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ARTICLE

Environmental-Based Supply Chain Integration for the Development of Carrageenan Production Centers in Laikang Village Takalar Regency, South Sulawesi Province

Leffy Hermalena [1*], Melinda Noer [1], Novizar Nazir [2], Rika Ampuh Hadiguna [3]

[1] *Agriculture Science Doctoral Program, Faculty of Agriculture, Andalas University, Padang 25163, Indonesia*

[2] *Faculty of Agricultural Technology, Andalas University, Padang 25163, Indonesia*

[3] *Faculty of Industrial Engineering, Andalas University, Padang 25163, Indonesia*

ABSTRACT

The rapidly growing seaweed farming contributes to food, feed, biofuel, and biochemicals, with Indonesia being the largest exporter of raw seaweed (53.35%) but low in carrageenan derivative products (4.49%). Sustainable farming supports SDG 13 and SDG 14 through emission reduction, marine ecosystem conservation, and increased biodiversity. However, its supply chain faces challenges in raw material availability, such as fluctuating harvests, inconsistent quality, limited logistics infrastructure, and market price volatility. Therefore, good environmental management is needed to optimize raw materials in carrageenan production through resource efficiency, environmentally friendly products, environmental regulations, and market and stakeholder awareness. This study identifies factors in the environment-based supply chain that influence the development of carrageenan production centers and analyzes their ecological impacts using quantitative SEM analysis. SEM analysis reveals that resource efficiency, waste management, environmental regulations, and stakeholder awareness and commitment are the main influencing factors. shows significant factors including raw material efficiency, waste management, and environmental regulations. Environmentally based supply chain integration for the development of carrageenan production center areas can be done by; focusing on sustainability and minimal environmental impact, support for achieving SDG 12, 13, and 14, strategies for sustainable raw material management, circular economy, sustainability

*CORRESPONDING AUTHOR:

Agriculture Science Doctoral Program, Leffy Hermalena, Faculty of Agriculture, Andalas University, Padang 25163, Indonesia;
Email: viecoremapii@gmail.com

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certification, renewable energy and environmentally friendly technology, and stakeholder collaboration and awareness.
Keywords: Seaweed; Carrageenan; Environmental Sustainability; Supply Chain; Production Center Area

1. Introduction

Sustainable agricultural development plays a role in forming and providing food, industrial raw materials, feed, bioenergy, employment, foreign exchange sources, and income sources, as well as environmental conservation through environmentally friendly agricultural practices [1]. It emphasizes the efficient use of natural resources such as land, water, and energy to maintain sustainable production without damaging or depleting ecosystems [2–4]. Sustainable agricultural systems support the conservation of biodiversity and integrate practices such as agroforestry, crop rotation, and the use of organic fertilizers [5, 6], This sector not only maintains the balance of ecosystems and land quality but also plays a strategic role in national development. This sector provides benefits from farmers to end consumers, contributing to economic development, poverty reduction, food security, and creating an inclusive value chain [7, 8].

The seaweed industry is a rapidly growing sector in several countries. Currently, seaweed is produced on a large scale, mainly for food, feed, bioenergy, and biochemicals. Seaweed cultivation provides various ecosystem services that have ecological and economic value [8]. The market leader for high-value seaweed products, especially those containing carrageenan, is the food sector [9]. In addition, seaweed has great potential as a carbon sink and reducer of greenhouse gas (GHG) emissions through the absorption of carbon dioxide (CO_2) during photosynthesis. Seaweed can absorb CO_2 from seawater, thereby helping to reduce the concentration of CO_2 in water and the atmosphere. The rate of CO_2 absorption by seaweed can reach 5–10 times faster than land plants. In addition, seaweed can also be used as a raw material for bioplastics or bioenergy, replacing fossil-based products, thereby reducing carbon emissions from the industrial sector [10, 11].

Indonesia is currently a producer of seaweed fresh, chilled, frozen, and dry (53.35%) the second largest in the world after China, increasing exportin early 2021 reached a volume of 500 tons, while for carrageenan derivative products the lowest (4.49%). Dried seaweed products dominate Indonesia's exports, followed by gelatin and carrageenan products. Consumption of this commodity continues to increase by an average of 10.4% per year (between 2020 and 2022), the increase reaching 11.2% to 16.2% with a value reaching USD 7.71 billion [12, 13]. However, the demand for this raw material has not been met because the supply of raw materials for carrageenan derivative products does not meet international standards. The importance of seaweed for future needs emphasizes the right supply chain strategy, considering the specific characteristics of agro-food products that contribute to risk [14]. The supply chain of this commodity faces complex problems, such as the instability of raw material availability resulting in the inability to meet customer needs. Poor quality can be harmful to reducing long-term customer satisfaction. Fluctuations in seaweed prices greatly affect profitability resulting in losses. In addition, intensive planting and harvesting practices can damage marine ecosystems through environmentally unfriendly methods, namely the use of synthetic materials polluting the waters, waste from cultivation activities, the impact of climate change (increased seawater temperatures and changes in current patterns), damage to marine ecosystems, destructive organisms, and microplastic pollution in the waters.

Seaweed is not only the main raw material for carrageenan, gelatin, and alginate products but also has great potential in the development of bioenergy and environmentally friendly biomaterials [15]. Carrageenan is a hydrocolloid (water-based for fats and oils) as a derivative product obtained from red seaweed has an important function in the food industry as a stabilizer, thickener, and gel former. Carrageenan is found in a variety of consumer goods, industrial products, and biotechnological applications, especially in dairy products, such as ice cream, chocolate milk, milk pudding, processed cheese, water-based mouthwash gels, low-calorie jellies, and baby food; as well as pet food. Consumer uses of carrageenan include a binder for toothpaste, a thickener for shampoos and cleansers, an agent in skin creams and lotions, and air fresheners. Carrageenan is also used in industrial products such as abrasives, pigments, pharmaceutical products, textiles, and agricultural agent solutions.

Carrageenan can also be used as an immobilization biocatalyst in the field of biotechnology [16]. This industry supports the achievement of SDG 12 and SDG 13 (helping mitigate climate change and conserve marine ecosystems).

Environmentally based supply chain integration is needed to create a balance between meeting market needs and preserving the environment, by optimizing resource efficiency, improving raw material quality, and minimizing the ecological impact of production activities. Sarkis [17], Green Supply Chain Integration (GSCI) involves internal and external processes within the supply chain to minimize environmental impacts while optimizing economic efficiency. This involves the management of raw materials, production processes, distribution, and environmentally friendly waste management. The main components of the integration framework are (1) Green Procurement (procurement of raw materials from sustainable sources, such as selecting seaweed with sustainable harvesting methods), (2) Green Manufacturing (production processes that reduce waste and carbon emissions, including recycling wastewater or energy in the carrageenan extraction process), (3) Green Logistics (product distribution by minimizing environmental impacts, for example by reducing the carbon footprint of transportation) [18].

The approach to developing production center areas can streamline the availability of raw materials from various subsystems; upstream subsystems (provision of agricultural production facilities), agricultural production subsystems, downstream subsystems (processing of agricultural products), and marketing, which are interrelated with each other [19–23]. The production center area is a concept that can encourage the acceleration of increasing added value followed by increasing production centers from the food crop agriculture sub-sector, plantation sub-sector, forestry sub-sector, fisheries sub-sector, and livestock sub-sector supported by relevant facilities and infrastructure, with attention to environmental management. The production center area is formed in a production area ranging from small scale (micro) to large scale (macro) and economical [24].

The theoretical framework of this research is based on the Green Supply Chain Integration (GSCI) approach which involves managing the entire supply chain process in an environmentally friendly manner for the development of carrageenan production center areas with a focus on economic, environmental, and social sustainability. The integration emphasizes several key aspects: (1) collaboration among multiple stakeholders, including businesses, government, local communities, and academia, to develop sustainable production and distribution methods; (2) the Life Cycle Assessment (LCA) system, which evaluates the environmental impact at each stage of carrageenan production, from raw material sourcing to the final product; and (3) waste management, involving the adoption of a circular economy approach for efficient waste processing [25]. The development of this area is also supported by the principles: (1) eco-efficiency [26], producing more products with fewer resources and minimal environmental impact, and (2) technological innovation for more efficient and energy-saving carrageenan extraction, such as enzymatic or high-pressure methods.

The advantages of integrating environmentally conscious practices into the supply chain include; (1) environmental sustainability (reducing emissions and waste from the production process), (2) operational efficiency (reducing costs through optimizing energy and raw materials), (3) competitive advantage (environmentally friendly carrageenan products have added value in the global market) [27]. So it can be implemented in the carrageenan industry by paying attention to the involvement of local communities in managing raw materials and meeting global standards (ISO 14001) as a form of commitment to sustainability [28].

Economically, regional development plays a role in economic efficiency through waste reduction and optimal resource utilization, thus reducing production costs. Optimizing the carrageenan production process using energy-saving technology or recycling liquid waste, reducing waste of raw materials through proper harvesting methods and efficient extraction processes [25]. Products produced through eco-friendly processes tend to have greater added value. In the carrageenan industry, sustainable products can be positioned as premium offerings that comply with sustainability standards such as organic certification or ISO 14001. With the growing consumer preference for low-carbon footprint products, there is an opportunity to achieve higher market prices [27]. Environmentally focused supply chain management can enhance the economic well-being of seaweed farmers through sustainable harvesting practices and fair partnerships while also creating new job opportunities in waste management and the development of eco-friendly production technologies. In the Triple Bottom Line concept, environmental sustainability reduces long-term economic risk, in carrageenan production can reduce dependence on unsustainable resources to maintain the stability of raw materials and reduce the risk of fines or penalties due to violations of environmental regulations [29]. Additionally, there are opportunities for product innovation that align with consumer demands, such as carrageenan-based bioplastics or eco-friendly food additives. These innovations can also enhance collaboration prospects with companies specializing in green technology [28].

Seaweed farming is an economic activity that aligns with environmental sustainability goals. Seaweed supports marine ecosystems through water quality control, marine habitat provision, and carbon sequestration. Sustainable practices provide economic opportunities for coastal communities while supporting adaptation to climate change. So this activity not only provides direct financial benefits but also contributes to the protection of the global ecosystem. Circular Economy is an economic approach that aims to minimize waste and maximize resource use through regenerative systems. Unlike the traditional linear economic model (take-make-dispose), the circular economy adopts the principles of reducing, reuse, and recycling. The circular economy is a structured approach focused on reducing waste and pollution, extending the lifespan of products and materials, and restoring natural ecosystems. It aims to establish closed-loop systems that promote sustainability through three core principles: (1) designing to eliminate waste and pollution, (2) ensuring products and materials remain in use for longer periods, and (3) revitalizing natural ecosystems [30].

The concept of a circular economy can be implemented in the procurement of raw materials and carrageenan production through; (1) utilization of production waste (wastewater, residue) as raw material for fertilizer or feed, (2) environmentally friendly technology to reduce carbon emissions in the extraction process, (3) a sustainable seaweed harvesting system that maintains the balance of the marine ecosystem. The circular economy provides several key advantages, including (1) decreasing reliance on primary resources, (2) lowering greenhouse gas emissions, (3) generating new economic value through recycling and innovation, and (4) prolonging product lifespan while enhancing supply chain efficiency. This approach serves as a strategic solution to achieving both economic and environmental sustainability simultaneously [31].

The development of the area through environmental-based supply chain integration (GSCI) is expected to achieve a balance between meeting market needs and environmental conservation, optimizing resource efficiency and production processes, improving raw material quality, and minimizing ecological impacts. Through the implementation of the main components of GSCI, it is expected to; (1) increase economic efficiency by reducing waste of resources, while reducing environmental impacts such as carbon emissions, waste, and pollution, (2) build a sustainable seaweed industry by supporting responsible raw material management, and increasing product competitiveness in the global market, (3) reduce the negative impacts of production processes, transportation, and waste on the marine environment and its surroundings, (4) produce high-quality and environmentally friendly derivative products such as carrageenan, thus meeting market needs and international regulations, (5) contribute directly to the achievement of sustainable development goals, especially SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Protection of Marine Ecosystems). So that this integration not only has an impact on the success of the supply chain but also supports environmental sustainability and the welfare of coastal communities through regional development.

The purpose of this study is to identify environmental-based supply chain integration factors that influence the development of carrageenan production centers and to analyze the ecological impact of supply chain management on the carrageenan production process so that good environmental management and provision of carrageenan raw materials in terms of quality and quantity are realized to increase biodiversity and sustainability of the seaweed agroindustry.

2. Literature Review

2.1. Supply Chain Concept

The agri-food supply chain is a network system leading from the farm to the market, thus making agricultural products and services to the end consumer to satisfy consumer demand. The agri-food supply chain can be divided into three categories: perishable goods supply chains, non-perishable goods supply chains, and processed food products supply chains. Perishable products are fresh items with a limited shelf life and fluctuating supply and demand such as fruits, vegetables, and flowers. In contrast, Non-perishable products are items that can be stored for extended periods such as coffee, grains, and nuts [32]. Processed food products contain agricultural materials and other materials that help in the processing of food physically and chemically. These products are ready for direct consumption by consumers, including canned food, dairy products, chips, and others.

Supply chain systems are closely related to logistics systems and inventory systems. Logistics is defined as the management of various resources, including capital, labor, and information, which are utilized for receiving, handling, storing, transporting, and delivering physical materials [33] and argues that logistics is part of the supply chain process in terms of planning, implementing, and controlling efficiently and effectively the flow and storage of materials, services, and related information from the point of origin to the point of destination to meet customer needs and satisfy the needs of stakeholders [34]. Aspects of logistics consist of customer service, transportation, storage, plant location selection, inventory control, ordering process, distribution, procurement, and demand forecasting.

The driving axis (driver) of the supply chain in improving the performance of the supply chain is described as follows [35]:

1. Facility
   A facility is a physical location in a supply chain network; where a product is produced, assembled, or fabricated. There are two types of facilities: production process locations and warehouse or storage locations. Decisions about the role, location, capacity, and flexibility of a facility will have an impact on the performance of the supply chain.
2. Supply
   In the supply chain, inventory can be divided into raw materials, semi-finished goods, and finished goods. Changes in inventory policies can dramatically change the efficiency and responsiveness of the supply chain.
3. Transportation.
   Transportation causes the movement of inventory from one point to another in the supply chain. Transportation can occur from several combinations of modes and routes, and each combination of modes and routes will have different performances from each other. The choice of transportation has a huge impact on the level of efficiency and effectiveness of the supply chain.
4. Information Technology
   Information technology consists of data and analysis about the facilities, inventory, transportation, costs, prices, and customers of the supply chain. Information is the biggest driving force in the supply chain because it directly affects the other driving forces of the supply chain. Information allows management to make a supply chain very responsive and very efficient.
5. *Sourcing*
   Sourcing is the selection of who will perform a particular supply chain activity such as production, storage, transportation, and information management. At the strategic level, sourcing decisions determine which activities will be performed by the company and which activities will be performed by third parties. Sourcing decisions affect the level of responsiveness and efficiency of the supply chain.
6. Price
   Price determines how much a company can charge for the goods and services it produces that make them available in the supply chain. Price will affect the behavior of buyers of goods and services, and in turn, will affect the performance of the supply chain.

2.2. Supply Chain Management (SCM) Concept

Supply Chain Management (SCM) is the integration of planning, implementation, coordination, and control of all business processes and activities to produce and deliver products efficiently to meet market needs and as a method, tool, or approach to supply chain management [36, 37]. It is described as a collection of strategies aimed at effectively coordinating suppliers, production, warehousing, and storage to ensure that products are manufactured and delivered in the correct quantities, to the right locations, and at the appropriate times. This approach seeks to minimize total system costs while fulfilling demands at all levels [34]. Supply chain management is the simultaneous management of the flow of materials and information within and between facilities such as vendors, production, assembly, and distribution [38].

SCM of fishery and marine products represents the management of the entire production process from processing, distribution, and marketing until the desired product reaches the hands of consumers. The supply chain management system can be defined as a unified integrated marketing system, which includes the integration of products and actors, to provide decisions on customer SCM of agricultural products is different from SCM of manufacturing because: (1) agricultural products are perishable, (2) the planting, growing and harvesting processes depend on climate and season, (3) the harvests vary in shape and size, (4) agricultural products are perishable and therefore difficult to handle [39, 40]. All of these factors must be considered in the design of agricultural product supply chain management because the condition of the agricultural product supply chain is more complex than the supply chain in general. In addition to being more complex, agricultural product supply chain management is also probabilistic and dynamic [41].

SCM is a series of approaches applied to integrate suppliers, entrepreneurs, warehouses, and other storage places efficiently. Products produced can be distributed in the right quantity, place, and time to minimize costs and satisfy customers. SCM aims to make the entire system efficient and effective, minimizing costs from transportation, and distribution to raw material inventory, materials in process, and finished goods. Several main players have an interest in SCM, namely suppliers, processors (manufacturers), distributors (distributors), retailers (retailers), and customers (customers) [42].

The main members of the seaweed supply chain in Indonesia have vertical collaborations that can be distinguished as seaweed farmers, local collectors; wholesalers or exporters, and seaweed manufacturers. Seaweed farmers, local collectors, and large traders are grouped into seaweed suppliers [43, 44]. The implementation of supply chain management has several basic components including [45]:

1. Plan.
   The beginning of the success of supply chain management is in the process of determining the supply chain management strategy. The main purpose of the strategy formulation process is to achieve efficiency and cost-effectiveness and ensure the quality of the products produced until they reach consumers.
2. Source.
   Companies must choose credible raw material suppliers who can support the production process to be carried out. Therefore, supply chain management managers must be able to set prices, manage delivery and payment of raw materials, and maintain and improve business relationships with suppliers.
3. Make.
   This component is the manufacturing stage. The supply chain management manager schedules the activities needed in the production process, product testing, packaging and preparation for product delivery. This stage is the most important in supply chain management. The company must also be able to measure quality, production output, and worker productivity.
4. Deliver.
   The company fulfills orders from consumer demand, manages a network of storage warehouses, selects distributors to deliver products to consumers, and arranges payment systems.
5. Return.
   Supply chain management planners must create a flexible and responsive network for defective products from consumers and form a consumer complaint service that has problems with the products delivered. Companies need to make regular business performance reports. So that company leaders can find out the changes in business performance that have been carried out in accordance with the initial objectives of supply chain management that have been set.

2.3. Seaweed Supply Chain

Global red seaweed production has increased significantly in recent years, especially *E. cottonii* and *Gracilaria*. Global demand for dried seaweed species *E. cottonii,* continues to increase due to increased carrageenan processing, especially in China. *E. cottonii* can be processed into semi-finished materials, such as alkali-treated carrageenan (ATC) in flake form, semi-refined carrageenan (SRC), and refined carrageenan (RC) in powder form. Most agar companies in Indonesia use *Gracilaria* sp. as their raw material because it is widely available in Indonesia and easy to cultivate. *Gracilaria* is usually sold to agar producers or used as traditional food [43].

Supply chain management (SCM) is concerned with the integration of network organizations consisting of suppliers, manufacturers, logistics providers, wholesalers/distributors, and retailers. The goal of SCM is to collaborate and manage the flow of products, services, finances, and information from suppliers to customers to achieve customer satisfaction, profitability, added value, and to create efficiency and effectiveness. In the long run, the benefits of SCM are to achieve competitive advantage in a system [35, 44, 47]. Although there are various definitions of SCM, they all have several factors in common: collaboration with suppliers and customers, flow activities, and balance of supply and demand. Supply chain combines the concepts of supplier relationship management (SRM) and customer relationship management (CRM) including customer service management, demand management, order fulfillment, manufacturing, flow management, product development, and commercialization and returns management [47].

The agri-food supply chain is a network system leading from the farm to the market, which then brings agricultural products and services to the end consumer to satisfy consumer demand. The agri-food supply chain can be divided into three categories: perishable goods supply chain, non-perishable goods supply chain, and processed food products supply chain. Perishable products are fresh products with limited shelf life and variable supply and demand such as fruits, vegetables and flowers. Non-perishable products are products that can be stored for a longer period such as coffee, grains, and nuts [32, 48].

Processed food products contain agricultural materials and other materials that help in the physical and chemical processing of food. These products can be directly consumed by consumers such as canned food products, dairy products, chips, etc. An important aspect of SCM is the identification of supply chain members who can be further distinguished as primary and supporting members. Primary members of the supply chain are all companies that carry out operational and/or managerial activities that are directly related to producing a particular product for a particular customer or market. Supporting members are companies that provide resources, knowledge, utilities, or assets to primary members of the supply chain; they are not directly involved in the main work of the production process of converting raw materials into products [44]. The main members of the seaweed supply chain in Indonesia have a vertical collaboration that can be distinguished as seaweed farmers, local collectors; wholesalers or exporters, and seaweed manufacturers. Seaweed farmers, local collectors, and wholesalers are grouped into seaweed suppliers.

One of the derivative products of seaweed is carrageenan which has hydrocolloid content. Hydrocolloids are made using long chains of polysaccharides and proteins that have hydrophilic substances and dietary fiber [49]. Stated, hydrocolloids come from plants, algae, microbes, and animal sources. They produce several hydrocolloids that are widely used in the food industry. Carrageenan can replace gelatin especially for vegetarians. The concentration of carrageenan is from 0.005% to 2% by weight of food products. Carrageenan is an ingredient in food, various consumer goods, industrial products, and biotechnology applications. In a number of food uses, carrageenan can be found in human food, especially in dairy products, such as ice cream, chocolate milk, evaporated milk, milk pudding, processed cheese, desserts, low-calorie jellies, and baby and pet foods. The use of carrageenan includes toothpaste, thickener for shampoo and cleansers, facial creams and skin lotions, and air fresheners. Carrageenan is also used in industrial products such as for abrasives, pigments, pharmaceutical products, and textiles. In the field of biotechnology, carrageenan as a biocatalyst [50]. Some studies on carrageenan; (1) Carrageenan Quality of Seaweed *Kappaphycus Alvarezii* from Maumere and Tembalang in Longline Cultivation System [51], showed that the gel strength and acid-insoluble ash in Maumere and Tembalang seaweed were not significantly different, while the viscosity, water content, sulfate and ash content of Maumere seaweed carrageenan were higher than those of Tembalang seaweed. (2) Carrageenan Quality From *Kappaphycus Alvarezii* Seaweed At Different Locations In Southeast Maluku Waters [52]. Carrageenan from Letman seaweed had the best appearance compared to Letvuan and Revav with a whiteness value of 68.22%. Based on the test results, only carrageenan from the Revav location met FAO quality standards. (3) Environmental impacts and implications of tropical carrageenophyte seaweed farming stated that *Kappaphycus* and *Eucheuma* seaweed cultivation in the field is widespread in tropical areas and is mostly carried out to extract carrageenan polysaccharides, which are used in commercial applications [53]. The impacts of seaweed cultivation may be less severe than some other human activities, to reduce the impact on local ecosystems by moving seaweed cultivation to deeper sandy bottom areas. (4) Environmental performance of seaweed cultivation and use in different industries: A systematic review cultivation can generate climate benefits if biogenic carbon sequestration and uptake are considered. However, the stability of the stored carbon requires further research. Seaweed has significant potential in various sectors, including bioenergy, food, feed, fertilizers, nanomaterials, construction, and cosmetics, supporting a circular bioeconomy [54].

3. Materials and Methods

3.1. Survey Procedure

This study uses a mixed method approach with an exploratory sequential design type; combining qualitative and quantitative research methods sequentially, where the first stage of the study was conducted with qualitative methods and the second stage was conducted with quantitative methods [55]. The priority of qualitative data collection and analysis was carried out in the early stages. Building on the results of the exploratory analysis in the first stage, the researcher continued the next stage with quantitative methods to test or generalize based on initial findings. This study was conducted in the largest seaweed production center in Indonesia, namely in Laikang Village, Mangarabombang District, Takalar Regency.

Laikang Village has a potential area for cultivation of approximately 10,000 Ha with a cultivated area of 3,773 Ha. Seaweed production in Laikang Village in 2021 reached 195,399.03 tons or around 32 percent of the total seaweed production in Takalar Regency [56]. Furthermore, Laikang Village became the main producer in South Sulawesi Province for seaweed commodities. Specifically for the Eucheuma cottonii type of seaweed, Takalar Regency is the number one producer, so it was designated as a seaweed cultivation village in South Sulawesi Province.

The research sample was determined using the simple random sampling technique. Simple random sampling was chosen because the research population was considered homogeneous and had relatively similar characteristics. To determine the sample from the entire population whose population size is known, it was determined using the Yamane formula [57]. The sample was determined as many as 352 people, namely seaweed farmers in Laikang Village, with the sampling technique being simple random sampling, because the research sample tended to be homogeneous, namely 90% of the community cultivated seaweed.

$$\mathrm{n} = \frac{\mathrm{N}}{1+\mathrm{N}(e)^2}$$

$$\mathrm{n} = \frac{2934}{1 + 2934(0.05)^2} = 352 \tag{1}$$

Information:
n = Number of samples
N = Population size
e = *Sampling error* (5%)

Qualitative data collection was carried out by: in-depth interviews [7, 55]; Focus Group Discussion (FGD) or focused group discussions [58]; Observation [54, 56]; Documentation [54, 56] to seaweed farmers, collectors, and agro-industry actors. Then quantitative data collection was carried out with questionnaires, Surveys [7].

3.2. Analysis Method

Analysis techniques in qualitative methods are used to compile and analyze data and draw conclusions to be conveyed to others [59]. The qualitative data analysis technique used in this study is the interactive model of [59], this model emphasizes an iterative and dynamic process, where researchers continuously interact with the data during the analysis process. The components of data analysis are as follows: data collection, data condensation, data presentation, drawing conclusions. This analysis flow seeks the required characteristics by referring to regional theory, supply chain management theory, economic and environmental theory. Then studying the meaning and providing interpretation of the process of environmental-based supply chain integration in inventory management for the development of carrageenan production center areas. Furthermore, the process and substance are analyzed in the form of a combination by considering several aspects such as planning, suppliers, manufacturing, delivery, return, and inventory management [60].

The quantitative data analysis technique used in this study is to use the statistical analysis method of Structural Equation Modeling (SEM). The reason for using this method is because SEM has many advantages, namely being able to test complex research models simultaneously and being able to analyze unobserved variables and taking into account measurement errors SEM can be a very effective analysis tool to explore factors in the integration of environmentally based supply chains that influence the development of carrageenan production centers and the ecological impact of the seaweed industry on the environment and help improve environmental management. The structural model image was created using SMARTPLS4 software which can produce estimates of the factor loading of each variable that shows the magnitude of the influence, both direct and indirect.

The variables measured; planning, suppliers, manufacturing, delivery, return, and inventory management. These variables were selected based on related theories in forming an integrated and environmentally based supply chain system, which can; (1) identify key factors that influence the efficiency and sustainability of the supply chain, (2) provide recommendations for inventory management that supports the development of sustainable carrageenan production center areas, (3) create a balance between environmental sustainability, market needs, and regional economic profitability. These variables represent core components in an environmental-based supply chain, through SEM the relationship between these variables can be measured systematically; (1) complex interrelationships (these variables influence each other in shaping the efficiency and sustainability of the supply chain, making them suitable for analysis with SEM which is designed to understand the complex relationships between variables), (2) qualitative and quantitative dimensions (testing direct and indirect relationships between variables such as process efficiency, environmental impact, and customer satisfaction), (3) Holistic models (helping to model the impact of these variables in an integrated manner on supply chain performance and environmental sustainability), (4) Hypothesis Validation (facilitates hypothesis testing on how each variable contributes to sustainability goals in the carrageenan supply chain).

3.3. Research Model, Variables and Hypothesis

3.3.1. Research Model

This study uses a mixed method approach with a sequential exploratory type, namely combining qualitative and quantitative research methods sequentially. Qualitative methods function to find hypotheses in limited samples, while quantitative methods function to test hypotheses in a wider population, so this method is included in the type of qualitative research useful for finding hypotheses and at the same time proving the external validity of the hypothesis [56, 61].

Figure 1 shows the flow or stages in quantitative research methods, especially in the process of testing hypotheses, including: (1) Problems and Potential (research begins with identifying problems or opportunities that require solutions or analysis. At this stage, researchers determine the background of the problem, research objectives, and research relevance), (2) Theoretical Review (after the problem is identified, a literature or theory review is conducted. The goal is to understand relevant concepts, theories, and previous research, so that hypotheses can be formulated based on scientific foundations), (3) Data Collection and Analysis (data is collected through certain methods, such as surveys, experiments, or observations. The collected data is then analyzed using statistical techniques to answer research questions or test hypotheses), (4) Hypothesis Findings (the results of data analysis are used to determine whether the hypothesis is accepted or rejected. This stage is the basis for making scientific conclusions. Next, focus on the quantitative process (testing hypotheses); (5) Population and Sample (researchers determine the research population (target group) and select a representative sample, (6) Data Collection (data is collected from samples using appropriate instruments, such as questionnaires, structured interviews, or tests), (7) Data Analysis (data that has been collected is processed using statistical techniques. This stage aims to identify patterns, relationships, or differences in the data, (8) Conclusions and Suggestions (researchers draw conclusions based on the results of data analysis. In addition, suggestions are given for practical applications, policies, or further research).

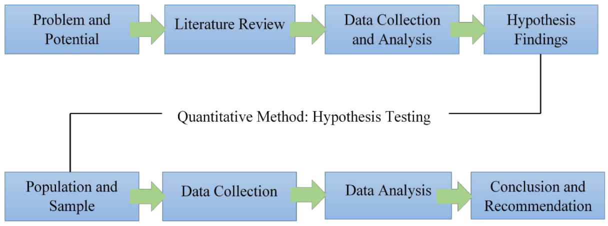

Figure 1. Sequential Exploratory Design Combination Method (Creswell & Plano Clark [61]; Sugiyono [56]).

3.3.2. Variables and Hypotheses

Research variables are attributes, characteristics, or values of a person, object, organization, or activity that have certain variations determined by the researcher to be studied and then conclusions drawn [62].

The variables in this study are needed to answer the research questions and achieve the research objectives. The variables include:

1. **Planning** (indicators: raw materials, production capacity, seaweed cultivation, technology, seeds, demand trends, harvest period, marketing institutions, raw material specifications, environmental monitoring, post-harvest waste management).
2. **Suppliers** (indicators: level of education, experience in seaweed farming, cultivation period planning).
3. **Manufacturing** (indicators: production equipment, production process efficiency, labor, carrageenan products, product testing, waste management).
4. **Distribution** (indicators: product quality and quantity, timeliness of product delivery, duration in selecting delivery services, transportation, product guarantee).
5. **Return** (indicators: return of defective products, replacement of defective products, timeliness of return of defective products).
6. **Inventory Management** (indicators: sustainability of seaweed supply from natural resources, level of organic waste from seaweed production, use of cultivation methods such as longlines that minimize environmental damage, raw material inventory, raw material storage).

The selection of planning, supplier, manufacturing, delivery, return, production capacity, inventory management and institutional variables is based on their respective important roles in supporting environmentally based supply chain integration, including; (1) Planning (strategic planning ensures coordination of the entire supply chain process, from raw material procurement to product distribution, planning includes efficient resource management, waste reduction, and environmentally friendly production schedules), (2) Suppliers (suppliers have a key role in ensuring the availability of high-quality seaweed raw materials from sustainable sources, relationships with suppliers need to be managed so that harvesting and cultivation practices are in accordance with sustainability principles), (3) Manufacturing (production process (manufacturing) is at the heart of converting raw materials into final carrageenan products), the focus on environmentally friendly manufacturing includes energy efficiency, waste recycling, and carbon emission reduction during the production process, (4) Deliver (distribution process involves transporting products from production locations to markets, environmentally friendly distribution aims to minimize carbon footprints, such as the use of low-emission transportation and efficient logistics management), (5) Return (returns, the return process is important for managing product waste, unused materials, or defective products, environmentally based returns enable the reuse of waste into value-added products, such as organic fertilizer or bioenergy), (6) Inventory management (inventory management ensures that raw materials and products are available on time, without waste or excess. stock, with an environmentally based approach, inventory management focuses on waste reduction, logistics efficiency, and environmentally friendly storage).

The research hypothesis will analyze the relationship of each variable's influence on the development of the production center area. The variables will be arranged into a hypothesis as follows; (H1) Planning influences inventory management, (H2) Planning influences the development of the production center area, (H3) Suppliers influence inventory management, (H4) Suppliers influence the development of the production center area, (H5) Manufacturing influences inventory management, (H6) Manufacturing influences the development of the production center area, (H7) Deliver (Demand fulfillment) influences inventory management, (H8) Return (raw material guarantee) influences inventory management, (H9) Inventory management influences the development of the production center area.

3.4. Structural Equation Modeling (SEM)

SEM is one of the methods used to analyze path equation models and SEM has advantages in conducting path analysis with latent variables [63, 64]. SEM is one of the analysis techniques to test and estimate causal relationships by integrating path analysis and factor analysis [65].

The stages in SEM analysis include:

1. Development of theoretical model: The most common critical error is omitting one or more significant predictor variables, known as Specification Error.
2. Creating a causal path diagram.
3. Converting path diagrams into structural equation models and measurement models.

Once the theoretical model is developed and described in a path diagram, the next step is to transform the theoretical model into a structural equation model. This model consists of:

(1). Structural equations are relationships between constructs (latent variables).

$$\eta = B\eta + \Gamma\xi + \zeta \tag{2}$$

(2). Measurement equation is the relationship between latent variables and indicator variables

$$\xi = \Lambda\xi\eta + \delta \tag{3}$$

The notations in the above equation:
x is an observable exogenous variable vector of size p x 1
η is a random vector of endogenous latent variables sized m x 1
ξ is a random vector of exogenous latent variables n x 1
δ is a measurement error vector in x size q x 1
Λx is the regression coefficient matrix x above ξ is sized q x n
Γ is the matrix of variable coefficients ξ in structural equations of size m x n
B is the matrix of variable coefficients η in a structural equation of size m x m
ζ is a vector of equation confusion in structural relationships between η, ξ sized m x 1

The following are the assumptions of modeling structural equations:

1. δ not correlated with ξ
2. ζ not correlated with ξ
3. δ and ζ mutual freedom

SEM is a very effective analytical tool to explore factors in the integration of environmentally based supply chains that affect the development of carrageenan production centers, the ecological impact of the seaweed industry, and help improve environmental management. This includes:

1. **Analysis of complex relationships in the supply chain**
Environmental supply chains include many interacting variables, such as production efficiency, waste management, environmental regulatory compliance, and economic sustainability. SEM allows authors to test direct relationships (e.g., environmental management on supply chain efficiency) and indirect relationships (e.g., the impact of green technology on sustainability through production efficiency).
2. **The use of latent variables for complex phenomena**
This research involves abstract concepts such as ”Environmental Sustainability”, ”Supply Chain Efficiency”, or “Production Performance”, which are difficult to measure directly. SEM allows the use of latent variables, which are measured through indicators such as: environmental sustainability (indicators: waste management, carbon emissions), supply chain efficiency (indicators: delivery time, logistics costs), production performance (indicators: production output, product quality).
3. **Separation of Measurement and Structural Models**
This research requires analysis at two levels: measurement models (validating the relationships between indicators and constructs such as supply chain efficiency or environmental sustainability), structural models (testing causal relationships between constructs, for example how environmental sustainability affects supply chain integration).
4. **Comprehensive Model Evaluation**
SEM provides model fit indicators such as CFI, RMSEA, SRMR, and Chi-square, which help authors evaluate whether the proposed model fits the empirical data. In the context of developing a carrageenan production center, this model can test whether the environmental supply chain design has a good fit with operational reality.
5. **Integrated Multivariate Analysis**
Research on supply chain integration involves many independent and dependent variables simultaneously, for example: independent variables (green technology, regulatory policies), dependent variables (supply chain efficiency, production performance). SEM can handle all these variables in one model, unlike other methods such as multiple regression that require separate

approaches.

6. **Theory Testing and Model Confirmation**
   Covariance-based SEM (CB-SEM) is often used to test a strong theory. In this study, the theory of environmental-based supply chain integration can be tested with the hypothesis.
7. **Ability to Measure Mediation and Moderation Effects**
   SEM allows authors to test mediation and moderation effects, such as: inventory management as a mediator between environmental-based supply chains and the development of production center areas (Mediation), The role of government regulation in strengthening the relationship between environmental sustainability and supply chain efficiency (Moderation). Methods such as regression or path analysis are not as comprehensive as SEM in dealing with mediation and moderation simultaneously.
8. **Flexibility to Data Types**
   In carrageenan supply chain research, the data used can be ordinal (sustainability assessment), continuous (production costs), or categorical (technology type). SEM is able to handle a combination of these data types easily, especially when using the PLS-SEM approach.
9. **Relevance to Carrageenan Supply Chain**
   Carrageenan production centeroften involves multiple stages in the supply chain, such as: seaweed farming, processing of raw materials into semi-finished products, distribution and marketing. SEM allows simultaneous analysis of the impact of each stage of the supply chain on the environment and operational efficiency.

Statistical testing using SEM, then compares the results of the robustness test to verify the stability or consistency of the results of statistical analysis against variations in data, models, or certain assumptions. Robustness testing is carried out by Parameter Stability Testing using bootstrapping to test the stability of the path coefficients in the SEM model. Bootstrapping, the process of resampling the original data with replacement to produce a parameter distribution with the aim of testing whether the parameter results (e.g., path coefficients) remain stable when the data changes slightly.

4. Results and Discussion

4.1. Overview of Research Location and Characteristics of Research Respondents

This research was located in the seaweed cultivation center area of Eucheumma cottonii in Laikang Village, Mangarabombang District, Takalar Regency, South Sulawesi Province. Seaweed cultivation in this area is carried out independently by the community [66]. Seaweed cultivation is carried out individually by the surrounding community and still uses traditional equipment, most of them learn seaweed cultivation techniques independently because there is no more extension from the local government. Running a seaweed cultivation business in Laikang Village requires investment costs. The amount of investment incurred is adjusted to the scale of the business being run and the level of income or profit. Facing such situations and conditions, this business can be said to be profitable and can continue to be sustainable, if it is able to provide decent profits and can meet the financial obligations of the business [67]. Farmers in Laikang Village generally produce high-quality seaweed with a water content of less than 35%. Some farmers are familiar with post-harvest procedures and cultivation that the market requires. High-quality seeds are selected before marine cultivation begins to greatly increase the harvest. If the growth cycle is successful and disease-free, farmers will usually use seeds from the previous harvest [68]. However, farmers usually buy seeds from other areas in Takalar Regency or even from other regencies, such as Jeneponto Regency, if the previous cycle's harvest results were of low quality.

Seaweed farmers are the main respondents in this study, while seaweed traders and seaweed agroindustry are supporting respondents. Respondents are supply chain actors in the seaweed agroindustry, consisting of; Laikang Hamlet (83 people), Boddia (74 people), Puntondo (63 people), Ongkoa (49 people), Pandala (43 people), and Turikale (40 people). The profile of seaweed farmer respondents generally has an average experience as seaweed farmers for 15 years. Based on interviews in the field, the longer the experience of growing seaweed, the more farmers understand how to run their agricultural business. The cultivation process is related to how to cultivate seaweed including the stages of seed preparation, land preparation, maintenance, harvesting and handling during harvest time. The capacity of buyer demand per year is generally adjusted to the availability of seaweed in dry form. The availability of raw materials at the farmer level still does not meet the demand of traders. In addition to seaweed farmers who are the main respondents of the study, this study also uses dried seaweed collectors with the number of respondents in this study totaling 30 small collector respondents and 7 large collector respondents. Based on the characteristics of dried seaweed trader respondents, it is known that the activities carried out by traders include taking seaweed from partner farmers. The difference between collectors lies in the role of each trader in the seaweed agro-industry supply chain. Collectors will buy seaweed from farmers and sell it to wholesalers. Wholesalers will buy seaweed from collectors and sell it to the agro-industry.

4.2. Overview of Seaweed Cultivation Business

Seaweed has bright prospects as one of the commodities traded, both to meet domestic and foreign demand. This opportunity must be utilized by seaweed farmers and entrepreneurs by cultivating commodity land in quantity, quality and price that is competitive in the international seaweed market share, such as Hong Kong, France, England, Canada, the United States, Japan and several other advanced industrial countries. The creation of export opportunities and the formation of an international seaweed market have not been fully utilized by seaweed farmers and entrepreneurs in South Sulawesi Province in terms of quantity, quality and selling price that can compete in the international market. Mangarabombang District in Takalar Regency is the area of the Center for Marine and Fisheries Development (PPK) of seaweed in South Sulawesi Province in recent years, the Takalar Regency Government has made efforts to increase seaweed production. Laikang Village is ideally located because it is protected from the effects of wind and large waves, has good currents, has clean and pollution-free water, has a water base in the form of sand mixed with coral fragments, has sufficient labor, and is close to the marketing area for the results. The seaweed economic chain of Laikang Village starts from suppliers, seaweed farmers who produce seeds, local traders and collectors who buy seaweed directly from farmers. Regional traders obtain goods from district traders, who store them in warehouses located in Makassar City and Takalar Regency. After being processed domestically into derivative products such as carrageenan, the seaweed is sold both domestically and exported. There are three types of processed carrageenan produced: semi-refined carrageenan, refined carrageenan, and *E. cottonii* processed with alkali solution [62]. Both in Indonesia and internationally, carrageenan is used in the production of industrial goods, food products, and pharmaceuticals.

The seaweed raw material supply chain for various derivative products involves overlapping roles. For example, village seaweed farmers can also supply seeds, while village collectors can act as traders or processors. Seaweed farmers, who run their own seed businesses at the village level without financial support, are seed suppliers. While large suppliers periodically collect seeds from different regions or exchange them between regions to obtain genetic quality, small-scale suppliers sell only a few tons of seeds per cycle. For example, a supplier in Laikang Village transports seeds to Laikang Village for sale after purchasing them from a regional collector in Jeneponto District. In addition, this supplier buys wet seaweed from farmers in Laikang Village and sells them to farmers in Jeneponto District. Furthermore, other suppliers obtain seeds from Punaga and Laikang villages and distribute them to other sub-districts. Farmers in Laikang Village cultivate and harvest throughout the year, so seeds are available whenever needed. Monthly sales can reach 30 tons, with the largest sales occurring in November and December at the beginning of the peak season.

Seed quality is determined by its color and cleanliness; high-quality seeds are greenish or brownish and free from dirt, moss, and barnacles. *E. cottonii* seaweed seeds grow faster, and demand for them is higher in Takalar Regency. In 2022, the cost of raw dried seaweed has increased, and so has the cost of seaweed seeds. The price was around 4,500 rupiah per kilogram at the end of 2021, 8,000 rupiah per kilogram in March, and 10,000 rupiah per kilogram in October. The price of seaweed binding increased from 3,000 to 4,000 rupiah per row as a result of this increase. The rapid price increase over the past year has led to adjustments in seed pricing and binding labor costs, which are now in line with the increase in selling prices. To manage production risks such as unsuitable water temperature or salinity, farmers in Laikang Village cultivate seaweed in certain plots and several plots in different locations, each varying in distance from the coast. To maintain individual ownership in the area, farmers used temporary anchors to delimit their plots as part of a local regulatory system with agreements on different property rights.

Seaweed is grown in rows of 40-meter-long ropes and cycles seven to eight times a year on average. Laikang Village seaweed farmers use an effective longline cultivation technique in deep waters. This technique involves using plastic ropes to secure pieces of seaweed weighing seven to eight kilograms to 40-meter-long longlines. Using plastic bottles, these ropes are tied to the seabed and attached to permanent anchors that hang at one-meter intervals. Depending on the season and the farmer, the seaweed is harvested between 30 and 50 days after planting. Motorized boats are used for planting, maintenance and harvesting, moving the wet seaweed to drying areas. During the busiest harvesting season, the boats can carry up to 500 kg, or about eight rows of wet seaweed. By tying the ropes between two wooden slats, farmers can untie the seaweed from the longlines after taking it out of the water with the bottles attached. Seaweed prepared for sale is dried in the sun by spreading it on bamboo (para-para) for two days and on land for three to five days. Seaweed selected for seed is replanted for the next farming cycle. Local vendors provide plastic bags tightly filled with dried seaweed and weighing between 100 and 110 kg each.

The main determinant of the price of dried seaweed is its water content; according to some farmers, a one percent increase in water content can result in a decrease in the selling price of 2,000 rupiah/kg. A water content of 35% to 38% is expected to meet the quality standard. According to market prices, farmers who exceed the quality standard do not receive the highest price. Farmers claim that the color and dirt content of dried seaweed do not affect the selling price, but collectors and traders use this information to their advantage by taking one kilogram from each bag of seaweed when they see that the bag is heavier than usual.

The price received by farmers of dried seaweed with a water content of 37% to 38% varies between 34,000 and 37,000 rupiah per kilogram during the harvest season, with an average of 34,500 rupiah per kilogram. Wet seaweed is sometimes sold to other farmers as seeds at a price of 5,500 to 6,000 rupiah per kilogram. Seeds, labor, non-labor variable costs (fuel, repairs, plastic bottles, equipment such as knives, gloves, and other items such as raffia rope and kerosene), and fixed costs (such as the cost of racks, boats and engines, ropes, tarpaulins, storage, ties/ties, anchors, and shelters) are the operational costs incurred by farmers in cultivating seaweed.

4.3. Measurement of Factors that Influence Environmentally Based Supply Chain Integration for Development of Carrageenan Production Center

Measuring factors that influence environmental supply chain integration (ECM) in the development of carrageenan production centers using Structural Equation Modeling (SEM) analysis requires a systematic approach; model analysis and hypothesis testing with two model assessment evaluations, namely assessing the outer model and the inner model or structural model.

4.3.1. Convergent Validity Test

This test is one of the validity tests in factor analysis that aims to assess the extent to which the indicators used to measure a latent variable (a variable that cannot be observed or measured directly, but its existence can be estimated through measurable indicators) are highly correlated with each other. This means that the indicators truly represent the same concept or latent construct (a theoretical idea designed to help researchers understand, explain, and measure a particular phenomenon. Constructs often cannot be measured or observed directly, so they are represented by a number of measurable or observable indicators) that are being measured. The validity of each relationship between an indicator and its construct or latent variable is assessed using a convergent validity test. The factor loading value (a statistical value that indicates how big the relationship is between an indicator (observable variable) and a latent variable) and the AVE value (a statistical measure used in SEM analysis to assess the convergent validity of latent variables in a model) are indicators of convergent validity. If a study has an AVE value greater than 0.5 and a loading factor above 0.700, then the study is considered to have passed the convergent validity test. Indicator D4.1 on the shipping variable has the highest loading factor value (0.833), while indicator MP2.4 on the inventory management variable has the lowest loading factor value (0.701), as shown in **Table 1** and **Figure 2**.

Table 1. Loading factor validity test results.

Variables	Indicators	Loading Factor	*Cut Off*	Descriptions
Planning	P1.1	0.755	0.7	Valid
	P1.2	0.744	0.7	Valid
	P1.5	0.766	0.7	Valid
	P1.6	0.776	0.7	Valid
	P1.7	0.759	0.7	Valid
	P1.9	0.742	0.7	Valid
	P1.14	0.749	0.7	Valid
	P1.15	0.710	0.7	Valid
Suppliers	PM2.1	0.810	0.7	Valid
	PM2.2	0.821	0.7	Valid
	PM2.3	0.823	0.7	Valid
	PM2.4	0.748	0.7	Valid
	PM2.5	0.776	0.7	Valid
Manufacturing	M3.1	0.823	0.7	Valid
	M3.2	0.795	0.7	Valid
	M3.3	0.709	0.7	Valid
	M3.4	0.769	0.7	Valid
Deliver	D4.1	**0.833**	0.7	Valid
	D4.2	0.787	0.7	Valid
	D4.3	0.710	0.7	Valid
Return	R5.2	0.766	0.7	Valid
	R5.4	0.712	0.7	Valid
	R5.5	0.781	0.7	Valid
	R5.6	0.830	0.7	Valid
Inventory Management	MP1.2	0.754	0.7	Valid
	MP1.3	0.790	0.7	Valid
	MP1.4	0.701	0.7	Valid
	MP1.6	0.729	0.7	Valid
Deveplomment of Production Center Areas	KP1.1	0.810	0.7	Valid
	KP1.2	0.808	0.7	Valid
	KP1.3	0.810	0.7	Valid
	KP1.4	0.762	0.7	Valid
	KP1.5	0.763	0.7	Valid

Indicator D4.1 (product delivery according to the schedule agreed with consumers) means that product delivery according to schedule can reduce additional trips (re-delivery or delays that cause double trips). This helps reduce fuel consumption and greenhouse gas emissions. Good scheduling supports logistics efficiency, providing an environmental impact in reducing the carbon footprint of transportation. Product delivery on schedule helps prevent waste (perishable products, timeliness is important to avoid damage to goods that lead to waste), minimizing waste supports sustainability principles, such as reducing food or goods waste. Furthermore, the availability of sufficient products in the warehouse or distribution center is closely related to explaining the variable of fulfilling consumer demand and so on as explained in other indicators. For farmers, the availability of sufficient products in the warehouse or distribution center means the certainty that the amount of product stored in the warehouse or distribution center is sufficient to meet customer demand or market needs without shortages. This availability refers to the optimal amount of stock so that the company is ready to fulfill customer orders on time.

Indicator MP1.4 (Having a reserve stock of raw materials to anticipate demand fluctuations or supply disruptions) means the need to ensure the availability of reserve raw materials, companies must have a wise policy in managing natural resources, by having a reserve of raw materials, the industry can regulate the use of resources more efficiently, prevent waste, and reduce negative impacts on the environment that can occur due to drastic fluctuations in demand, this efficiency also includes reducing waste or pollution resulting from the production process. Fluctuations in the supply of raw materials are often influenced by environmental conditions, such as natural disasters or climate change that affect the production of raw materials. Reserve raw material supplies can be one strategy to deal with disruptions caused by these environmental factors, by ensuring the continuity of production even if there is a disruption in supply.

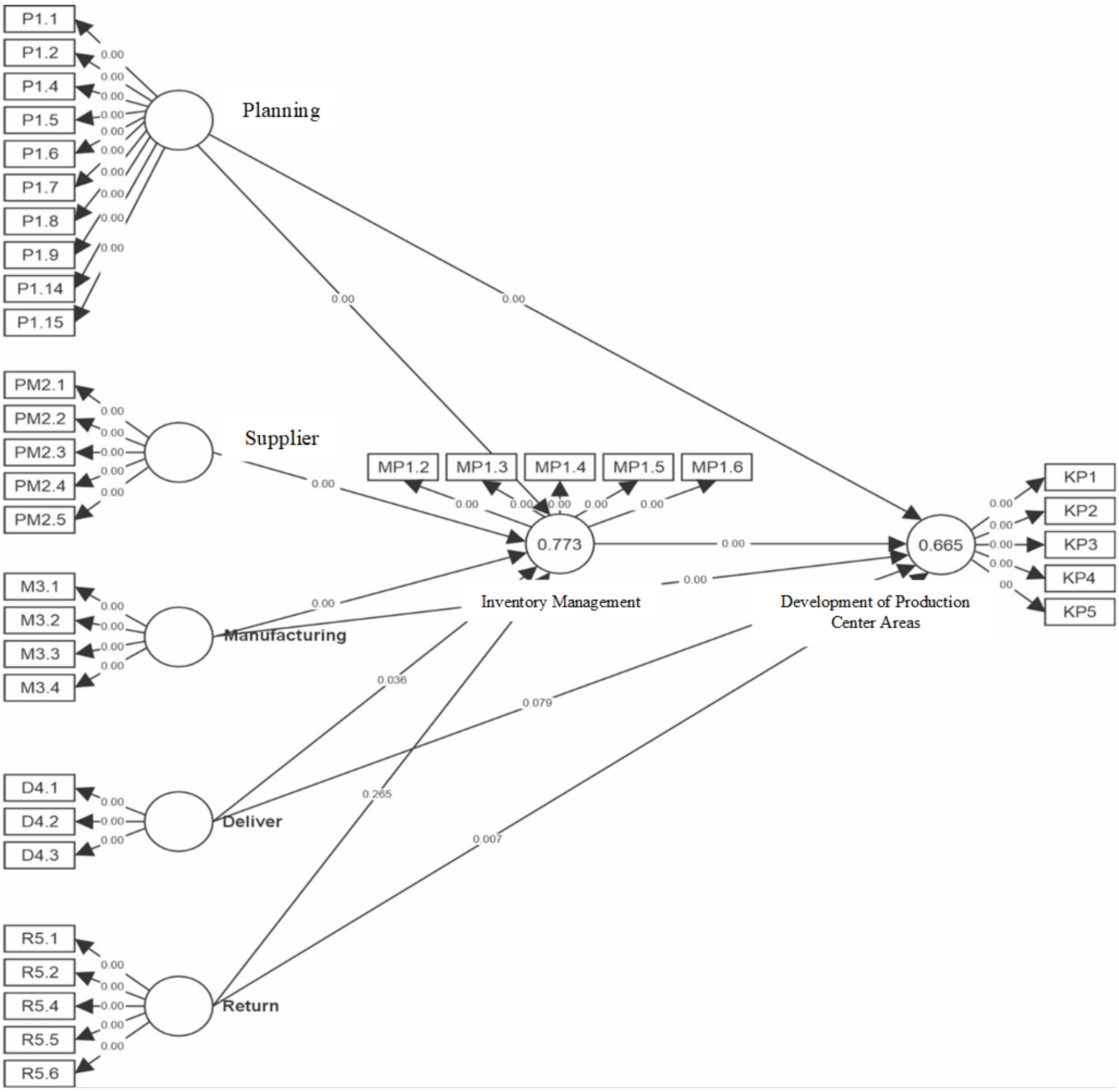

Figure 2. Outer model results.

Although the loading factor value of 0.701 is the lowest among other indicators, this value is still valid because it is above the threshold of 0.700. This shows that the reserve raw material inventory indicator is still relevant in explaining inventory management variables, but has a smaller influence than other indicators.

The planning variable P1.6 is known to have a loading factor of 0.776 on the indicator of the availability of raw materials always on time and according to production needs. This shows that the indicator of the availability of raw materials for production is always on time is closely related to explaining the planning variable. Production of raw materials is always on time, which means the certainty that the raw materials needed for the production process are always available when needed, without experiencing delays. Raw materials are produced or provided with a schedule that is in accordance with the main production schedule, so that there is no waiting time or disruption due to lack of materials. Timely management of raw material availability is closely related to better environmental management, optimizing resources, reducing waste, and ensuring a more environmentally friendly production process.

Other indicators in the planning variables have high value in environmental management, where seaweed cultivation and processing of carrageenan derivative products provide economic benefits and contribute to environmental protection, such as; (1) Reducing Greenhouse Gas (GHG) emissions which have great potential as absorbers of carbon dioxide (CO_2) from seawater during photosynthesis, which helps reduce CO_2 concentrations in water and the atmosphere. Seaweed can absorb CO_2 5-10 times faster than land plants. Seaweed can also be used as raw material for bioplastics or bioenergy, replacing fossil-based products, thereby reducing carbon emissions from the industrial sector. (2) Able to absorb nitrates, phosphates, and ammonia from seawater, which often come from agricultural runoff or other human activities. This helps prevent eutrophication, which can cause dead zones in coastal waters. (3) Providing habitat for marine organisms such as small fish, shrimp, and molluscs, which shelter, feed, or breed around the cultivation area. (4) Utilization of carrageenan products as a sustainable alternative, replacing fossil-based products by replacing synthetic additives, thus helping to reduce dependence on petroleum-based chemicals. (5) Organic fertilizer and bioenergy from cultivation waste can be processed into organic fertilizer, replacing chemical fertilizers that often pollute the environment and have the potential to be used as bioenergy (biogas), which can be an alternative renewable energy source.

The PM2.3 supplier variable is known to have a loading factor of 0.823 on the indicator of the amount of raw materials and delivery schedules according to consumer needs. This shows that the amount of raw materials and delivery schedules according to consumer needs is a supply chain management strategy where the amount of raw materials provided and the delivery schedule are arranged based on consumer demand or special needs. The company's certainty to provide raw materials in the right amount at the right time to avoid hoarding or shortages that can disrupt the production or distribution process.

It is known that the manufacturing variable M3.1 has a loading factor of 0.823, on the infrastructure feasibility indicator in supporting the smooth running of the production process. This shows that the feasibility of infrastructure in supporting the smooth running of the production process is the quality, availability, and readiness of various physical facilities and technologies needed to run the production process effectively and efficiently. The infrastructure in question includes; roads and transportation, electricity and water, information technology, warehouses and storage, production equipment. Adequate infrastructure ensures that there are no significant disruptions that can slow down or stop the production process, thereby increasing productivity and quality of production results and reducing costs arising from repairs or delays.

The return variable R5.6 is known to have a loading factor of 0.830 on the indicator of the process of returning rejected raw materials. This indicates that the return of rejected raw materials in question is the process of returning raw materials that do not meet the quality standards or specifications that have been determined to the supplier. These rejected raw materials are generally damaged, defective, or the quality does not match that required for the carrageenan production process.

The MP1.3 inventory management variable is known to have a loading factor of 0.790 on the reserve raw material inventory indicator to anticipate demand fluctuations or supply disruptions. This shows that the intended raw material inventory control is to maintain a number of additional raw material stocks outside of routine needs so that suppliers are ready to face sudden changes in demand or problems in the supply chain to ensure smooth production.

The variables for developing production center areas are known to be KP1.1 and KP 1.3 having a loading factor of 0.810 on the indicators of human resource quality and availability of raw materials as superior commodities. This shows that the quality of human resources in question is the important role of skills, knowledge, and competence of the workforce in determining the success and sustainability of the development of areas used as centers of production activities. The quality of human resources is the main factor that influences the efficiency, innovation, and competitiveness of a region in the industrial world. Furthermore, it is a key factor in determining whether the production center area can develop well, sustainably, and compete globally. Good human resource development in an industrial area supports the creation of a productive and innovative ecosystem.

The availability of raw materials as superior commodities in question is seaweed raw materials, available in sufficient quantities and of high quality to support production activities in areas designated as seaweed processing or production centers. These raw materials are superior commodities because they are the main ingredients in the seaweed processing industry. Important aspects to support this are: (1) stability of raw material supply, maintaining the smooth running of the production process in seaweed production center areas, raw materials

The results of the outer model show that the indicators of each construct can be used to assess the extent to which supply chain integration supports the development of environmentally-based carrageenan production center areas. This integration contributes to; (1) Logistics and operational efficiency (including inventory management, shipping, and returns), (2) Reducing environmental impacts (carbon emissions and production waste), (3) Sustainability of production center areas, which become more competitive by adopting environmentally friendly practices. The validity of the indicators in the outer model is evidence that an environmentally-based supply chain system can be implemented effectively to support the development of production center areas that focus on carrageenan.

For each construct or latent variable, the Average Variance Extracted (AVE) approach can also be used to assess convergent validity. If the Average Variance Extracted (AVE) of an instrument is greater than 0.5, then it is considered to have passed the convergent validity test. The results of the construct validity test using AVE are shown in **Table 2**.

Table 2. Result of constrct validity testing using AVE.

Variabel	Average Variance Extracted (AVE)	Limit	Conclusion
Planning	0.533	0.5	Valid
Suppliers	0.634	0.5	Valid
Manufacturing	0.601	0.5	Valid
Deliver	0.606	0.5	Valid
Return	0.576	0.5	Valid
Inventory management	0.530	0.5	Valid
Production center area development	0.632	0.5	Valid

Table 2 shows that the Average Variance Extracted (AVE) value for each variable is more than 0.5. Therefore, it can be said that all indicators have the ability to measure their variables. The seaweed industry to produce carrageenan derivative products has an ecological impact in the form of environmental pressure, such as increased greenhouse gas emissions, ecosystem degradation, and climate change. This can be overcome through the development of carrageenan production center areas with supply chain integration and attention to environmental management, including; (1) Organic fertilizer production (Seaweed waste in the form of seaweed cultivation residues, such as unused plant parts, can be processed into organic fertilizer or compost, seaweed-based fertilizers that can improve soil structure, increase water retention, and reduce the need for chemical fertilizers. Provides microelements such as potassium, magnesium, and calcium, which are beneficial for land plants). (2) Prevention of land degradation, Seaweed-based bioplastics replace conventional plastics, reducing soil pollution by microplastics. (3) Increased carbon absorption, (4) Climate change mitigation, can provide direct and indirect contributions to reducing the impacts of climate change. The large area of seaweed cultivation can act as a global carbon sink, reducing the concentration of carbon dioxide in the atmosphere. (5) Multi-stakeholder collaboration for sustainability in addressing environmental pressures effectively through cooperation between government, the private sector, and communities.

4.3.2. Discriminant Validity Test

Discriminant validity aims to ensure that the data obtained does not contain overlap between constructs, helping to increase confidence in the research results because it shows that each construct measures a specific concept and is not biased by the measurement of other constructs. This test is assessed using cross loading and the Fornell-Locker method. Specifically, the target construct loading value must be greater than the loading value of other constructs. To ensure that there is sufficient discrimination in the construct, the Fornell-Locker method (**Table 3**) and cross loading are used to calculate discriminant validity.

Table 3. Fornel-Locker.

Variables	Deliver	Inventory Management	Manufacturing	Supplier	Developent of Production Center Area	Planning	Return
Deliver	**0.778**						
Inventory Management	0.469	**0.728**					
Manufacturing	0.421	0.777	**0.775**				
Supplier	0.355	0.734	0.738	**0.796**			
Development of Production Center Area	0.355	0.739	0.735	0.989	**0.795**		
Planning	0.468	0.728	0.635	0.414	0.417	**0.730**	
Return	0.368	0.455	0.395	0.205	0.208	0.644	**0.759**

Table 3 shows the Fornel-Locker research results as follows:

a. The highest correlation value for the shipping variable, which represents the relationship between shipping and inventory management, is 0.469, while the AVE root value is 0.778. The AVE value of 0.778 indicates that the shipping variable has good convergent validity and is able to explain most of the variance of its indicators, the shipping construct is reliable in the model used. The correlation value of 0.469, indicates a moderate relationship between shipping and inventory management, although there is a significant positive relationship between the two.

   Delivery and inventory management are two important elements in an environmentally-based supply chain. A moderate correlation value (0.469) indicates that efficient, timely, and appropriate delivery of inventory is very important in reducing environmental impacts, such as carbon emissions from transportation, fuel use, and raw material waste in carrageenan production centers. The high AVE root (0.778) in the delivery variable indicates that this aspect can be managed well to support an environmentally friendly supply chain by optimizing raw material delivery to carrageenan production center areas. Supply chain integration supports sustainability by minimizing the environmental impact of production will have competitiveness in the global market.

b. The highest correlation value of the inventory management variable is 0.739, and the AVE root value is 0.728, which is the correlation of inventory management with the development of production center areas. The AVE root value of 0.728 indicates that the inventory management construct has good convergent validity, this variable is strong enough to explain the indicators related to it, indicating a fairly strong positive relationship between inventory management and the development of production center areas. Improvements in inventory management tend to be closely related to improvements or planning in the development of production center areas. The better the inventory management, the more likely it is to support the development of the area efficiently, or vice versa.

c. The AVE root value of the manufacturing variable is 0.775, and the largest correlation value is the relationship between manufacturing and inventory management is 0.728. The highest correlation value of 0.728 between manufacturing and inventory management indicates a strong positive relationship between the two. Thus indicating that these two variables influence each other, and an increase in one variable tends to contribute to an increase in the other variable.

d. The largest correlation value of the supplier variable is 0.775, and the AVE root value is 0.796, which is the correlation between suppliers and inventory management. The AVE root value of 0.796 indicates that the supplier construct has very good convergent validity. This value is much greater than 0.5, indicating that more than 50% of the indicator variance can be explained by the supplier construct. The supplier construct has a very good ability to explain related indicators and can be considered very reliable in the model used. Improving supplier relationships tends to improve inventory management performance. Conversely, an efficient inventory management system also has the potential to improve supplier relationships and performance.

e. The regional development variable has an AVE root value of 0.795 and a maximum correlation value of 0.775, which is the correlation between inventory management and planning. The AVE root value of 0.795

indicates that regional development has very good convergent validity, which means that this construct is very influential in explaining related indicators. Although this relationship better illustrates the relationship between planning and inventory management, it can be interpreted in regional development that good planning in regional development can improve the efficiency and effectiveness of inventory management, so that these two factors interact positively with each other.

f. The AVE root value for the planning variable is 0.730 while the highest correlation value of the planning variable is 0.795, which is the correlation of planning with regional development. A correlation of 0.795 indicates that there is a strong relationship, good and effective planning greatly supports regional development. If the planning process is carried out well, then regional development will also be more structured and run more smoothly, or conversely, success in regional development is highly dependent on the quality and effectiveness of the planning carried out. Better planning tends to be associated with improved inventory management and conversely, the existence of a better inventory management system can improve the planning process. Improvements in the planning process can contribute to increased effectiveness in inventory management, which in turn can improve overall operational efficiency.

g. The AVE root value for the return variable is 0.759 while the highest correlation value of the return variable is 0.728, which is the correlation of returns with inventory management. The correlation of 0.728 indicates that there is a fairly close relationship between returns and inventory management. The better the inventory management, the more efficient the process of returning damaged, misplaced, or inappropriate goods or products. Better inventory management will facilitate the return of goods that need to be reprocessed into the system, reducing waste or losses that arise. Efficiency in return management can support success in the development of production center areas, or conversely, better development of production areas can affect the return system more efficiently.

Supply chain management is concerned with the integration of network organizations consisting of suppliers, manufacturers, logistics providers, wholesalers/distributors, and retailers. The goal is to collaborate and manage the flow of products, services, finances, and information from suppliers to customers to achieve customer satisfaction, profitability, added value, and to create efficiency and effectiveness. In the long term is to achieve competitive advantage in a system [35, 44, 46].

4.3.3. Reliability Test

Reliability testing can be done using Cronbach's alpha and composite reliability. The testing criteria state that if the composite reliability is greater than 0.7 and Cronbach's alpha is greater than 0.6, then the construct is declared reliable. **Table 4** shows the results of the reliability testing.

Table 4. Reliability test result.

Variabel	Cronbach's Alpha	Composite Reliability	Conclusion
Planning	0.903	0.919	Reliable
Suppliers	0.855	0.896	Reliable
Manufacturing	0.778	0.857	Reliable
Deliver	0.674	0.821	Reliable
Return	0.817	0.871	Reliable
Inventory Management	0.777	0.849	Reliable
Production center area development	0.854	0.896	Reliable

Table 4 shows that each variable produces a composite reliability value better than 0.7 and a Cronbach's alpha value greater than 0.6. As a result, each dimension is considered reliable to measure its variables. Each variable produces a composite reliability score higher than 0.7 and a Cronbach's alpha value greater than 0.6. High Cronbach's alpha and composite reliability scores indicate that the planning variable has very strong reliability. When measuring planning, this tool is reliable and consistent. The supplier variable also shows very good reliability. This value has strong consistency, so this instrument is trusted to measure supplier factors. The manufacturing variable has good reliability. Its

value is above the minimum limit of 0.7, indicating that this variable is consistent in measurement.

This reliability is able to analyze involving policies or evaluations of production center areas, because measurement consistency is the key to obtaining accurate and valid results. Consistent measurements prove that what is collected will reflect higher actual conditions and increase the validity of the instrument. So that it is able to make more precise decisions regarding the development of production center areas. Furthermore, it can be trusted to evaluate the effectiveness or impact of production center area development policies. This reduces the risk of errors in analysis and increases confidence in the research results.

High reliability in planning, supplier, and manufacturing variables strongly supports the implementation of environmentally-based supply chain integration. With consistency and reliability in measurement, each stage in the supply chain can be analyzed, evaluated, and optimized to reduce environmental impacts while increasing the sustainability of the carrageenan production center area.

4.4. Inner Model Evaluation

Evaluation of the deep model, also known as the structural model, is a step in assessing the goodness of fit involving R^2 and hypothesis testing. The direct relationship equation obtained is as follows:

a. Development of production center area = 0.609 * inventory management, error var = 0.335, R^2 = 0.665. The R^2 value of development of production center area is = 0.665, meaning that development of production center area is influenced by inventory management variable as much as 66.5% of the variation in development of production center area can be explained by inventory management variable, while 33.5% or 0.335 of the rest is influenced by causes not studied. The relationship is unidirectional, as indicated by the inventory management path coefficient of 0.609, which is positive. Development of production center area will increase by 0.69 if inventory management increases by one unit. Development of production center area is positively influenced by inventory management, as seen from the coefficient value of 0.609.

b. Inventory management = Planning + 0.400 * supplier + 0.199 * manufacturing + 0.049 * shipping + 0.017 * returns = 0.403 * inventory management, error var = 0.227, R^2 = 0.773 With an R^2 value of 0.773, inventory management is influenced by the variables of planning, supplier, manufacturing, shipping, and returns by 51.9%, while the remaining 77.3% comes from other factors not studied. With a positive direction and a planning path coefficient of 0.403, the relationship is unidirectional. Production capacity will increase by 0.404 for every one unit increase in planning. With a positive direction and a supplier path coefficient of 0.400, the relationship is unidirectional. Production capacity will increase by 0.400 if the supplier increases by one unit. With a positive direction and a manufacturing path coefficient of 0.199, the relationship is unidirectional. Production capacity will increase by 0.199 if manufacturing increases by one unit. With a positive direction.

c. The indirect relationship equation obtained is as follows: Development of production center area = 0.609 inventory management + 0.403 planning + 0.400 suppliers + 0.199 manufacturing + 0.049 shipping + 0.017 returns, Errorvar = 0.335, R^2 = 0.665. The R^2 value of the development of production center area is = 0.665, meaning that the development of production center area is directly influenced by inventory management variables; indirectly influenced by planning, supplier, manufacturing, shipping, returns variables mediated by inventory management by 66.5% while the rest is influenced by other factors not studied, namely 0.335 or 33.5%.

4.5. Coefficient of Determination R^2

The coefficient of determination R^2 is used to determine the extent to which the endogenous variable is able to explain the diversity of the exogenous variable or in other words to determine the extent to which the exogenous variable contributes to the endogenous variable. This effect ranges from 0 to 1, with 1 representing complete prediction accuracy. Since R^2 is adopted by various disciplines, researchers must rely on the rule of thumb regarding acceptable R^2, with prediction accuracy levels of 0.75 (substantial), 0.50 (moderate), and 0.25 (weak). **Table 5** is the result of the determination analysis (R^2). and **Figure 3** is the interpretation of the inner model results.

Table 5. Results of determination coefficient (R^2) in farmers.

Variable	R-Square	R-Square Adjusted
Inventory Management	0.773	0.770
Development of Production Center Area	0.665	0.661

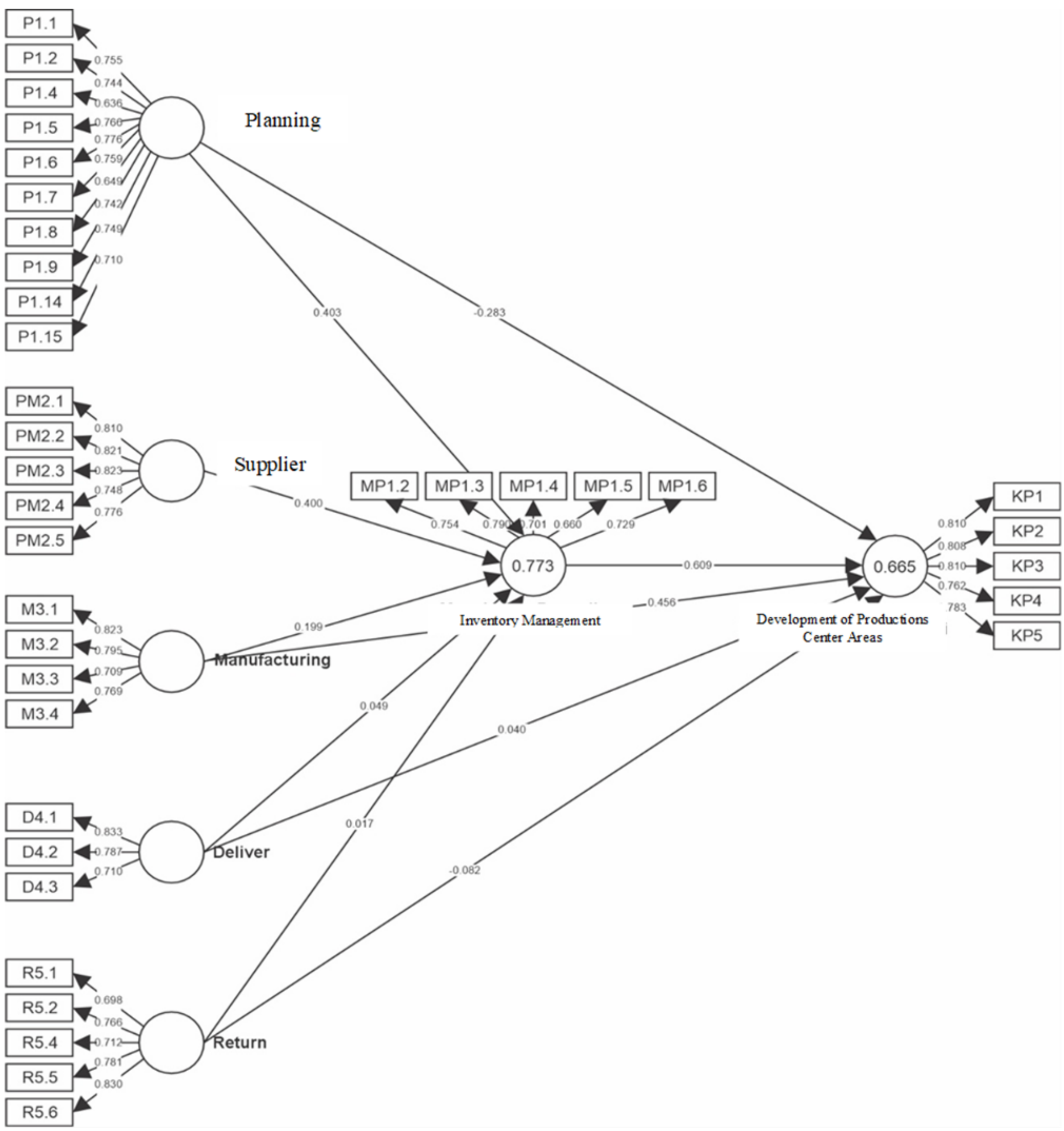

Figure 3. Inner model results.

Table 5 shows that:

a. **The R^2 value of the inventory management variable is 0.773 (in the substantial category)**, shows that the variables of planning, suppliers, manufacturing, shipping, and returns explain 77.3% of the influence and explanation of inventory management, with the remaining part coming from other factors not included in this study. Inventory management is greatly influenced by the combination of these five variables and is relevant and contributes significantly in determining the effectiveness or efficiency of inventory management for the development of production center areas. The R^2 value approaching 1 indicates that the model is able to explain 77.3% of the variation of the dependent variable and is very good.

b. **The R^2 value of the variable for the development of the production center area is 0.665 (in the medium category, Figure 2)**, indicating that 66.5% of the variation in the development of the production center area can be explained by the model used. This value is in the medium category, indicating that the model has a fairly adequate but not too strong fit. Most of the variation in the development of the production center area can be explained by the independent variables included in this model. The factors included in inventory management analyzed in this model contribute quite significantly to the development of the production center area.

4.6. Robustness Test Bootstrapping (Path Analysis)

Robustness testing is used to verify the reliability of the analysis results and ensure that the research findings remain valid despite changes in data, assumptions, or models. The Robustness Test used Parameter Stability Testing with Bootstrapping. The results of the significance and model tests are shown in **Figure 4** and **Table 6**. Hypothesis testing is used to test the effect of exogenous variables on endogenous variables. The testing criteria state that if the T-statistic value ≥ T-table (1.96) or the P-Value value < alpha significant 5% or 0.05, then it is stated that there is a significant effect of the exogenous variable on the endogenous variable. Hypothesis testing is used to test whether there is an effect of the exogenous variable on the endogenous variable or not. The testing criteria state that if the T-statistic value ≥ T-table (1.96) or the P-Value value < alpha significant 5% or 0.05, then it is stated that there is a significant effect of the exogenous variable on the endogenous variable.

The shipping variable is not significant to inventory management because the industry has a large enough stock and implements an inventory management strategy that is independent of shipping, so shipping does not have a significant impact on inventory. The industry focuses more on other factors such as production planning, supplier relationships, or manufacturing processes, which results in shipping playing a minor role in inventory management decisions and is not a major factor influencing inventory management. This occurs in an integrated supply chain model, where logistics and inventory factors are managed separately. In addition, shipping-related data does not vary significantly (for example, delivery frequency or time is relatively constant). Other variables, such as supplier relationships or inventory planning strategies, have a greater and more dominant influence on inventory management, so the effect of shipping does not appear significant.

Table 6. Significance and model test results for farmer.

Hipotesa		Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values	Descriptions
H1	**Deliver ->Inventory Management**	0.027	1.805	0.036	**Not Significant**
H2	**Deliver ->Development of Production Center Area**	0.028	1.413	0.079	**Significant**
H3	**Inventory Management ->Development of Production Center Area**	0.058	10.590	0.000	**Significant**
H4	**Manufacturing ->Inventory Management**	0.046	4.302	0.000	**Significant**
H5	**Manufacturing ->Development of Production Center Area**	0.052	8.851	0.000	**Significant**
H6	**Supplier ->Inventory Management**	0.040	10.040	0.000	**Significant**
H7	**Planning ->Inventory Management**	0.045	8.970	0.000	**Significant**
H8	**Planning ->Development of Production Center Area**	0.045	6.306	0.000	**Significant**
H9	**Return ->Inventory Management**	0.027	0.628	0.265	**Not Significant**
H10	**Return ->Development of Production Center Area**	0.033	2.479	0.007	**Significant**

In the inventory system, the return component tends to have a relatively small or irregular volume compared to the inflow (suppliers) and outflow (production and distribution). Therefore, inventory management does not prioritize returns as an important part of stock management in the supply chain. Insignificant also indicates that the return process does not cause major changes to inventory policies or stock requirements, because the inventory system is flexible enough to accommodate the volume of returns without requiring major adjustments in inventory operations. Suppliers or planning, have a very important role in determining the amount of inventory compared to the return component.

Furthermore, the insignificant relationship indicates that the return process does not have a major role in overall inventory management. Other factors such as suppliers, planning, and manufacturing are more important in managing inventory. In the context of this study, returns are not an important element in inventory management strategies. So that the industry focuses more on factors that have a greater impact on inventory, such as suppliers and planning, in maintaining stock stability and supporting production and distribution operations.

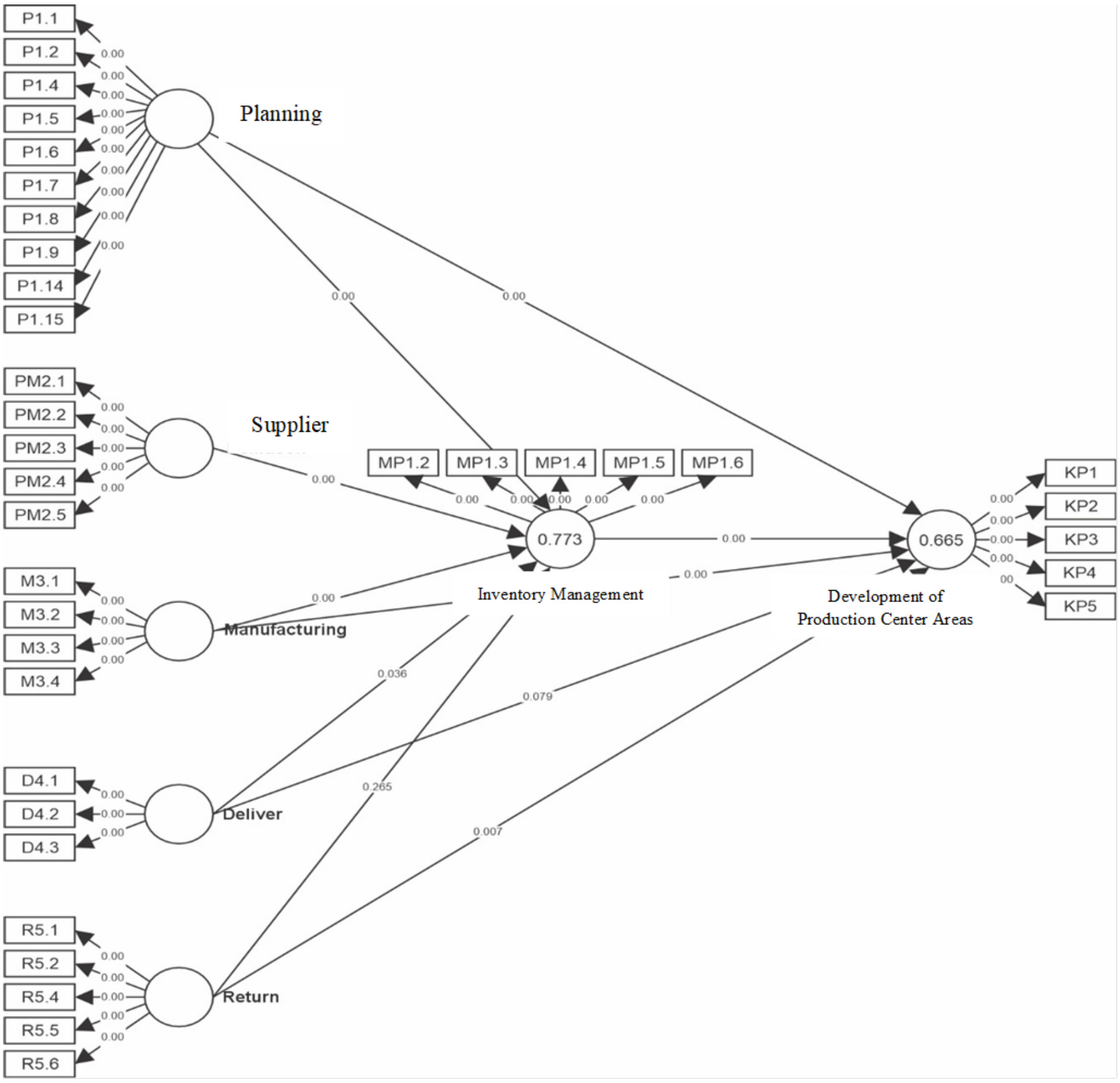

Figure 4. Bootstrapping hypothesis testing (path analysis).

The results of the above tests show that environmental-based supply chain integration for the development of carrageenan production center areas requires strategic solutions that pay attention to sustainability and minimal environmental impact, as well as supporting the achievement of SDG goals 12, 13, and 14, as follows; (1) Sustainable natural resource management by optimizing the use of raw materials for carrageenan production without damaging the marine ecosystem (ensuring the sustainability of seaweed as a raw material by rotating planting), (2) Supply chain optimization by implementing circular economy principles where waste from the production process (such as seaweed waste or wastewater) can be reused in production or processed into valuable by-products, (3) Certification and Standards by encouraging sustainability certification for carrageenan producers that focus on environmentally friendly practices and ensuring that the supply chain follows strict environmental standards, (4) Encouraging the use of renewable energy such as solar energy or biomass to reduce dependence on fossil fuels in the carrageenan production process, (5) Adopting more environmentally friendly production technologies, such as the use of efficient equipment that reduces greenhouse gas emissions, and utilizing energy-efficient production methods, (6) Building adaptation systems that support carrageenan production areas in facing the impacts of climate change, such as rising sea temperatures or changes in marine ecosystems, (7) Developing technologies that enable seaweed harvesting with minimal impact on marine ecosystems, such as planting and harvesting methods that do not damage the seabed or biodiversity, (8) Increasing awareness among stakeholders in the carrageenan industry about the importance of maintaining marine ecosystems and implementing sustainability principles in raw material sourcing, (9) Involving local communities, governments and environmental organizations in decision-making to ensure that management policies in this area are sustainable and support SDG goals.

4.7. Implications Policies to Support Environmentally Based Seaweed Supply Chains and Sustainable Carrageenan Production

Sustainability of seaweed cultivation and carrageenan production can be achieved if the government can develop a holistic policy and legal framework. This framework must include environmental regulations, economic incentives, institutional strengthening, and efforts to encourage sustainability-oriented industry practices.

1. Government policy to support seaweed cultivation, through:
   a. Integrated Marine Zoning Planning
   Ecosystem Based Zoning (identifying marine areas suitable for aquaculture)seaweed without sacrificing important ecosystems, such as: mangrove forests, grasslands seagrass, and coral reefs. Establishing special spaces for cultivation through Marine Spatial Planning (MSP) to avoid conflicts with other activities, such as fisheries, tourism, or shipping), the application of Carrying Capacity Analysis (determine the capacity of the ecosystem to support cultivation without causing overexploitation)
   b. Infrastructure Strengthening
   Production and Processing Facilities (investment in developing carrageenan processing facilities close to seaweed production sites to reduce transportation costs and improve supply chain efficiency). Green Technology Development (encouraging the adoption of environmentally friendly technologies in aquaculture, such as IoT-based water management, quality monitoring systems and the use of biodegradable ropes)
   c. Economic Incentives
   Subsidies for Sustainable Technology (providing subsidies to farmers and producers to switch to environmentally friendly technologies). Ease of Access to Finance (providing access to low-interest credit to encourage the development of micro, small and medium enterprises (SMEs) in the seaweed industry)
   d. Training and Capacity
   Train farmers and industry players in sustainable farming practices, product diversification, and environmental impact mitigation, Promote Integrated Multi-Trophic Aquaculture (IMTA) methods to improve production efficiency.
2. Regulations to Support Sustainable Carrageenan Production
   a. Production Sustainability Standards
   Establish national standards for carrageenan processing that comply with sustainability principles, such as Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP). Promote sustainability certification (e.g., Eco Label or ASC Certification) to enhance product competitiveness in the global market.
   b. Production Waste Management
   Require carrageenan processing plants to have adequate waste treatment systems to prevent environmental pollution. Provide incentives for companies that use waste as secondary raw materials (e.g., for bioplastics or bioenergy).
   c. Circular Economy Promotion

Promote the use of seaweed biomass waste as renewable fuel or compost, supporting the Zero Waste principle of the supply chain.

3. Environmental Protection and Resource Management
    a. Coastal Ecosystem Conservation
    Marine Pollution Control (banning the use of single-use plastics in aquaculture, and encouraging the use of biodegradable materials to reduce microplastic pollution)
    b. Implementation of the Blue Carbon Principle (recognizing seaweed cultivation as a form of climate change mitigation through carbon sequestration (blue carbon). Integrate cultivation into carbon market schemes to obtain global funding.
4. Promoting Best Practices in the Industry
    a. Monitoring and Evaluation System
    Using technologies such as satellites, drones, or IoT to monitor water quality and ecosystem health around the cultivation area. Implementing regular evaluation mechanisms to ensure compliance with environmental standards.
    b. Strengthening the Supply Chain (promoting transparency in the supply chain through blockchain technology to trace seaweed sources and ensure compliance with sustainability principles)
    c. Product Diversification (promoting the development of high value-added seaweed-based products, such as bioplastics, bioenergy, and pharmaceuticals, to increase industrial competitiveness)
5. Strengthening the Legal Framework
    a. Fisheries and Marine Law (Revise relevant laws to include principles of sustainable aquaculture, ecosystem conservation and industrial waste management).
    b. Strict Legal Sanctions (applying strict sanctions for violations of regulations, such as the use of hazardous chemicals, destruction of coastlines, ecosystems, or illegal cultivation practices)
6. Collaboration and Cooperation
    a. Inter-Ministerial Cooperation (strengthening coordination between the Ministries of Marine Affairs and Fisheries, Environment, Maritime Affairs, and Industry to ensure synergistic policy implementation)
    b. Public-Private Partnerships (facilitating collaboration between government, the private sector and communities to support investment in green infrastructure development and environmentally friendly technologies)
7. International Cooperation (leveraging global initiatives such as the Blue Economy Framework to access international funding and share knowledge on best practices)

Effective policies and legal frameworks to support environmentally sustainable seaweed supply and carrageenan production through the development of sustainable production center areas require a cross-sectoral approach that includes strict regulations, green incentives, ecosystem-based management, and multi-stakeholder collaboration. With integrated policies, the seaweed industry can become a driver of sustainable development while supporting environmental protection and responsible resource management. Relevance and potential. The agricultural industry based on supply chain management emphasizes the importance of collaboration, commitment, and joint decision-making in the success of regional development and agribusiness. This is relevant to the results of the study which stated the need for coordination between supply chain actors (seaweed farmers, producers, distributors, and exporters) to improve efficiency. In this case, good collaboration between stakeholders will drive better efficiency and performance. Inventory management innovation improves supply chain efficiency which underlines the importance of environmental management, improved storage facilities and transportation infrastructure that support the supply chain. Simplification of operations and efficient stock management will improve supply chain performance, which is also reflected in the importance of raw material quality and production processes that are in accordance with demand.

5. Conclusions

The results of the interpretation of factors in the integration of the environmental-based supply chain that affect the development of the carrageenan production center area by analyzing the ecological impact of supply chain management on the carrageenan production process are planning (indicators; raw materials, production capacity, seaweed cultivation, technology, seeds, demand trends, harvest periods, marketing institutions, raw material specifications, environmental monitoring, post-harvest waste management), suppliers (indicators; education level, seaweed cultivation experience, cultivation period planning), manufacturing (indicators; Production equipment, Production process efficiency, Labor, carrageenan products, product testing, waste management), delivery (indicators; product quality and quantity, timeliness of product delivery, length of time in choosing a shipping service, transportation, product guarantee), returns (indicators; return of defective products, replacement of defective products, timeliness of return of defective products), inventory management (indicators; measuring the sustainability of seaweed supply from natural resources (eg, proper crop rotation), the level of organic waste generated from seaweed production, the use of cultivation methods such as hanging ropes (longlines) that minimize environmental damage, raw material inventory, raw material storage).

Environmentally based supply chain integration for the development of carrageenan production center areas can be done by: (1) Focusing on Sustainability and Minimal Environmental Impact, supply chain integration must be oriented towards sustainability by prioritizing responsible natural resource management, ensuring the sustainability of marine ecosystems, and minimizing negative impacts on the environment. (2) Support for the Achievement of SDG 12, 13, and 14. (3) Strategy for Environmentally Based Supply Chains; Sustainable Raw Material Management, Circular Economy (utilizing waste from the production process as a valuable by-product), Sustainability Certification (encouraging the adoption of international standards to ensure environmentally friendly practices in the supply chain), Renewable Energy and Environmentally Friendly Technology (reducing dependence on fossil fuels by utilizing solar or biomass energy, and using efficient equipment to reduce emissions), Adaptation to Climate Change (developing a production area adaptation system to the impacts of changes in the marine ecosystem). (4) Stakeholder Collaboration and Awareness; the importance of collaboration between local communities, government, environmental organizations, and industry players in decision-making, as well as increasing awareness of the importance of maintaining the sustainability of the marine ecosystem.

Recommendations

1. The need for government support in providing regulations and policies for carrageenan exports and protection for local actors.
2. Human resource development, both in terms of cultivation, processing, and regional development models for carrageenan production centers.

Author Contributions

Conceptual framework, data analysis, manuscript review, revision –L.H.; Conceptualization, methodology, formal analysis, approved final manuscript –M.N.; Conceptual framework implementation, methodology, data analysis and interpretation, reviewed manuscript, approved final manuscript – N.N.; Methodology, reviewed manuscript, approved final manuscript –R.A.H. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Ethical review and approval were waived for this study because it is the result of doctoral research that has been examined by the advisory committee and the examination committee.

Informed Consent Statement

This study involved 352 seaweed farmers as respondents, all of whom provided their consent before participating in interviews and completing questionnaires. The interview results constitute the research findings presented in this article.

Data Availability Statement

Not applicable.

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Conflict of Interest

The author declares no conflict of interest.

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