An application of partial least squares-structural equation modeling (PLS-SEM) to analyze the factors contributing to the decline in *Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva, 1996 seaweed production in the Kepulauan Seribu, Indonesia

[1]Wisnu Sujatmiko, [2]Nieke Karnaningroem, [2]Irwan B. Santoso, [1]Ratu S. Aliah

[1] Research Center for Fishery, National Research, and Innovation Agency. Jalan Raya Bogor KM 46 Cibinong, Nanggewer Mekar, Bogor 16912 Indonesia. [2]Department of Environmental Engineering, Institute Teknologi Sepuluh Nopember, Jalan Arief Rahman Hakim, Surabaya 60111 Indonesia. Corresponding author: W. Sujatmiko, wisnu.sujatmiko31@gmail.com.

Abstract. *Kappaphycus alvarezii* (Doty) Doty ex P.C.Silva, 1996 is one type of seaweed that is most widely cultivated in Indonesia due to its relatively easy cultivation methods, with a harvest period of only 45 days and profitability. However, in recent years, the production of seaweed has continued to decline. This research aims to analyze the factors causing the decline in seaweed production in the Kepulauan Seribu, including environmental factors consisting of physical, chemical, and biological parameters, as well as human resources, seaweed characteristics, and technology. The analysis is conducted using the Partial Least Squares-Structural Equation Modeling (PLS-SEM) method with SmartPLS version 4.10.8 software. The results of the total effect analysis of Chemical parameters on production show a strong negative influence of 54.3%, although it is not significant. The total effect of Human resources factors on production demonstrates a strong influence of 46.9% and is significant. The results of the effect size analysis of Chemical parameters and Human resources factors are both strong and significant. Technological factors show a moderate influence of 17.7% and are significant, while the effect size has a moderate influence but is not significant. The total effect size of Seaweed Factors on production is very small, at 0.89%, and this effect size is also insignificant. The results of this analysis can be used as a basis for developing strategies and policies to improve environmental conditions to support the successful cultivation of seaweed.
Key Words: PLS-SEM, environment quality; decline production; *Kappaphycus alvarezii* seaweed; Kepulauan Seribu.

Introduction. Indonesia is one of the world's largest producers of tropical seaweed, especially the *Kappaphycus alvarezii* type. Indonesia's seaweed production is approaching 10 million metric tons of farmed fresh seaweed in 2019 and is ranked second after China (Heijden et al 2022). China and Indonesia will supply 56 percent and 27 percent of the global market share of farmed seaweed by volume in 2020 (World Bank 2023). However, production over the last 5 years has declined from 11,050,031 matrix tons in 2016 to 9,753,410 matrix tons in 2023 (MMAF 2024). Several factors that can influence the production of seaweed from cultivation include choosing a suitable location, good seeds, appropriate cultivation methods, and human resources who diligently carry out maintenance (Anggadirdja et al 2006). Success can also be influenced by other external factors, namely environmental, technological, social, and economic (Blankenhorn 2008) as well as internal factors, namely the thallus and age of the seaweed itself (Fortes 1990).

One of the locations for seaweed cultivation that has experienced a significant decline in production is the Kepulauan Seribu archipelago, where in 2000 production reached 126,563 matrix tons (Kasih 2017) to 10.49 matrix tons in 2023 (MERI 2004). Therefore, this research is needed to analyze the factors causing the decline in production.

Considering the many variables that can cause a decrease in production, both those that can be measured directly and those that cannot be measured directly (latent) will be analyzed using the Partial Least Squares-Structural Equation Modeling (PLS-SEM). PLS-SEM is good for predictive-oriented research and can be used to measure formative and reflective constructs (Hanafiah 2020). PLS-SEM can accommodate sample sizes with small populations of at least 30-100 samples (Hair et al 2020). PLS-SEM is also very appropriate to use for research that aims to develop theory because it can be used to test predictive relationships between constructs by seeing whether there is a relationship or influence (Hair et al 2017). PLS-SEM evaluation uses two stages: evaluation of the measurement model and the structural model (Hair et al 2020). It is hoped that the research results will provide an overview of what variables significantly influence the decline in seaweed production and the magnitude of the influence of each variable.

Material and Method

Data collection. Data collection on water environmental quality variables, including physical, chemical, and biological parameters, was carried out during the rainy season and the dry season. The measurement and analysis of water quality during the rainy season were conducted from May 23 to June 9, 2023, and during the dry season, from August 24 to 28, 2023. Data collection for each season was carried out once, while field water quality measurements and laboratory analysis were conducted in triplicate. The survey was conducted at 12 sampling points around Panggang Island, Karya Island, Pramuka Island, and Congkak coral Semak Daun Island in Kepulauan Seribu Regency, Indonesia (Figure 1). Data collection on physical parameters includes current velocity, transparency, temperature, salinity, and TSS; chemical parameters include pH, BOD, DO, NO_3-N, PO_4-P, NH_3-N, oil, and fat content; and biological parameters include plankton and Chlorophyll-a. Equipment used for sampling consists of a Water Quality Checker (Horiba U5000G), Secchi Disk, JFE Current Meter (Infinity Series) AEM 1618, Colorimeter (Hach DR900), Vacuum pump, and filter paper with a pore size of 2.5 μm, plankton, and binocular microscope (Olympus cx22led), and other laboratory equipment for water quality analysis at LAPTIAB-BRIN, National Research and Innovation Agency.

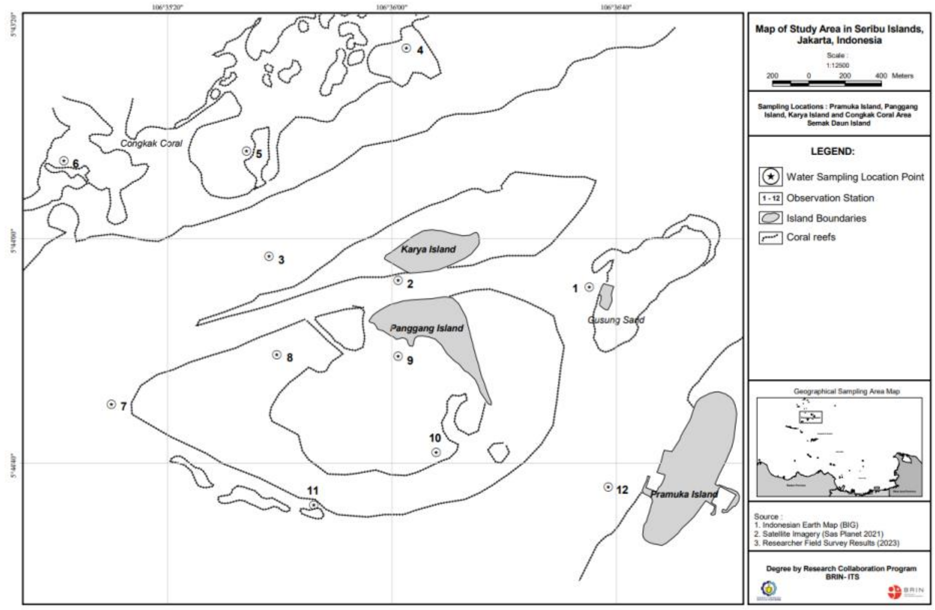

Figure 1. Map of study area in Kepulauan Seribu, Indonesia.

Data collection for the Human resources, Seaweed Factors, and Technological Factors variables was obtained through interviews with seaweed cultivators in the Kepulauan Seribu using a questionnaire. The questionnaire was prepared using a Likert scale with answers to each variable given a score including Strongly Disagree (STS) with a score of

1, Disagree (TS) with a score of 2, Neutral (N) with a score of 3, and Agree (S) with a score of 4. and Strongly Agree (SS) with a score of 5. The Human Resource Factors variable questionnaire consists of 10 questions, Seaweed Factors with 8 questions, and the Technological Factors variable with 3 questions. The number of seaweed cultivators at the 12 sampling locations was 50 people.

Data analysis. Analysis of the factors that influence seaweed production in the Seribu Islands was carried out by looking at the influencing variables and the magnitude of their influence using the Partial Least Square Structural Equation Modeling (PLS-SEM) method approach. The variables in this study used six exogenous latent variables and one endogenous latent variable (Table 1). The six exogenous variables consist of 3 reflective and 3 formative indicator variables. Data analysis uses SmartPLS version 4 software with stages of analysis procedure according to Hanafiah (2020) Hair (2020):

a. Outer model testing to prove validity and estimate the reliability of indicators and constructs includes convergent validity, discriminant validity, and composite reliability.
b. Inner model testing to test the significance of the influence of exogenous variables on endogenous variables includes simultaneous and partial effect size testing (R-square and F-square), multicollinearity (Variance Inflation Factor/VIF), and Path Coefficient.
c. Evaluation of the model through Goodness of Fit (GoF) testing to test the feasibility of the model and the predictive power of the model by assessing SRMR (Standardized Root Mean Square Residual) and NFI (Normal Fit Index).

Table 1

Formative variables on seaweed production

Variable	*Variable definition*	*Symbol*	*Indicators*	*Standard*
Production	Endogenous variable (Y)	Y	Production (lifespan)	
Physical Parameters*	(X.1) Exogenous variable	X.1.1	Current	0.2-0.4 m s^{-1}
		X.1.2	Transparency	>5 m
		X.1.3	Temperature	26-32 (°C)
		X.1.4	Salinity	28-34 (mg L^{-1})
		X.1.5	TSS	<25
Chemical Parameters*	(X.2) Exogenous variable	X.2.1	pH	7.5-8.5
		X.2.2	BOD	2 mg L^{-1}
		X.2.3	DO	>5
		X.2.4	NO3-N	0.9-3.2 (mg L^{-1})
		X.2.5	PO4-P	0.2-0.5
		X.2.6	NH3-N	<0.1 (mg L^{-1})
		X.2.7	Oil and Fat	<1 (mg L^{-1})
Biological Factors**	(X.3) Exogenous variable	X.3.1	Plankton	Not blooming
		X.3.2	Chlorophyll-a	>10 (µg L^{-1})

Source: * (Anggadiredja 2006); (MEF 2021); (Julianto 2023); ** (ANZECC 2000); (MERI 2004).

Table 2

Reflective variable on seaweed production

Variable	*Variable definition*	*Symbol*	*Indicators (brief questionnaire explanation)*
Production	(Y) Endogenous variable	Y.	Production (Lifespan)
Human resources factors*	(X.4) Exogenous variable	X.4.1	Education affects production
		X.4.2	Experience affects production
		X.4.3	Understanding the types of seaweed
		X.4.4	Mastering cultivation techniques
		X.4.5	Understanding the quality of good seeds
		X.4.6	Having adequate facilities and infrastructure
		X.4.7	Using personal capital
		X.4.8	Excitement because it has become the main job
		X.4.9	Understanding the conditions of the cultivation location
		X.4.10	Stay motivated even when experiencing frequent crop failures
Seaweed factors**	(X.5) Exogenous variable	X.5.1	Same types of seaweed
		X.5.2	Seeds come from harvested crops
		X.5.3	Seeds come from tissue culture
		X.5.4	Seedlings are healthy and disease-free
		X.5.5	Clean seeds from moss and epiphytes
		X.5.6	Many branches, lush, fresh
		X.5.7	Bright color, not pale
		X.5.8	The age of the seeds is 25-30 days
Technological factors***	(X.6) Exogenous variable	X.6.1	Applying the Long-line method
		X.6.2	Apply the off-bottom or raft method
		X.6.3	Applying new innovative technology

Source: * Anggadiredja et al 2006, ** NSA 2011 ; Julianto et al 2023, ***NSA 2010.

Results

Water quality analysis and interviews. Data on water quality variables, including physical, chemical, and biological parameters, were obtained from direct surveys of the Kepulauan Seribu waters during the rainy season and dry season. Table 3 and Table 4 show water quality data in the rainy season and dry season.

Table 3

Environmental water quality for seaweed cultivation during the rainy season, Kepulauan Seribu, Indonesia

Parameters	*Stations*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
						Physical						
Current (cm s^{-1})	16.42±0.53	26.76±1.09	13.78±0.83	12.41±0.54	20.41±0.75	8.40±0.65	12.17±0.90	11.81±0.60	12.05±0.43	18.24±0.85	14.20±1.18	16.60±0.69
Transparency (m)	10.00±1.00	7.00±1.00	10.00±1.73	5.00±1.00	5.50±0.87	7.00±1.00	11.00±1.00	1.00±0.00	5.00±0.00	4.50±0.00	9.00±1.00	9.50±0.50
Temperature (^{0}C)	29.82±0.34	29.92±0.17	29.90±0.28	29.44±0.21	29.64±0.43	29.84±0.27	29.99±0.19	30.17±0.24	30.18±0.22	30.09±0.11	30.14±0.25	30.19±0.27
Salinity (ppt)	29.00±0.03	28.90±0.12	28.90±0.18	28.40±0.27	28.90±0.22	28.90±0.24	29.00±0.51	28.80±0.29	28.70±0.16	28.90±0.20	28.90±0.31	28.90±0.27
TSS (mg L^{-1})	16.2±0.10	18.4±0.17	15.8±0.26	12.4±0.17	15.6±0.17	15.8±0.35	15.0±0.36	19.4±0.10	18.8±0.26	19.2±0.35	18.2±0.44	17.0±0.36
						Chemical						
pH	7.94±0.17	8.03±0.12	8.07±0.20	8.06±0.21	8.11±0.14	8.08±0.17	8.13±0.13	8.21±0.20	8.13±0.16	8.13±0.23	8.14±0.2o	8.14±0.19
BOD (mg L^{-1})	1.70±0.10	2.00±0.17	1.50±0.20	1.50±0.26	1.80±0.10	1.80±0.26	2.10±0.30	1.70±0.26	1.00±0.17	2.10±0.36	0.80±0.10	0.90±0.20
DO (mg L^{-1})	5.00±0.26	5.00±0.17	4.60±0.20	4.90±0.20	4.30±0.10	4.30±0.44	4.30±0.35	5.40±0.44	4.80±0.35	4.80±0.52	5.50±0.53	5.20±0.10
NO_3-N (mg L^{-1})	1.60±0.30	1.90±0.20	2.40±0.17	2.90±0.26	2.60±0.10	2.90±0.44	4.10±0.17	4.00±0.26	4.50±0.17	5.40±0.46	6.30±0.62	5.80±0.26
PO_4-P (mg L^{-1})	0.07±0.02	0.16±0.05	0.12±0.11	0.28±0.06	0.10±0.07	0.19±0.09	0.10±0.02	0.13±0.05	0.14±0.06	0.12±0.05	0.06±0.01	0.28±0.06
NH_4-N (mg L^{-1})	0.06±0.02	0.07±0.01	0.05±0.02	0.05±0.02	0.07±0.02	0.07±0.03	0.04±0.01	0.05±0.01	0.05±0.01	0.06±0.02	0.03±0.01	0.07±0.01
Oil & Fat (mg L^{-1})	36±2.00	45±2.65	12±1.00	51±3.61	12±1.73	17±1.00	22±2.65	16±1.00	16±2.00	7±1.00	35±3.00	9±1.00
						*Biological**						
Plankton (individual L^{-1})*	110	125	119	71	76	36	855	102	9070	2529	972	214
Chlorophyll-a (μg L^{-1})*	0.81	1.00	0.82	0.37	0.36	0.68	0.85	4.24	4.20	3.55	0.93	0.89

Note (*) No replication

Table 4

Environmental water quality for seaweed cultivation during the dry season, Kepulauan Seribu, Indonesia

Parameters	*Stations*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Physical												
Current (cm s^{-1})	16.92±1.03	40.95±2.13	33.46±1.15	39.40±1.61	18.88±2.08	33.56±2.08	37.55±1.20	36.22±1.10	31.65±1.41	22.93±1.52	28.93±1.35	28.93±1.02
Transparency (m)	7±1.00	6.5±1.32	6.2±0.98	6.7±0.75	4.5±0.62	6.0±0.46	7.0±1.08	1.0±0.00	2.8±0.26	5.3±0.75	8.0±0.50	7.5±0.44
Temperature (^{0}C)	30.14±0.92	30.21±0.88	29.96±0.27	29.68±0.94	29.85±0.51	30.23±0.63	30.34±0.54	30.65±0.53	30.78±0.80	30.46±0.48	30.56±0.49	30.66±0.61
Salinity (ppt)	29.3±0.75	29.1±0.53	29.4±0.44	28.7±0.52	28.9±0.62	29.4±0.70	29.9±0.44	29.6±053	29.7±0.36	29.5±0.44	29.3±0.36	29.5±0.72
TSS (mg L^{-1})	4.8±0.26	16.8±0.36	13.6±0.46	11.4±0.66	6±0.50	14±0.61	13±0.35	14±0.44	17.8±0.30	18±0.70	14.4±0.53	16.2±0.35
Chemical												
pH	7.65±0.17	7.63±0.44	7.6±0.45	7.65±0.44	7.6±0.27	7.58±0.37	7.65±0.42	7.68±0.45	7.58±0.40	7.62±0.31	7.64±0.25	7.68±0.30
BOD (mg L^{-1})	1.50±0.20	1.80±0.26	1.00±0.10	0.90±0.10	1.30±0.17	1.60±0.26	1.80±0.20	1.90±0.17	1.30±0.20	1.50±0.26	1.20±0.10	1.00±0.10
DO (mg L^{-1})	4.20±0.20	4.3±0.26	4.3±0.36	7±0.44	6.5±0.26	6.3±0.20	6.1±0.50	6.7±0.17	6.0±0.44	6.0±0.26	6.2±0.36	6.1±0.30
NO3-N (mg L^{-1})	1.50±0.17	1,5±0.26	2.2±0.10	2.2±0.17	3.6±0.20	3.3±0.17	3.5±0.10	4.9±0.26	4.2±0.10	2.5±0.17	2.7±0.36	2.8±0.26
PO4-P (mg L^{-1})	0.04±0.02	0.27±0.05	0.06±0.02	0.47±0.08	0.29±0.02	0.18±0.06	0.27±0.01	0.25±0.05	0.04±0.02	0.01±0.01	0.25±0.08	0.27±0.06
NH4-N (mg L^{-1})	0.11±0.03	0.09±0.04	0.07±0.02	0.06±0.02	0.08±0.01	0.08±0.02	0.09±0.03	0.07±0.01	0.08±0.02	0.11±0.03	0.09±0.01	0.08±0.03
Oil & Fat (mg L^{-1})	11±2.00	20±2.65	31±1.73	25±1.00	71±2.00	10±1.00	18±2.00	31±1.73	18±2.00	21±1.00	26±1.73	40±2.00
*Biological**												
Plankton (individual L^{-1})*	77	93	135	63	54	76	140	94	68	84	94	124
Chlorophyll-a (μg L^{-1})*	0.80	0.9	0.95	0.54	0.6	0.56	1.19	0.83	1.66	1.54	0.76	0.87

Note: (*) No replication.

The water quality data serve as exogenous variables for the physical, chemical, and biological parameters in the PLS-SEM model. On the other hand, the endogenous variable should ideally be derived from the seaweed production data from each research station. However, due to the absence of production data, the production variable is represented by the lifespan of the cultivated seaweed measured in days (Table 5).

Table 5

Endogenous variables for production using lifespan (days)*

Sampling time	*Stations*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Rainy season	6	7	13	14	13	12	13	12	14	20	7	19
Dry season	15	13	6	22	7	20	14	8	6	14	15	7

Source: * The results of the interviews with seaweed farmers at each research location.

Data on the Human Resources, Seaweed Factor, and Technological Factors variables were obtained through interviews with 36 seaweed cultivators in the Kepulauan Seribu using a questionnaire with 21 questions. The total results of interviews or opinion polls were 721 data.

PLS-SEM analysis results. The results of the first stage are the preparation of a PLS-SEM model by creating the concept of latent variables and indicators. The PLS-SEM measurement and structural model in this research is composed of six exogenous indicators consisting of 3 reflective variables and 3 formative variables on 1 endogenous variable of seaweed production (Figure 2).

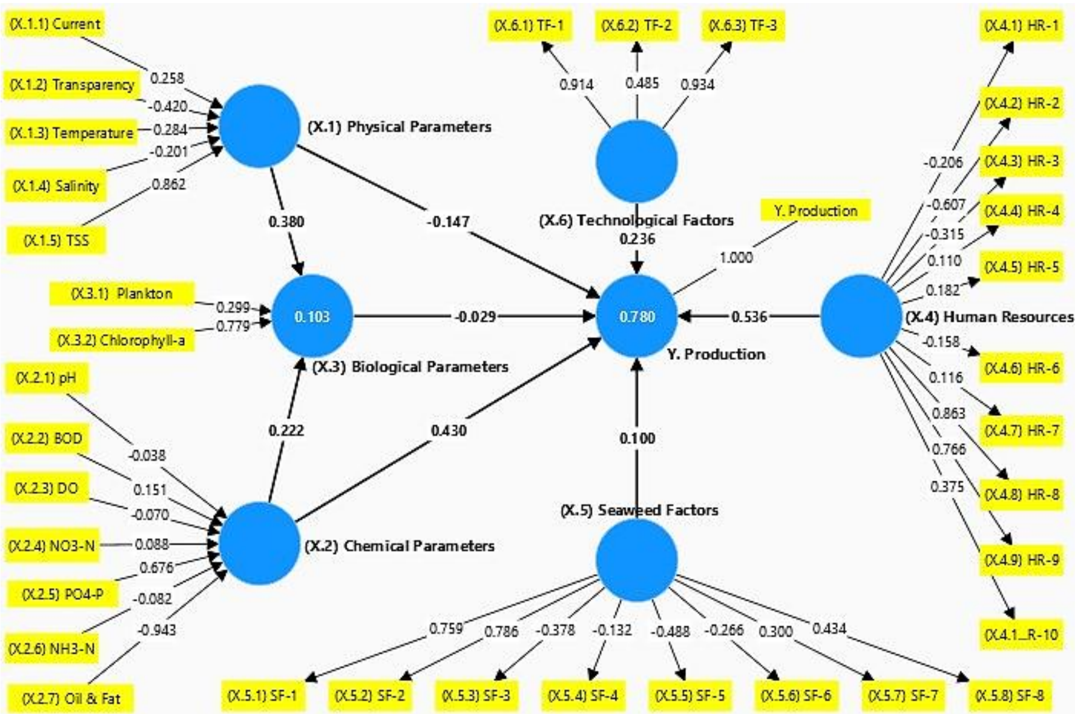

Figure 2. Measurement and structural model and results of running the PLS-SEM algorithm.

The next stage is to evaluate the measurement model through a convergent validity test by looking at the loading factor value from the results of running the PLS-SEM algorithm. Next, invalid indicators were removed from the model and continued by running the PLS-SEM algorithm again so that the results were that all indicators were valid (Figure 3).

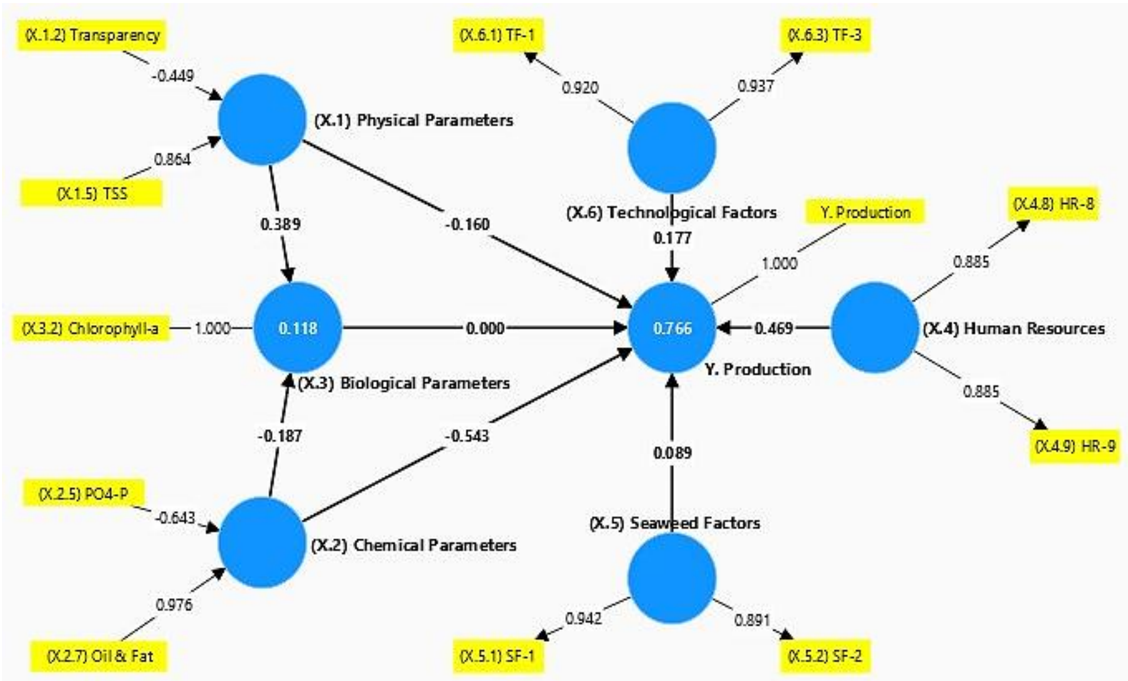

Figure 3. The results of running the PLS-SEM algorithm show that all indicators are valid.

The convergent validity test results of the reflective variables by examining the value of the outer loadings. The result indicated that all indicator values > 0.7 are valid (Table 6).

Table 6

Results of outer loadings of reflective variables

Variables	*Outer loadings*
(X.1.2) Transparency -> (X.1) Physical parameter	-0.506
(X.1.5) TSS -> (X.1) Physical parameter	0.894
(X.2.5) PO4-P -> (X.2) Chemical parameters	-0.358
(X.2.7) Oil & Fat -> (X.2) Chemical parameters	0.789
(X.3.2) Chlorophyll-a -> (X.3) Biological parameters	1.000
(X.4.8) HR-8 <- (X.4) Human resources	0.885
(X.4.9) HR-9 <- (X.4) Human resources	0.885
(X.5.1) SF-1 <- (X5) Seaweed factors	0.942
(X.5.2) SF-2 <- (X5) Seaweed factors	0.891
(X.6.1) TF-1 <- (X.6) Technology factors	0.920
(X.6.3) TF-3 <- (X.6) Technology factors	0.937
(Y) Production <- (Y) Production	1.000

After confirming the validity of all indicators, the analysis proceeded with a construct reliability test (Table 7), followed by discriminant validity assessments using the Fornell-Larcker criterion (Table 8) and cross-loading (Table 9) for the reflective variables in the model.

Table 7

Construct reliability and validity

Variables	*Cronbach's alpha*	*Composite reliability (rho_a)*	*Composite reliability (rho_c)*	*Average variance extracted (AVE)*
(X.4) Human resources	0.723	0.723	0.878	0.783
(X.5) Seaweed factors	0.815	0.869	0.913	0.841
(X.6) Technology factors	0.841	0.850	0.926	0.863

Table 8

Discriminant validity – Fornell-Larcker criterion

Variables	*(X.4)*	*(X.5)*	*(X.6)*	*Y*
(X.4) Human Resources	0.885			
(X.5) Seaweed Factors	0.135	0.917		
(X.6) Technology Factors	-0.270	-0.157	0.929	
(Y) Production	0.706	0.279	-0.072	1.000

Table 9 presents the results of the discriminant validity test using cross-loading values, indicating that the values for the measured indicators are greater than those of the other indicators.

Table 9

Discriminant validity-cross loading test results

Variables	*(X.1)*	*(X.2)*	*(X3)*	*(X.4)*	*(X.5)*	*(X.6)*	*Y*
(X.1.2) Transparency	-0.506	-0.185	-0.169	0.045	0.223	0.015	0.165
(X.1.5) TSS	0.894	0.044	0.337	-0.037	-0.151	-0.075	-0.242
(X.2.5) PO_4-P	-0.245	-0.358	-0.242	0.253	-0.067	0.034	0.329
(X.2.7) Oil & Fat	-0.038	0.798	-0.303	-0.331	-0.267	0.249	-0.573
(X.3.2) Chlorophyll-a	0.367	-0.140	1.000	0.216	-0.192	-0.028	0.097
(X.4) HR-8	0.022	-0.547	0.241	0.885	0.037	-0.224	0.624
(X.4) HR-9	0.071	-0.314	0.142	0.885	0.166	-0.253	0.625
(X.5) SF-1	0.081	-0.284	-0.126	0.190	0.942	-0.187	0.289
(X.5) SF-2	-0.391	-0.086	-0.247	0.035	0.891	-0.087	0.213
(X.6) TF-1	-0.079	0.194	-0.031	-0.265	-0.012	0.920	-0.063
(X.6) TF-3	-0.055	0.216	-0.021	-0.237	-0.265	0.937	-0.070
(Y) Production	-0.283	-0.770	0.097	0.706	0.279	-0.072	1.000

The testing of formative variables was conducted through significance testing by examining the outer weights after performing bootstrapping with 10,000 samples and a p-value <0.050 (Figure 4). The results of the PLS-SEM bootstrapping run are presented in Table 10.

Table 10

Results of outer weight testing of formative variables

Variables	*Original sample (O)*	*Sample mean (M)*	*Standard deviation (SD)*	*T statistics (O/STDEV)*	*P values*
(X.1.2) Transparency -> (X.1) Physical parameters	-0.449	-0.017	0.551	0.814	0.208
(X.1.5) TSS -> (X.1) Physical parameter	0.864	0.599	0.574	1.507	0.066
(X.2.5) PO4-P -> (X.2) Chemical Parameters	-0.643	-0.301	0.574	1.120	0.131
(X.2.7) Oil & Fat -> (X.2) Chemical parameters	0.976	0.707	0.643	1.518	0.064
(X.3.2) Chlorophyll-a -> (X.3) Biological parameters	1.000	1.000	0.000	n/a	n/a
(X.4.8) HR-8 <- (X.4) Human resources	0.565	0.571	0.082	6.862	0.000
(X.4.9) HR-9 <- (X.4) Human resources	0.565	0.559	0.066	8.573	0.000
(X.5.1) SF-1 <- (X5) Seaweed factors	0.626	0.614	0.298	2.100	0.018
(X.5.2) SF-2 <- (X5) Seaweed factors	0.461	0.430	0.311	1.482	0.069
(X.6.1) TF-1 <- (X.6) Technological factors	0.506	0.527	0.391	1.295	0.098
(X.6.3) TF-3 <- (X.6) Technological factors	0.570	0.494	0.388	1.469	0.071
(Y) Production <- (Y) Production	1.000	1.000	0.000	n/a	n/a

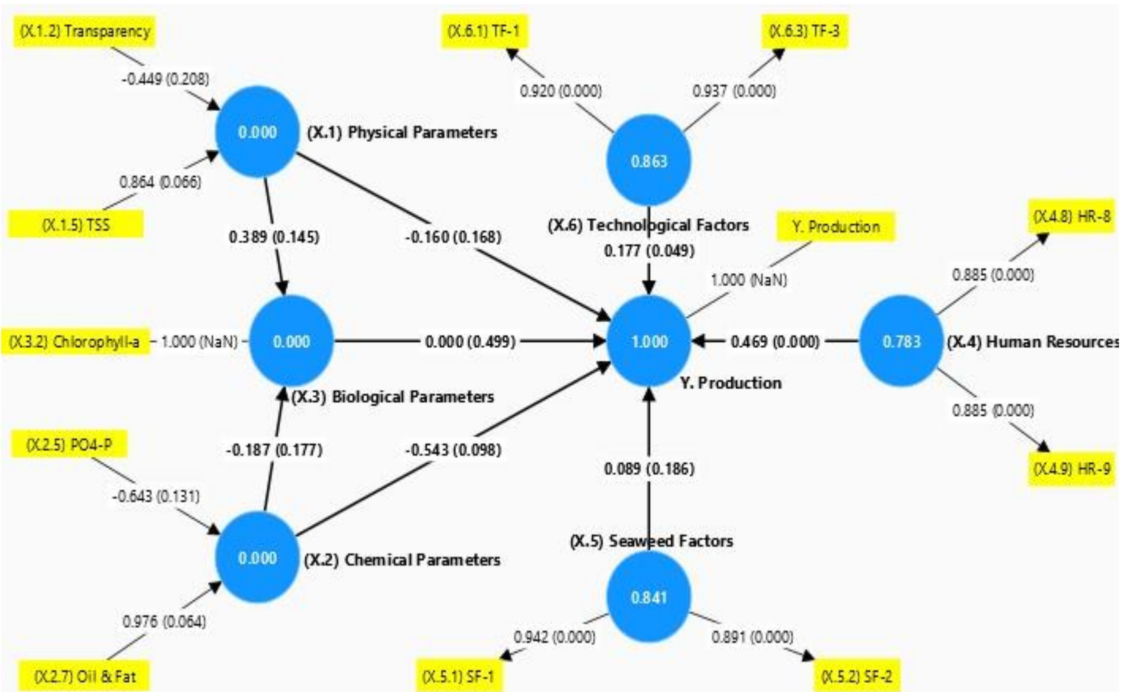

Figure 4. Results of running PLS-SEM *bootstrapping* 10,000 samples.

The next step involved testing for multicollinearity by examining the Variance Inflation Factor (VIF) values to determine the presence of collinearity among the indicators (Table 11).

Table 11

The Variance Inflation Factor (VIF) value of an outer model

Indicators	*VIF*
(X.1.2) Transparency	1.005
(X.1.5) TSS	1.005
(X.2.5) PO_4-P	1.093
(X.2.7) Oil & Fat	1.093
(X.3.2) Chlorophyll-a	1.000
(X.4.8) HR-8	1.471
(X.4.9) HR-9	1.471
(X.5.1) SF-1	1.896
(X.5.2) SF-2	1.896
(X.6.1) TF-1	2.115
(X.6.3) TF-3	2.115
(Y) Production	1.000

The next criterion for testing is the discriminant validity analysis using the Heterotrait-Monotrait Ratio (HTMT) for all reflective variables used to measure their impact on production. The results are presented in Table 12.

Table 12

Results of HTMT analysis

Variables	*HTMT*
(X.5) Seaweed Factors <-> (X.4) Human Resources	0.179
(X.6) Technology Factors <-> (X.4) Human Resources	0.347
(X.6) Technology Factors <-> (X.5) Seaweed Factors	0.203
(Y) Production <-> (X.4) Human Resources	0.830
(Y) Production <-> (X.5) Seaweed Factor	0.303
(Y) Production <-> (X.6) Technology Factors	0.078

The final stage involves evaluating the structural model to examine the relationships among the latent variables hypothesized in the study. This includes analyzing multicollinearity, path coefficients, R-squared, F-squared, and SRMR, as detailed in Table 13.

Table 13

Collinearity statistics (VIF) – Inner model

Variables	*VIF*
(X.1) Physical Parameter -> (X.3) Biological parameters	1.015
(X.1) Physical parameter -> (Y) Production	1.248
(X.2) Chemical parameters -> (X.3) Biological parameters	1.015
(X.2) Chemical parameters -> (Y) Production	1.392
(X.3) Biological parameters -> (Y) Production	1.289
(X.4) Human resources -> (Y) Production	1.416
(X.5) Seaweed factors -> (Y) Production	1.152
(X.6) Technological factors -> (Y) Production	1.127

In the structural model, path coefficient analysis is carried out to determine the influence of the independent variable on the dependent variable partially and whether the direction of the variable relationship is positive or negative. The results of the path coefficients for each variable are presented in Table 14.

Table 14

Path coefficient analysis results

Variables	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
(X.1) Physical parameters -> (X.3) Biological parameters	0.389	0.229	0.368	1.058	0.145
(X.1) Physical parameters -> (Y) Production	-0.160	-0.105	0.159	1.004	0.158
(X.2) Chemical parameters -> (X.3) Biological parameters	-0.187	-0.183	0.202	0.928	0.177
(X.2) Chemical parameters -> (Y) Production	-0.543	-0.371	0.418	1.299	0.097
(X.3) Biological parameters -> (Y) Production	0.000	0.003	0.094	0.001	0.499
(X.4) Human resources -> (Y) Production	0.469	0.434	0.116	4.045	0.000
(X.5) Seaweed factors -> (Y) Production	0.089	0.096	0.099	0.895	0.186
(X.6) Technological factors -> (Y) Production	0.177	0.157	0.107	1.652	0.049

Furthermore, from the results of the path coefficients analysis, the following equation can be prepared: production =-0.160 physical parameters -0.543 chemical parameters + 0.469 human resources + 0.089 seaweed factors + 0.177 technological factors + error.

$$Y= -0.160\ X1 -0.543\ X2 +0.469\ X4+0.089\ X5+0.177\ X6+Z6\ (error) \quad (6)$$

Where:

$$X1 = -0.449*X.1.2 + 0.864* X.1.5+z1 \quad (1)$$
$$X2 = -0.643*X.2.5 + 0.976*X.2.7+z2 \quad (2)$$
$$X3 = 0.000*X3.2= 0$$
$$X4 = 0.565*X4.8 + 0.565*X.4.9+z3 \quad (3)$$
$$X5 = 0.626*X.5.1 + 0.461*X.5.2+z4 \quad (4)$$
$$X6 = 0.506*X.6.1 + 0.570*X.6.3+z5 \quad (5)$$

$$Y= -0.160*(-0.449*X1.2+0.864*X.1.5+z1) - 0.543*(-0.643*X2.5+0.976*X2.7+z2) + 0.469*(0.565*X4.8+0.565*X4.9+z3) + 0.089*(0.626*X5.1+0.461*X5.2+z4) + 0.177*(0.506*X6.1+0.570*X6.3+z5) + Z6 \quad (7)$$

$$Y= 0.072*X1.2-0.138*X1.5-0.160*z1 - 0.349*X2.5-0.530*X2.7-0.543*z2 + 0.265*X4.8+0.265*X4.9+0.469*z3 + 0.056*X5.1+0.041*X5.2+0.089*z4 + 0.089*X6.1+0.100X6.3 + 0.177*z5+z6 \quad (8)$$

Table 14 and the equation above can explain the relationship between each variable and its significance as follows:

a. There is a relationship between Physical Parameters and Biological Parameters of 0.389, which shows that if Physical Parameters increase by one unit, Production can increase directly and indirectly through Biological Parameters by 38.9% with a positive influence but no significant ($p < 0.05$).
b. There is a direct relationship between Physical Parameters and Production with a value of -0.160, which shows a negative effect of 16.0%, and a P value of 0.158 shows no significant effect ($p < 0.05$).
c. There is a relationship between Chemical Parameters and Biological Parameters with a value of -0.187. This shows that if the Chemical Parameters increase by one unit, Production can increase directly and indirectly through Biological Parameters by

18.7%, even though the effect is negative. The P value of 0.177 indicates no significant effect (p > 0.05).

d. There is a relationship between Chemical Parameters and Production with a value of -0.543, which shows a negative influence of 54.3%. The P value of 0.097 indicates that this relationship is not significant (p < 0.05) but is important at a P value of 0.100.
e. There is a relationship between Biological Parameters and Production with a value of -0.000, which indicates that there is no influence on Production. The P value of 0.499 indicates that this relationship is not significant (p > 0.05).
f. There is a relationship between Human Factors and Production with a value of 0.469, which shows that if Human Resources increase by one unit, Production can increase directly by 46.9%. The effect is positive, and a P value of 0.000 indicates that this relationship is significant (p > 0.05).
g. There is a relationship between the Seaweed Factor and Production with a value of 0.089, which shows that if the Seaweed Factor increases by one unit, Production can increase directly by 0.89%. Even though the effect is positive, the P value of 0.186 indicates that this relationship is insignificant (p > 0.05).
h. There is a relationship between Technology Factors and Production of 0.177, indicating that if the Technology Variable increases by one unit, Production can increase directly by 17.7% with a positive influence, and a P value of 0.049 has no significant effect (p < 0.05).

The next stage is to measure the model quality criteria by looking at the value and quality of the model, including analysis of the coefficient of determination (R-square), F-square, SRMR, and NFI. The coefficient of determination shows the magnitude of the influence of several exogenous latent variables on endogenous latent variables by looking at the predictive power through R-square. The R-square value criteria include a value of 0.25 for low influence, an R-square of 0.50 for medium (moderate), and an R-square of 0.75 for strong or high influence (Hair et al 2011). Table 15 shows the results of the analysis of the coefficient of determination (X.1) and (X.2) for the Biological Parameters variable of 0.169, which means a weak influence of 16.9%. Meanwhile, variables (X.1), (X.2), (X.3), (X.4), (X.5), and (X.6) for the Production variable are 0.806, meaning that all exogenous variables can explain 80.6% Production is an endogenous variable and is included in the strong influence category, R-square > 0.75 strong/high influence.

Table 15

R-square values

Variables	*Original sample (O)*	*Sample mean (M)*	*Standard deviation (STDEV)*	T Statistics (|O/STDEV|)	*P values*
(X.3) Biological Parameters	0.169	0.216	0.137	1.233	0.109
(Y) Production	0.806	0.834	0.059	13.744	0.000

The next evaluation of the structural model is the analysis of the f-square value (effect size), which explains the magnitude of the influence of each variable at the structural level. The F-square value guidelines are: 0.02 indicates a small effect, 0.15 indicates a medium (moderate) effect, and 0.35 indicates a strong effect (Hair et al 2019). Table 13 shows the F-square values (effect sizes) that can explain the magnitude of the influence among variables in model assessment and prediction as follows:

a. The relationship between Physical Parameters and Biological Parameters is 0.180, indicating a moderate effect and not statistically significant (p < 0.05).
b. The relationship between Physical Parameters and Production is 0.106, indicating a moderate effect and not statistically significant (p < 0.05).
c. The relationship between Chemical Parameters and Biological Parameters is 0.041, indicating a low effect and not statistically significant (p < 0.05).

d. The relationship between Chemical Parameters and Production is 1.093, indicating a strong effect and significant effect (p > 0.05).
e. The relationship between Biological Parameters and Production is -0.000, indicating a low effect and not statistically significant (p < 0.05).
f. The relationship between Human Factors and Production is 0.802, indicating a strong and significant effect (p > 0.05).
g. The relationship between Seaweed Factors and Production is 0.035, indicating a low effect and not statistically significant (p < 0.05).
h. The relationship between Technological Factors and Production is 0.144, indicating a moderate effect and not statistically significant (p < 0.05).

Thus, environmental factors, particularly chemical parameters and human resources, indicate a significant influence on seaweed production. As stated by Harley et al (2012), seaweed is known to be vulnerable to physical and chemical changes in the marine environment.

Table 16

F-square value of six variables on production

Variables	*Original sample (O)*	*Sample mean (M)*	*Standard deviation (STDEV)*	*T Statistics (|O/STDEV|)*	*P values*
(X.1) Physical Parameters -> (X.3) Biological Parameters	0.180	0.253	0.256	0.701	0.222
(X.1) Physical Parameters -> (Y) Production	0.106	0.183	0.270	0.391	0.348
(X.2) Chemical Parameters -> (X.3) Biological Parameters	0.041	0.100	0.150	0.276	0.391
(X.2) Chemical Parameters -> (Y) Production	1.093	1.188	0.665	1.667	0.048
(X.3) Biological Parameters -> (Y) Production	0.000	0.036	0.058	0.000	0.500
(X.4) Human Resources -> (Y) Production	0.802	0.774	0.449	1.784	0.037
(X.5) Seaweed Factors -> (Y) Production	0.035	0.089	0.123	0.286	0.387
(X.6) Technological Factors -> (Y) Production	0.144	0.189	0.224	0.643	0.260

The next evaluation of the model's goodness-of-fit is by examining the SRMR (Standardized Root Mean Square Residual) value, which represents the difference between the correlation matrix of the data and the correlation matrix estimated by the model. An SRMR value indicating a fit model is recommended to be less than 0.08, while a value less than 0.10 is still acceptable (Sarstedt et al 2017). The measured SRMR values for the model assessing the influence of all variables- Environment, Seaweed, Human Resources, and Technology on Production are 0.090 for the Saturated model and 0.096 for the estimated model. Since both are < 0.10, the model is fit (Table 17). The NFI value is determined within the range of 0 to 1, where values closer to 1 indicate a better model. The NFI measurement analysis shows a value of 0.682, which is close to 1, suggesting that the model can be considered good or suitable (Table 17). An accurate ecological prediction model can be used to determine management priorities because it will be invaluable for effective conservation and management (Harley et al 2012).

Table 17

Results of measuring SRMR and NFI values

Parameters	*Saturated model*	*Estimated model*
SRMR	0.090	0.096
NFI	0.682	0.645

Discussion*.* PLS-SEM was used to analyze the factors causing a decline in seaweed production through stages of data collection, testing, and model evaluation, indicating that all requirements have been met. The results of data collection and analysis show that the overall water quality is still suitable for seaweed cultivation. The temperature measurements during the rainy season ranged from 29.82 to 30.18°C, which is lower than during the dry season, where it ranged from 29.68 to 30.78°C. This temperature range still meets the standard of 26-32°C (Julianto et al 2023). Such temperatures are crucial for the growth, reproduction, photosynthesis, and spread of seaweed (Gultom et al 2019). The current speed ranged from 8.40 to 20.41 cm s^{-1} during the rainy season and from 22.93 to 40.95 cm s^{-1} during the dry season. Although relatively weak, these values still meet the standard (Luning 1991). The measurements of other physical parameters, such as transparency, salinity, and total suspended solids (TSS), all meet the standards as per Julianto (2023).

However, the chemical parameter measurements indicate that several indicators exceed the standards, particularly the very high levels of oil and fat, which surpass the quality standard of < 1 mg L^{-1} (MEF 2021). Measurements of oil and fat parameters are combined into one because they both have similar chemical properties, namely lipids. Oil and fat content analysis is used to identify oil spills or pollution. High levels of oil and fat in waters can be an indicator of pollution at seaweed cultivation locations. The oil and fat concentration during the rainy season reached 51 mg L^{-1} (Table 2), while during the dry season, it reached 71 mg L^{-1}, both exceeding the quality standards (Table 3). Additionally, in some locations, the nitrate content exceeded the quality standard of < 0.3 mg L^{-1} (MEF, 2021). The highest nitrate levels during the rainy season were recorded at Station 11, reaching 6.3 mg L^{-1}, while during the dry season, the highest levels at Stations 8 and 9 were 4.9 mg L^{-1} and 4.2 mg L^{-1}, respectively.

The elevated nitrate levels also correlate with the amount of Chlorophyll-a around Station 8, which reached 4.24 mg L^{-1} during the rainy season, and at Station 9, which reached 1.66 mg L^{-1} during the dry season. Stations 8, 9, and 10 are located near Panggang Island, in a coral atoll area where the water is relatively calm and the water current movement is very weak, below the minimum of 20 cm s^{-1} (Luning 1991). (Suman et al 2011) noted that the observed current speeds in the waters of the Kepulauan Seribu ranged from 1.6 to 8 cm s^{-1}. Current speed measurements in the Kepulauan Seribu were also conducted Sachoemar (2008) with varying results. During high tide, the current speeds at Pramuka Island, Panggang Island, and Karya Island ranged from 5 to 49 cm s^{-1}, while during low tide, the current speeds were recorded between 4 and 38 cm s^{-1}.

The results of measurements of physical, chemical, and biological parameters are then used as formative variables in PLS-SEM analysis. Meanwhile, interviews with 36 seaweed farmers using a questionnaire consisting of 21 questions generated 721 data points, which will be utilized as reflective variables in the PLS-SEM analysis. The PLS-SEM method is appropriate for measuring both formative and reflective constructs simultaneously (Hanafiah 2020). The measurement model for reflective variables was evaluated through convergent validity testing, examining the loading factor values obtained from the SEM-PLS algorithm run. Based on direct measurement results or the model in research development, an indicator is considered reliable if the loading factor value is >0.7 for reflective indicators or >0.4 for formative indicators (Hulland 1999). During the analysis process, invalid indicators were removed from the model, and the PLS-SEM algorithm was rerun until all indicators were validated (Figure 3).

The results of the convergent validity test for the reflective variables, as assessed by the outer loading values, indicated that all indicators were valid (Table 6). The results of Cronbach's alpha, Composite Reliability (rho_a), and Composite Reliability (rho_c) for all variables were greater than 0.70, and the Average Variance Extracted (AVE) for all variables was greater than 0.50 (Table 7). This indicates that the variables are valid and meet the requirements as measurement tools in the research (Hair et al 2021). The analysis of the square root of the AVE for each variable was greater than the correlations among constructs within the model, suggesting that the model has good discriminant validity (Table 8). The results of the discriminant validity test showed that all variables met the criteria for good discriminant validity (Table 9), as the measured indicator values were greater than those of other indicators (Hanafiah, 2020). Thus, the testing of the reflective variables meets all criteria for the measurement model.

The evaluation of the formative variables was conducted through significance testing, VIF values, and HTMT analysis. The results of the significance test, based on the outer weights, showed that the variables Transparency and TSS had values of -0.449 and 0.864, indicating a non-significant effect. The indicator PO4-P for Chemical Parameters had a value of -0.643, while Oil & Fat showed a value of 0.976, both of which were non-significant. In contrast, the variables (X.4.8) HR-8 and (X.4.9) HR-9 for Human Resources both showed a significant effect with values of 0.565 (P value 0.000). Additionally, (X.5.1) SF-1 had a significant effect on Seaweed factors with a value of 0.626 (P value 0.018), while (X.5.2) SF-2 did not show significance. The indicators (X.6.1) TF-1 and (X.6.3) TF-3 for Technological Factors had values of 0.506 and 0.570, respectively, indicating a non-significant effect. Thus, it can be concluded that each indicator for physical, chemical, and biological parameters had a non-significant effect at a P value of 0.050 but was significant at a P value of 0.100 for their latent variables (Table 10).

The analysis of multicollinearity for all formative indicators showed VIF values less than 5 (Table 11), indicating that there is no multicollinearity among all indicators, as per the criterion of being less than 5 (Sarstedt et al 2017). Similarly, the HTMT analysis indicated that all values were less than 0.90 (Table 12), confirming that the model does not have issues with discriminant validity (Hair et al 2019). The evaluation of the structural model through multicollinearity testing of the inner model showed that all VIF values were less than 5 (Table 13), allowing us to conclude that there are no collinearity issues among the variables.

The analysis of path coefficients indicated that Physical Parameters have a positive influence on Biological Parameters but a negative influence on Production, with a coefficient of -0.160, although this effect is not significant. Chemical Parameters negatively affect both Biological Parameters and Production, with a coefficient of -0.543, which is also not significant. The Biological Factor variable showed no influence and was not significant to Production. The Seaweed Factor had a positive but non-significant effect on Production. In contrast, the Human Resources variable (0.469) and Technological Factors (0.177) had positive and significant effects on Production (Table 14). These results align with the findings of (Blankenhorn 2008), which suggest that the success of seaweed cultivation can be influenced by external factors such as environment, technology, and social and economic conditions. Additionally, internal factors, such as thallus characteristics and the age of the seaweed itself, can also play a role (Fortes 1990).

The final evaluation of model quality, based on the R-square value for all exogenous variables affecting Production, was found to be 0.806 (Table 15), indicating a strong influence (Hair et al 2011). The F-square analysis demonstrated that Chemical Parameters had the strongest and most significant effect on Production, while Human Factors also exhibited a strong and significant influence (Table 16). Model fit was assessed using the SRMR values, with Saturated SRMR at 0.090 and estimated SRMR at 0.096 (Table 17), both of which are below 0.10, indicating that the model meets the fit criteria (Sarstedt et al 2017). Therefore, all criteria for measuring the outer model, inner model, and overall model evaluation were satisfied.

Thus, the results of the PLS-SEM analysis illustrate that each variable influences production separately. Therefore, a strategy for improving the seaweed cultivation system is needed. Following Langford's 2024 suggestion, various social, economic, and environmental changes have affected the cultivation of carrageenan seaweed, as well as livelihood systems. Therefore, community governance for seaweed cultivation must change to adapt to these new changes.

Conclusion. The PLS-SEM model that has been developed is feasible and valid for analyzing that each variable has different influence values and effects on seaweed production. The analysis of the total effect of Chemical Parameters on Production showed the largest influence at 54.3%, which is negative, although it is not statistically significant. In contrast, the effect size analysis revealed a very strong and significant impact on Production from two indicators: PO4-P and Oil & Fat. The total influence of Physical Parameters on Production shows a negative influence with a moderate and insignificant effect.

Meanwhile, the total effect of Human Resource Parameters on Production was strong, at 46.9%, positive, and significant. Additionally, the effect size indicated a significant impact with two indicators: motivation as a primary job and understanding of the cultivation location conditions. The total effect and effect size of Technology Parameters on Production showed a moderate and non-significant influence, with two indicators: the application of long-line methods and the implementation of innovative technologies accompanied by proper safeguarding of cultivation units. Similarly, the total effect of the Seaweed Factor on Production was very small, at 0.89%, with a minor and non-significant effect. Even the Biological Parameter, with a value of 0.00%, had no effect. As the total effect value approaches +1, the relationship between the two constructs gets stronger, whereas a value approaching -1 indicates a negative relationship (Sarstedt et al 2017).

The results of this PLS-SEM model analysis are expected to serve as a valuable consideration in formulating policies aimed at improving the factors affecting the decline in seaweed production, particularly focusing on Chemical Parameters and Human Resources Parameters.

Conflicts of interest. The authors declare that there are no conflicts of interest regarding the authorship or publication of this paper.

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Authors:
Wisnu Sujatmiko, Research Center for Fishery, National Research and Innovation Agency, Jalan Raya Bogor KM 46 Cibinong, Nanggewer Mekar, Bogor, 16912 Indonesia, email: wisnu.sujatmiko31@gmail.com
Nieke Karnaningroem, Department of Environmental Engineering, Institute Teknologi Sepuluh Nopember, Jalan Arief Rahman Hakim, Surabaya, 60111 Indonesia, email: n.karnaningroem@gmail.com
Irwan Bagyo Santoso, Department of Environmental Engineering, Institute Teknologi Sepuluh Nopember, Jalan Arief Rahman Hakim, Surabaya, 60111 Indonesia, email: irwan080565@gmail.com
Ratu Siti Aliah, Research Center for Fishery, National Research and Innovation Agency, Jalan Raya Bogor KM 46 Cibinong, Nanggewer Mekar, Bogor, 16912 Indonesia, email: ratusitialiah@yahoo.com

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