inclusive, integrated, and equitable development in Latin American countries [24]. It is here where the lack of qualified personnel that could benefit from the implementation of larger research centers becomes evident and where university higher education is favored with incentives that develop its training capacity in terms of market needs and the demands of society [25].

II. Materials and Method

This study, which was exploratory and descriptive in scope, used the theoretical bases of French strategic foresight as its methodological design. For this purpose, a structural analysis was used, a tool that allows us to visualize opportunities based on the impact of certain variables within a given system. Therefore, it is important to define the background and contextual recognition to identify the variables to select the most influential and decisive for the study. The structural analysis of this research had four phases, detailed in Table 1.

TABLE I
VARIABLES OF THE PRODUCTION CHAIN

Code	Variable
Procurement of Raw Materials	
V1	Accessibility to the Resource Description: Stranding intensity, number of times per week that sargassum is collected.
V2	Raw Material Conditioning Description: Number of days that the sargassum remains drying on the shore.
V3	Extraction Regulation Description: Number of regulatory processes by the central/regional government for the extraction of sargassum.
Primary Trading	
V4	Communication Routes Description: Kilometers of trails and access to beaches by trucks.
V5	Volume of Storage Description: Cubic meters of dry sargassum were collected.
V6	Transport Flow Description: Number of trucks transporting dried sargassum.
Transformation	
V7	Availability of Economic Resources (Financing) Description: Number of loans approved by rural banks and/or banks for working capital and the acquisition of machinery and equipment.
V8	Processing Time Description: Processing time to produce 100 30 kg bags of ground twill/standard processing time.
V9	Quality Assurance Description: % By weight that does not meet minimum quality standards/total weight of the lot.
V10	Production Costs Description: Annual costs incurred in production.
V11	Energy Efficiency Description: Level of savings generated by the energy source used in the transformation.
Final Trading	
V12	Trade Agreements Description: Number of trade agreements in force.
V13	Sales Level Description: Annual sales of dried sargassum.
V14	Potential Markets Description: Number of businesses willing to invest in a more sustainable product.
V15	Competitive Prices Description: The sales price of substitute products (Chilean market as a reference).

In the first phase, the variables involved in the production chain were defined and grouped into four dimensions: raw material supply, primary commercialization, transformation, and final commercialization. They were chosen based on recognizing the links that make up the production chain of commercial alginate obtained from sargassum. The variables were validated by seven Peruvian experts and academics with knowledge of the sector. The list of the 15 variables identified is shown in Table 2.

TABLE II
HIERARCHIZATION OF STAKEHOLDERS

Priority	Stakeholder
1	Processing Plants (A3)
2	Trading Companies (A4)
3	Peruvian Sea Institute (A9)
4	Regional Governments (A10)
5	Fishing Community (A5)
6	Algae Farmers (A1)
7	Collectors (A2)
8	Ministry of Foreign Trade and Tourism of Peru (A6)
9	National Council for Science, Technology and Technological Innovation (A8)
10	Ministry of Production of Peru (A7)

In the second phase, the same method used in the previous phase was used to identify the strategic stakeholders involved in the commercial alginate production chain. The following direct stakeholders were identified: algae farmers, collectors, algae processing plants, and trading companies. Concerning indirect stakeholders, the following entities were identified: the Marcona artisanal fishing community (Copmar), the Ministry of Foreign Trade and Tourism (Mincetur), the Ministry of Production (Produce), the National Council for Science, Technology and Technological Innovation (Concytec), the Peruvian Sea Institute (Imarpe) and the respective Peruvian regional governments.

For the third phase, a double-entry confrontation matrix established the degree of influence and dependence between the variables described above. To fill out the matrix, the seven experts were summoned to qualify the relationships of dependence and motricity between the system variables. The group of experts indicated whether the influence was strong, potential, moderate, weak, or null between the variables. It was convenient to analyze the information obtained to reach a consensus on the results, considering a consensus statistical criterion. Each variable of the system presented two ratings, the first of dependence (X) and the second of motricity (Y);

which can be shown as coordinates (X; Y) in a Cartesian plane. A unified matrix was then obtained that shows the relationship of motricity and dependence for the variables of the sargassum production chain. It is worth mentioning that the sum of the rows Y is related to the number of times that the variable impacts the others (motricity index). In contrast, the sum of the X columns indicates the number of times each variable depends on the missing variables (dependence index).

Based on the above, the hierarchy of variables and stakeholders was determined with the help of the MICMAC software (Matrix of Cross Impacts Multiplication Applied to a Classification) [26], which is used to classify the variables according to their direct and indirect relationships [27]. The results were plotted on a Cartesian plane, which reflects the degree of dependence versus the degree of motricity. Each axis was divided by its average line of motricity and dependence to visualize the location of the variables in each of the four zones (quadrants) generated: power, conflict, autonomy, and output. A fifth zone containing the platoon variables can be considered [28], located near the average line, as shown in Figure 3.

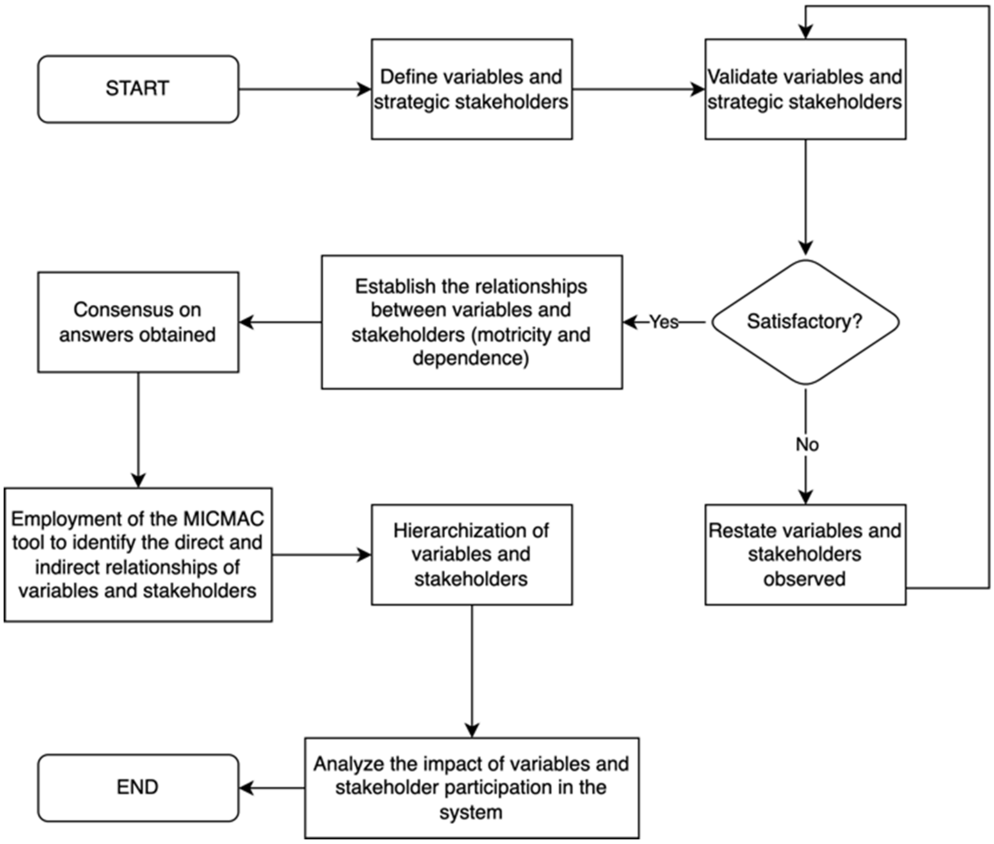


Fig. 3 Flowchart of the research method

In the last methodological phase, the impact between the intersected variables was analyzed with the stakeholders' participation in the system. All to offer a viable diagnosis for the possible conduction and planning of the system.

III. Results and Discussion

A. Results

The results obtained from the unified and consensual matrix, also called Direct Impacts Matrix (DIM), and its respective projection on the Cartesian plane present a priori the key variables of the system. According to the distribution of the variables in the plane, the evidence points to a relatively stable system (Figure 4). However, it was decided to highlight the possible existence of hidden impacts that affect the stability of the system to confirm the scheme of relationships already obtained. This was possible by raising the Direct Impacts Matrix (DIM) to a power *n* until reaching its stability in a new Indirect Impacts Matrix (IIM) that considers such indirect relationships [26].

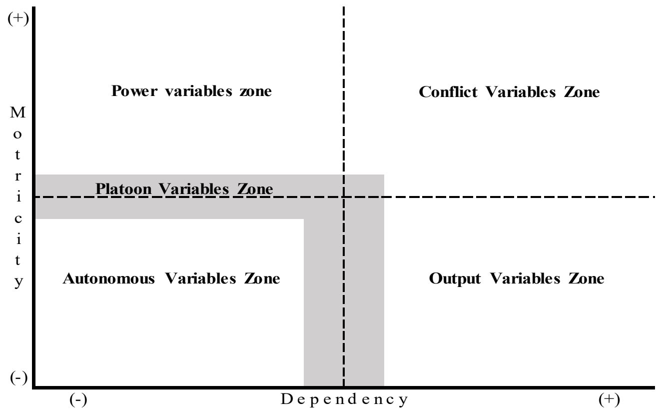
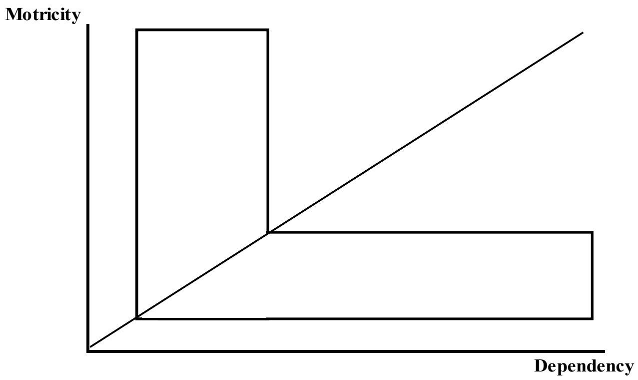


Fig. 4 Cartesian plane zones for variable characterization

Figure 5 below shows the Cartesian plane with the projection of the fifteen variables studied for the sargassum production chain. Each one is located in one of the zones mentioned above with a different degree of mobility and dependence. The plane shows the average lines and the bisector in a referential way based on the Indirect Impacts Matrix (IIM) (see Fig. 6).



1. Relatively stable system

Fig. 5 Stability of a system

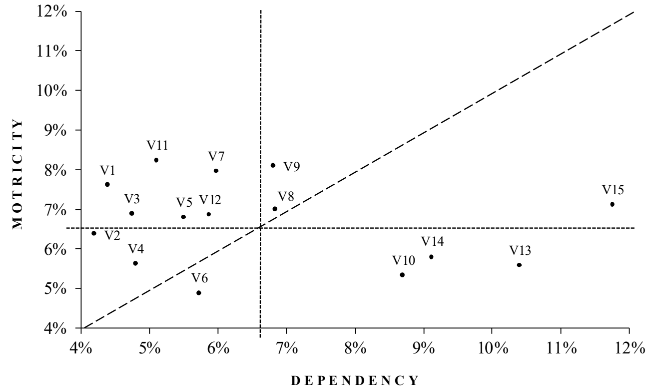


Fig. 6 Projection of the variables on the Cartesian plane (Indirect Impact Matrix)

The findings suggest the relative stability of the system and that the indirect relationships between variables are similar to those obtained in the Direct Impacts Matrix (DIM). After processing, validation, and projection of the variables, sufficient elements of judgment were compiled to define each variable's location within the zones (quadrants) mentioned.

Three variables configure the power zone:

- (V11): Energy Efficiency
- (V7): Availability of Economic Resources
- (V1): Accessibility to the Resource

These variables are characterized by low dependence and high influence. Actions within the system may have been oriented to these variables, as they are intuitively recognized as highly driving. Moreover, they can be considered explanatory of the system under study since they condition the system's dynamics as a whole.

The **conflict zone** is constituted of two variables:

- (V9): Quality Assurance
- (V15): Competitive Prices

These variables are highly dependent and influential simultaneously; in other words, their essence is instability, and every action taken on them will have immediate repercussions on the other variables, modifying the overall dynamics of the system. The existence of both variables depends, to a substantial extent, on the variables located in the power zone (energy efficiency, availability of economic resources, and accessibility to the resource).

Due to the influence of both variables, they will have implications on the three variables located within the **output zone**:

- (V13): Sales Level
- (V14): Potential Markets
- (V10): Production Costs

These variables are highly dependent and not very influential. Their evolution within the system can be explained mainly by the impacts of the variables in the power and conflict zone. They are interpreted as the hands of the clock, where they follow the winding (power variables) movement that arrives through the internal bearings of the clock, which allude to the conflict variables [29].

The **zone of autonomous variables** is the one that groups together those variables with little influence and dependence, which experience a relatively autonomous development within the system. In other words, they have negligible impact and can be excluded without further detriment to the analysis. Both variables belong to the primary marketing dimension:

- (V4): Communication Routes
- (V6): Transport Flow

The remaining variables are called **platoon variables** because they are located in the region next to the axes' mean in the Cartesian plane's intermediate region. They are not completely characterized since they result in average motility and dependence variables in the system. It was interesting that variables of all dimensions of the system are present in this zone:

- (V2): Raw Material Conditioning
- (V3): Extraction Regulation
- (V5): Volume of Storage
- (V8): Processing time
- (V12): Trade agreements

Finally, to rank and identify the potential strategic variables of the system, the projection of each variable's coordinates on the plane's bisector was analyzed, and those with the highest average value were selected. Those ranked first could be considered key variables of the system.

Due to the analysis of indirect impacts, the ranking of the variables revealed subtle shifts in the order of priority of some of them. This ranking allowed us to refine and rearrange the variables' priority and validate the correct hierarchy. The four variables presented below are the key variables of the system studied:

- (V15): Competitive prices
- (V13): Sales level
- (V14): Potential markets
- (V9): Quality assurance

The same analysis was conducted concerning the social stakeholders involved in the system, which revealed which stakeholders have the greatest mobility but are also very dependent.

B. Discussion

The results obtained from the structural analysis are consistent with some previous research findings. Competitive pricing, as a key system variable, is a fundamental factor because of its great direct and crucial impact on the business's profitability. In addition, it is important to establish an appropriate pricing strategy to increase competitiveness and thus gain a larger market share. Bixler and Porse [3] pointed out that hydrocolloids have become commodities, and therefore, the supplier with the lowest price is the one that would be more favored in the business.

In the global scenario, because demand has outstripped supply, algae prices have increased. At the same time, China has created a competitive environment that has made it difficult to pass on cost increases to the closing price. Only those industries that have control over both the supply of raw materials and their efficient manufacture will be able to survive. Peru has good availability and access to the hydrobiological resource studied, so it can compete effectively in the market since it would not import seaweed from other countries, thus avoiding cost increases.

On the other hand, the potential markets are influential in the study because they are latent business opportunities that aim to increase demand, which despite having expanded in recent years, is still small and focused on the level of potential that could grow. Therefore, their appearance as a key variable is not unexpected. This agrees with Ullmann and Grimm [30] when they mention that there is enormous potential for developing a sustainable algae industry along the entire value chain; thus, market research, technology valorization, product development, and new applications are requirements. In addition, it is worth noting that algae and algae-derived products are produced almost exclusively for high-value, low-volume products; therefore, they are far from competing with cheap products such as plant-based proteins.

From the evidence, it can be inferred that the key variables identified are strategically linked because they are interrelated, and their progress could be facilitated by the actions taken by the most important strategic stakeholders. The key variables found focus on the final part of the production chain, and the most important stakeholders (processing plants and marketing companies) are those that act and are related to them. This is because Peru has unrestricted access to the collection of this resource, so more attention should be paid to the last link in the chain, where the opportunity to industrialize the macroalgae studied lies.

Since the industrial development of marine macroalgae in Peru is extremely limited, it is necessary to establish diverse strategies to strengthen the formation of the commercial alginate production chain from the sargassum. First, it is necessary to clarify that in Peru no government regulation encourages state investment to industrialize this resource [31]. Therefore, the State should promote research and development of new novel products using marine macroalgae as raw material to promote the development of a feasible algae industry that will expand this resource towards new market opportunities.

In the current scenario, the global demand for algal biomass is rapidly increasing due to the development of the hydrocolloid industry and the increasing number of users who prefer to consume new sources of protein and healthy food supplements from marine algae. In this context, the analysis of the economic feasibility of large-scale seaweed production in various countries is taking on immense importance to increase the sustainable production of the source. This trend is expected to continue to increase over time as new applications and uses are found for the resource under study. Therefore, it is convenient to implement the best practices of countries such as Chile, China, and the United States since algae cultivation is experiencing a renewed boom.

Chile is a world reference that has achieved an advantageous position in the global aquaculture market [32]. Its contribution to this sector comes mainly from salmon and trout farming; only a small proportion corresponds to seaweed. However, it is considered the main producer of macroalgae in the West, which represents a development alternative to reduce the overexploitation of natural prairies and diversify the artisanal fishing sector [33]. It should be noted that approximately 17% of the algae that go through a production process are obtained from Chile, which is the only country in Latin America where algae cultivation is an advanced activity [31].

Aquaculture in Peru has a low level of development and is oriented to cultivating a few species, such as fan shells, shrimp, trout, and tilapia [34]. There are no hatcheries to produce marine macroalgae, which is an opportunity to develop a viable algae industry. In addition, it is necessary to specify that the extraction or harvesting of algae must be associated with cultivation for the resource to be sustainable and for the industry to be successful. The identification of key variables and strategic stakeholders clarifies the possible improvement opportunities for the industrial development of marine macroalgae in Peru.

IV. Conclusion

The key variables (competitive prices, sales level, potential markets, and quality assurance) were determined through the projection points on the diagonal of the cartesian plane of indirect impacts, where the higher the value, the greater the degree of motricity and dependence of these variables on the others. The projection points for the key variables were 9.43%, 7.99%, 7.46% and 7.45%, respectively; it was relevant that all key variables belong to the last links of the production chain (transformation and final trading). Therefore, the method used was very useful in clarifying the most relevant variables and strategic stakeholders involved in the system under study.

Finally, the characterization of the variables and strategic stakeholders in the commercial alginate production chain from sargassum (*Macrocystis pyrifera*) provides a starting point for the design and strategic planning of probable future scenarios in the medium and long term, opening new lines of research based on the evidence presented in the study. The current interruptions in the consolidation of the chain are evident opportunities for improvement that should be addressed. Peru has the resources to become a world power in the algae treatment and processing industry, and this diagnostic aims to contribute to this objective.

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