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Sustainability in Indonesian Coastal Areas: A Challenge to Develop a Blue Economy

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ABSTRACT

As an archipelagic country, Indonesia faces challenges in developing sustainable coastal areas and communities. Most studies have focused on specific regions, limiting broader generalizations. This study focuses on coastal villages in Indonesian provinces. The objectives are to classify provinces according to the environmental, economic, and social pillars of sustainability; classify provinces based on overall sustainability; and examine the sustainability level of coastal villages using macroeconomic indicators. A data mining approach was applied using the Knime Analytics Platform. The findings revealed that environmental sustainability tends to be less prominent than economic and social aspects. Provincial classifications show varying levels of sustainability across regions. Coastal villages in high-sustainability provinces tend to have higher life expectancy, lower poverty rates, and higher Human Development Index scores than those in low-sustainability provinces. These high-sustainability provinces also demonstrated vigorous blue economy activities, particularly aquaculture and marine tourism. In contrast, low-sustainability provinces lag in these areas. The study suggests prioritizing the development of aquaculture and marine tourism in low-sustainability coastal provinces as a strategic approach to promote inclusive and sustainable blue economy growth. A novel aspect of this research lies in the application of national-scale data mining using k-means clustering to uncover spatial and social, economic, and environmental patterns across regions, demonstrating the potential of large-scale analytics for sustainability understanding in coastal areas.

Keywords: *blue economy, coastal, data analytics, tourism, sustainability*

INTRODUCTION

Over three-quarters of countries have coastlines, offering advantages such as marine resources, trade, transportation, tourism, and scenic beauty. A coast is land beside the sea, and socially, it is where people rely heavily on marine resources (*Hossain et al. 2020*). Coastal countries seek to use these benefits for economic growth and community welfare, but this remains challenging for less developed ones.

The coastal area could be differentiated into the coastal rural and urban areas. Coastal urban areas have a growing population, rising real estate values, and large infrastructure (*Jurjonas and Seekamp 2018*). Sea resources, such as the aquaculture industry, can also be potentially developed to support food security in coastal urban areas (*Trottet et al. 2022*). Coastal rural areas are often linked to sustainability issues about the environment (e.g., flood, water pollution), economy (e.g., fishing, poverty), and society (e.g., health, sanitation). Therefore, sustainable development programs are pursued in coastal rural areas, such as supporting sustainable fisheries (*Tolentino-Zondervan and Zondervan 2022*), developing marine ecotourism (*Marlina et al. 2020*), and reducing marine pollution (*Willis et al. 2022*).

Sustainable development in coastal areas is related to the recent concept of a blue economy. The World Bank defined a Blue Economy as the sustainable use of marine resources for economic growth, improving livelihoods, and creating jobs while maintaining the health of marine ecosystems (*World Bank 2021*). The World Bank manages PROBLUE, a multi-donor trust fund, with a mission to create a Healthy Ocean, Healthy Economies, and Healthy Societies, indicating the three pillars of sustainability. A study investigating the association between the blue economy and SDGs reveals that the blue economy is highly associated with SDGs 14-17, where SDG 14, Life below water, is the top target (*Lee et al. 2020*).

Climate change and its impact on sustainability have become central themes in coastal studies. It triggers hazards such as erosion, floods, storm surges, and extreme waves. Research focuses on assessing current conditions and enhancing coastal resilience. Case studies include Malaysia, which examined climate vulnerability and socio-environmental impacts (*Bagheri et al. 2021*); Thailand, which analyzed socio-economic resilience (*Langkulsen et al. 2022*); the Philippines, which studied small-scale fisheries (*Macusi et al. 2025*); and Vietnam, which evaluated natural and human effects on sustainability (*Huong et al. 2022*).

Most coastal studies in Indonesia focus on specific regions, such as social vulnerability to disasters (*Putiamini et al. 2022*), marine health index assessment in a regency (*Joesidawati and Suwarsih 2022*), and social innovation partnerships in some villages (*Suryanto et al. 2023*). These localized studies limit generalization across the country and hinder the formulation of comprehensive recommendations. A nationwide understanding of coastal areas is essential for effective development planning.

Indonesia is an archipelagic nation with the sixth-largest exclusive economic zone in the world and manages enormous marine resources. The Government implements marine management with blue economy principles. The Indonesian Law Number 32 Year 2014 about the Sea states, "The blue economy is an approach to improving sustainable ocean management and the conservation of marine, coastal resources, and ecosystems to achieve economic growth, based on principles such as community involvement, resource efficiency, waste minimization, and multiple revenue creation." The National Development Planning Agency developed the Indonesian Blue Economy Roadmap to guide blue economy development from 2023 to 2045 (*Bappenas 2023*). The document states various efforts, such as empowering coastal communities, developing aquaculture, and promoting sustainable marine tourism.

Coastal communities play a vital role in developing the blue economy. In Indonesia, marine resources are mainly used in traditional sectors such as fishing, aquaculture, and processing, contributing 83% of value added and about 3.6% of GDP (*Bappenas 2023*). Significant challenges include low productivity, weak governance, unsustainable practices, and environmental degradation. To address these issues, capacity-building and innovation in small-scale fisheries and aquaculture for coastal communities are essential.

This study examines coastal village sustainability in Indonesia from a national rather than local perspective. A village is the smallest administrative unit led by a village head. As an archipelagic country with the world's third-longest coastline (*World Population Review 2024*), developing coastal areas is crucial. Poverty rates are higher in these regions due to limited job opportunities, education, and access to basic hygiene (*Komdigi 2021*). Understanding coastal communities is vital for effective government policies and development planning.

This study aims to classify provinces characterized by their coastal villages based on environmental, economic, and social pillars of sustainability, to classify provinces characterized by their coastal villages based on overall sustainability pillars, and to examine the level of sustainability based on macroeconomic indicators. This study focuses on Indonesian coastal villages, with the province serving as the unit of analysis, characterized by the presence of such villages.

MATERIALS AND METHODS

Research Framework and Variables

This is a secondary, quantitative, and exploratory research. Secondary numeric data were collected from the official statistics published by Statistics Indonesia in the annual report titled "Statistics on Marine and Coastal Resources 2023" (*BPS-Statistics Indonesia 2023*) published on 30 November 2023; and "Statistics on Marine and Coastal Resources 2024" (*BPS-Statistics Indonesia 2024*) published on 29 November 2024. Some macroeconomic data were gathered from Statistics Indonesia's official site (bps.go.id).

The 2030 Global Agenda for Sustainable Development is executed to accomplish 17 Sustainable Development Goals (SDGs) as a detailed framework for the sustainable development of each country. Each SDG does not refer to one pillar of sustainability, but assessing sustainable development performance based on the three pillars– environment, economy, and society– can help understand the balances and imbalances in achieving sustainable development in a region (*Mangukiya and Sklarew 2023*). Therefore, this study adopted a mapping of SDGs and three sustainability pillars (**Table 1**), for example, No Poverty is related to the economic aspect, Clean Water and Sanitation to the social aspect, and Climate Action to the environmental aspect. Some of the SDGs could be placed under multiple pillars, for example, SDG 11: Sustainable cities and communities could be placed under the social or environmental pillar. The study stated that the classification considered the objective of each SDG and which pillar it was closest to. For example, the objective of SDG 11 is "to make cities and human settlements inclusive, safe, resilient, and sustainable", which seems to relate more to the social than environmental aspect.

Assessing sustainable development in coastal areas has been a prevalent study area in which sustainability frameworks were developed, tested, and implemented. One of the holistic frameworks to assess coastal sustainable development is the circles of Coastal Sustainability (CCS) (*de Alencar et al. 2020*). The framework covers four interdependent domains: Environment and Ecology, Social and Cultural, Economics, and Governance and Policy. When comprehensive data are available, the framework will provide a holistic understanding of coastal development. However, when data are limited,, an operational framework that covers three sustainability aspects will be appropriate.

Furthermore, a research framework consisting of three elements of sustainability and macroeconomic indicators was designed (**Figure 1**). The sustainability elements are linked to relevant SDGs and related indicators of coastal villages (**Table 1**). Environmental sustainability was investigated with the environmental pollution associated with SDG 13 Climate Action and household cooking emissions associated with SDG 12 Responsible Consumption and Production. Economic sustainability was examined with the economic activity in using the sea resource, which is associated with SDG 8: Decent Work and Economic Growth, and micro-and-small enterprises' production, which is associated with SDG 9: Industry, Innovation and Infrastructure. Social sustainability was investigated with sanitation and drinking water, which was associated with SDG 6: Clean Water and Sanitation, and health facilities associated with SDG 3: Good Health and Well-being. The placement of macroeconomic indicators to each pillar was limited. Some of the indicators could be placed under multiple pillars; for example, cooking with wood could be associated with the environmental or socio-economic aspects. In some communities, gas was available, but some people preferred to gather wood for cooking. Therefore, the indicator was placed under SDG 12:

Table 1. Mapping SDGs and sustainability pillars.

Sustainability pillars	SDGs
Economic	1. No Poverty 4. Quality Education 7. Affordable and Clean Energy 8. Decent Work and Economic Growth 9. Industry, Innovation and Infrastructure 10. Reduced Inequality
Social	2. Zero Hunger 3. Good Health and Well-being 5. Gender Equality 6. Clean Water and Sanitation 11. Sustainable Cities and Communities 16. Peace and Justice Strong Institutions
Environmental	12. Responsible Consumption and Production 13. Climate Action 14. Life Below Water 15. Life on Land
All	17. Partnerships to achieve the Goals

Source: (*Mangukiya and Sklarew 2023*)

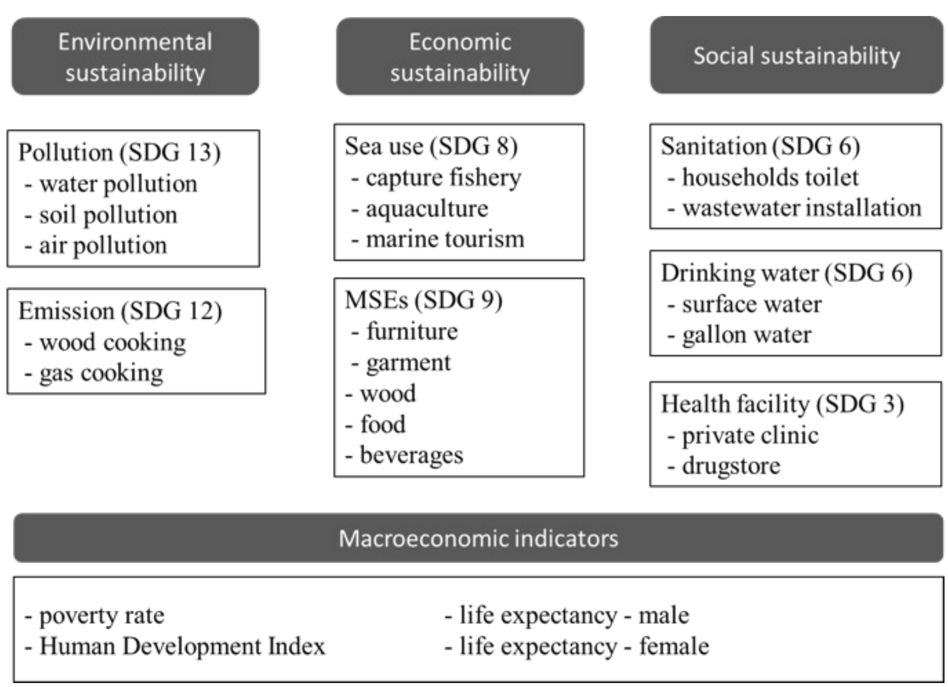

Figure 1. The research framework.

sustainable consumption and production. Each measure was expressed as the percentage of coastal villages in a province that do a particular measure, for example, the percentage of coastal villages in a province with water pollution (**Figure 1**).

The framework exhibits macroeconomic indicators, which characterize the coastal communities regarding poverty rate, life expectancy, and the Human Development Index (HDI) (**Figure 1**). The United Nations Development Programme (UNDP) defined HDI as a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable, and having a decent standard of living. The Indonesian HDI is measured by life expectancy, years of schooling, and per capita expenditure. Therefore, life expectancy and poverty rate are related to HDI.

Research object and unit of analysis

The study object is a coastal village, and the unit of analysis is a province characterized by the percentage of coastal villages. Indonesia is comprised of 32 provinces with a total of 107,473 km of coastline (**Table 2**).

The number of coastal villages in Indonesia is 12,510, representing 14.88% of the total villages (**Table 2**). The length of the coastline is about 107.000 km. The average length per village among provinces is 8.59 km, varying from a minimum of 2.85 km in Bengkulu to a maximum of 65.88 km in North Kalimantan. The number of provinces as a unit of analysis is 34. As a specific region, Jakarta was excluded because it has no rural coastal villages. Therefore, the study objects are 33 provinces.

Analysis Method

This study adopted data mining, an exploratory method in which the analysis aims to reveal the pattern extracted from the data instead of testing hypotheses. The methodology for data analysis was the Cross Industry Standard Process for Data Mining (CRISP-DM), the widely accepted method for practitioners and academics (*Martinez-Plumed et al. 2019*). It comprises six phases: business understanding, data understanding, data preparation, data modelling, evaluation, and deployment.

The activities in those six phases are as follows. The business understanding phase in this study refers to the purpose of data analysis. The data understanding phase involves collecting, exploring, and verifying data quality. The activities to access and select data published by Statistics Indonesia refer to the data understanding phase. Furthermore, the data preparation phase involves selecting, cleaning, formatting, and integrating data to construct the final dataset for further analysis. Moreover, the data modelling phase involves selecting the modelling techniques, building models, and assessing models. The evaluation phase refers to evaluating the modeling results and whether they meet the analysis objectives. Finally, the deployment phase refers to presenting the result and using the model for the new data set.

As the analysis aims to categorize provinces based on some measures, the appropriate statistical technique is cluster analysis. The K-means clustering was selected because it is appropriate for a small number of objects and is a simple clustering technique. The number of clusters was examined using the silhouette coefficient (between -1 and +1) to measure the goodness of fit. In addition, one-way ANOVA tests were performed to investigate whether the measures (variables) were significant in differentiating clusters. The cluster of provinces was visualized in Indonesia's geo-mapping.

The selected computational tool was the KNIME Analytics Platform, an open-source software and a noncoding data analytic tool for big data analysis. In KNIME, the computational analysis is performed through a KNIME workflow consisting of nodes that execute specific tasks. The KNIME presents a workflow covering reading, formatting, filtering, and constructing data (data preparation phase) to clustering with the K-means and Silhouette coefficient nodes (modelling phase) (**Figure 2**). Furthermore, the cluster model obtained from K-means is evaluated against analysis objectives with One-way ANOVA and GroupBy nodes (evaluation phase). Then, the cluster model is saved in a PMML writer node (deployment phase).

Furthermore, the second KNIME workflow forms the deployment phase (**Figure 3**). The PMML file from Data 2023 was called using a PMML reader node and then applied to Data 2024 using the PMML predictor node. The results from Data 2023 and Data 2024 could be compared to find any change.

RESULTS AND DISCUSSION

K-means clustering was performed to group provinces for environmental, economic, and social sustainability. The optimum number of clusters was decided by considering the highest mean score of silhouette coefficients. The One-way ANOVA test was conducted to investigate the significance of each measure in forming a cluster.

Table 2. Coastal village profiles of Indonesian provinces.

No.	Province	Code	Coastal Villages	Percent Coastal Village (%)	Coastline (km)	Average Coastline per Village (km)
1	Aceh	AC	662	10.16	2818	4.26
2	North Sumatra	SU	437	7.13	1300	2.97
3	West Sumatra	SB	133	10.33	2313	17.39
4	Riau	RI	244	13.01	2261	9.27
5	Jambi	JA	28	1.79	262	9.35
6	South Sumatra	SS	31	0.94	570	18.39
7	Bengkulu	BE	184	12.15	525	2.85
8	Lampung	LA	238	8.97	1322	5.56
9	Bangka Belitung Isl	BB	156	39.69	2379	15.25
10	Riau Islands	KR	364	85.05	8561	23.52
11	DKI Jakarta	JK	17	6.37	273	16.03
12	West Java	JB	221	3.71	988	4.47
13	Central Java	JT	353	4.12	1128	3.20
14	Yogyakarta	YO	33	7.53	135	4.10
15	East Java	JI	666	7.84	3544	5.32
16	Banten	BT	146	9.41	915	6.27
17	Bali	BA	175	24.44	633	3.62
18	West Nusa Tenggara	NB	281	24.41	2993	10.65
19	East Nusa Tenggara	NT	966	28.00	5700	5.90
20	West Kalimantan	KB	162	7.54	1398	8.63
21	Central Kalimantan	KT	40	2.54	704	17.60
22	South Kalimantan	KS	161	8.02	1363	8.47
23	East Kalimantan	KI	158	15.11	3895	24.65
24	North Kalimantan	KU	54	11.20	3558	65.88
25	North Sulawesi	SA	760	41.30	2442	3.21
26	Central Sulawesi	ST	950	47.03	7011	7.38
27	South Sulawesi	SN	520	17.04	1937	3.73
28	South East Sulawesi	SG	911	39.45	4136	4.54
29	Gorontalo	GO	185	25.20	904	4.88
30	West Sulawesi	SR	154	23.69	663	4.31
31	Maluku	MA	1040	83.33	10915	10.49
32	North Maluku	MU	898	74.65	6648	7.40
33	West Papua	PB	592	29.81	12455	21.04
34	Papua	PA	590	10.62	10826	18.35
	TOTAL	ID	12510	14.88	107473	8.59

Source: Statistics on Marine and Coastal Resources 2023 (*BPS-Statistics Indonesia 2023*)

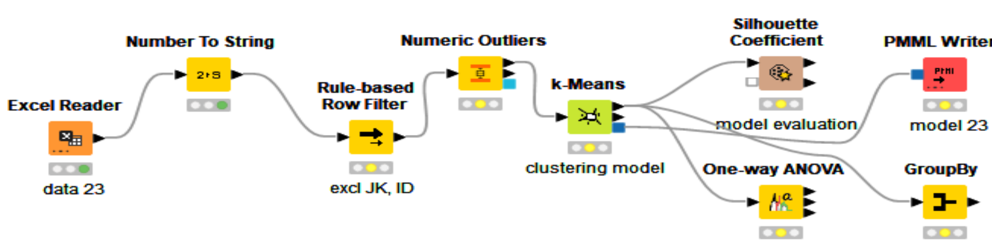

Figure 2. KNIME workflow for modeling.

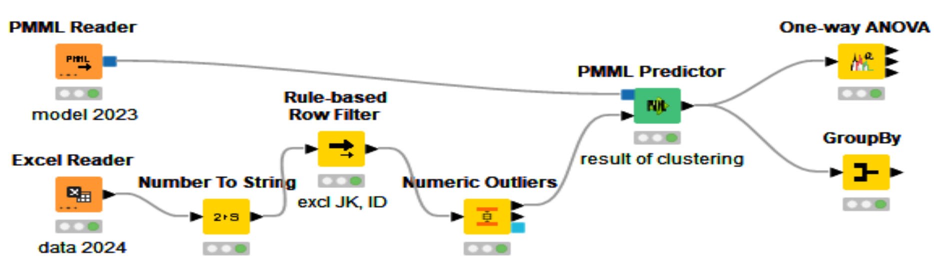

Figure 3. KNIME workflow for deployment.

Environmental Sustainability Mapping

Clustering was performed for three measures of environmental pollution (land, water, and air pollution) and two measures of household cooking emission (wood and gas cooking). The optimum cluster number is two, as suggested by the highest mean score of the Silhouette coefficients. The mean scores of the Silhouette coefficient for both clusters are 0.69 and 0.68, with an overall mean of 0.69. These scores are adequate to differentiate both clusters.

Furthermore, examining whether these environmental measures differentiate both clusters was performed using ANOVA and GroupBy nodes in the KNIME workflow **(Figure 2**). Three measures are statistically significant (p-value < 0.05) (**Table 3**). Considering the mean scores, two clusters could be named Low-environmental sustainability (L_environment) and High-environmental sustainability (H_environment) clusters. Coastal villages in High-environment provinces have better environmental conditions, as indicated by less water, land, and air pollution. Those coastal villages are more likely to cook with wood than gas. From a social perspective, societies that use gas for cooking are more developed than those that use wood.

Both cluster provinces of High and Low-environmental sustainability were plotted in an Indonesian geo-map using Tableau as a software for data presentation.Most provinces in eastern Indonesia, such as Papua, West Papua, Maluku, North Maluku, and East Nusa Tenggara, belong to high environmental sustainability (**Figure 4**). These provinces are less developed than other provinces. The findings suggest that development impacts environmental sustainability degradation. These results are supported by empirical research across various countries, which confirms a positive and bi-directional association between economic development and environmental degradation (*Singh et al. 2023*). The study among Indonesian provinces also supported that economic development impacted environmental degradation (*Ilham 2021*).

Economic Sustainability Mapping

For economic sustainability, cluster analysis was performed for eight economic activity measures. Three measures refer to the percentage of coastal villages conducting capture fishery, aquaculture, and marine tourism, (**Figure 1**). Furthermore, five measures refer to the percentage of coastal villages with micro-and-small enterprises (MSEs) producing furniture, wood, garments, food, and beverages. Based on the silhouette coefficients, the optimum number of clusters was two. The silhouette coefficients for each cluster were 0.46 and 0.51, with the overall mean of 0.48, which was sufficient to differentiate both clusters. A one-way ANOVA test was performed to discover which measures distinguished between the clusters. Seven of eight measures were significantly segregated in both clusters (p-value < 0.001) (**Table 4**). Capture fishery was insignificant (p>0.05), possibly

Table 3. Characteristics of environmental sustainability clusters.

Cluster	Water Pollution	Land Pollution	Air Pollution	Cooking with Gas	Cooking with Wood
L_environment (27)	**0.38**	**0.42**	**0.46**	**0.86**	0.14
H_environment (6)	0.09	0.23	0.26	0.09	**0.97**
p-value	0.021	0.186	0.153	0.000	0.000

Figure 4. Map of environmental sustainability clusters in Indonesia.

because most coastal villages engage in capture fishery as an essential economic activity. One cluster had higher average scores on all measures than another cluster. Therefore, two clusters were named High-economic sustainability (H_economic) with 18 provinces and Low-economic sustainability (L_economic) with 15 provinces. Coastal villages in provinces with high economic sustainability carry out more economic activities by utilizing marine resources and micro and small business economic activities.

Provinces in high and low economic sustainability clusters were mapped (**Figure 5**). Most provinces in Java and Sulawesi fell under high-economic sustainability regions.

Social Sustainability Mapping

Social sustainability was investigated through six measures (**Figure 1**). Two measures comprised the percentage of coastal villages with household toilets and wastewater installation. The following two measures referred to the percentage of coastal villages using gallon-bottled or surface water for drinking. Finally, two measures of health facilities denoted the percentage of coastal villages having private doctor clinics and drugstores. The availability of public health services was excluded as most coastal villages have those facilities.

The K-means clustering produced two optimum clusters with an overall mean silhouette coefficient score of 0.49, which was sufficient to discriminate between both clusters. The one-way ANOVA test revealed that all six measures were statistically significant ($p<0.05$) and differentiated both clusters. The clusters were High-social sustainability (H_social) and Low-social sustainability (L_social) (**Table 5**). Provinces in the high-social sustainability cluster had a higher percentage of coastal villages with more household toilets, more wastewater installation, more gallon-bottled water use, less surface water use, more private clinics, and more drugstores than those of the low-social sustainability cluster. In Indonesia, using gallon-bottled water (mainly mineral water) as drinking water is ordinary, and surface water is typically used for less developed communities.

Furthermore, the geo-map of provinces in high and low-sustainability clusters is portrayed (**Figure 6**). Coastal villages in Java and Bali provinces belonged to the high-social sustainability cluster. Java and Bali are considered more developed than other provinces. Therefore, it is reasonable to consider sanitation, clean water, and health facilities adequate for identifying social sustainability in coastal villages.

Overall Sustainability Mapping

The subsequent analysis executed all 19 measures into the K-means clustering technique. As presented above, coastal village data from 2023 (Data 2023) were

Table 4. Characteristics of economic sustainability clusters.

Cluster	Capture Fishery	Aquaculture	Marine Tourism	Food	Furniture	Beverages	Wood	Garment
H_economic (18)	**0.69**	**0.55**	**0.61**	**0.79**	**0.69**	**0.70**	**0.54**	**0.59**
L_economic (15)	0.54	0.24	0.33	0.39	0.26	0.31	0.13	0.18
p-value	0.062	0.001	0.000	0.000	0.000	0.000	0.000	0.000

Figure 5. Map of economic sustainability clusters in Indonesia.

analyzed using the KNIME workflow. Based on the evaluation of silhouette coefficients, the optimum number of clusters was two. The overall mean of silhouette coefficient scores for the two clusters was 0.28, which was not strong enough to differentiate between both clusters. A one-way ANOVA test was performed to investigate whether each variable differentiated both clusters. Table 6 shows the results, where 15 out of 19 variables were statistically significant ($p<0.05$) in distinguishing both clusters. Based on the mean scores of each measure, the first cluster with 22 provinces was named High Sustainability, and the second with 11 provinces was named Low Sustainability.

The clustering model obtained from Data 2023 (as a PMML file) was applied to Data 2024 (deployment phase). The analysis with Data 2024 produces two clusters with 22 and 11 provinces, similar to the result of Data 2023. The mean scores of each measure and p-value were presented (**Table 6**). The mean scores and p-values between the results of Data 2023 and 2024 showed a similar pattern.

All land, air, and water pollution were insignificant from an environmental perspective. This outcome implied that the percentage of polluted coastal villages was statistically the same among provinces. For this environmental aspect, the result in **Table 6** contradicts **Table 3**. The overall high sustainability provinces (**Table 6**) refer to low environmental sustainability (**Table 3**). The finding exposed that the level of sustainability in environmental aspects was not consistent with and was less prominent compared to the levels of economic and social sustainability.

For economic sustainability, the result showed a significantly higher percentage of coastal villages engaging in aquaculture and maritime tourism in the high-sustainability cluster than in the low-sustainability cluster. Capture fishery is an everyday economic activity in coastal communities, as shown by a high percentage of 89.5% for high sustainability and 89.2% for low sustainability. Thus, this variable could not differentiate between the clusters. MSE activities were significantly higher in the high-sustainability clusters. Table 6 indicates that, on average, 63.6% of coastal villages in the high-sustainability provinces have MSEs in the furniture sector, compared to 30.8% in the low-sustainability provinces.

Furthermore, social sustainability indicated that sanitation, clean water, and health facilities significantly differentiate provinces into high and low-sustainability clusters. High-sustainability provinces have a higher percentage of coastal villages with more household toilets and wastewater installations, more gallon-bottled water use, and less surface water. High-sustainability provinces have more coastal villages with private clinics and drugstores for health facilities.

Overall, the result showed that coastal villages in high-sustainability provinces seemed to be more developed than those in low-sustainability. Second, economic and social pillars of sustainability were more

Table 5. Characteristics of social sustainability clusters.

Cluster	Toilet	Wastewater	Gallon Water	Surface Water	Clinic	Drugstore
H_social (15)	**0.87**	**0.78**	**0.62**	0.12	**0.47**	**0.63**
L_social (18)	0.61	0.58	0.25	**0.52**	0.19	0.20
p-value	0.026	0.031	0.000	0.000	0.000	0.000

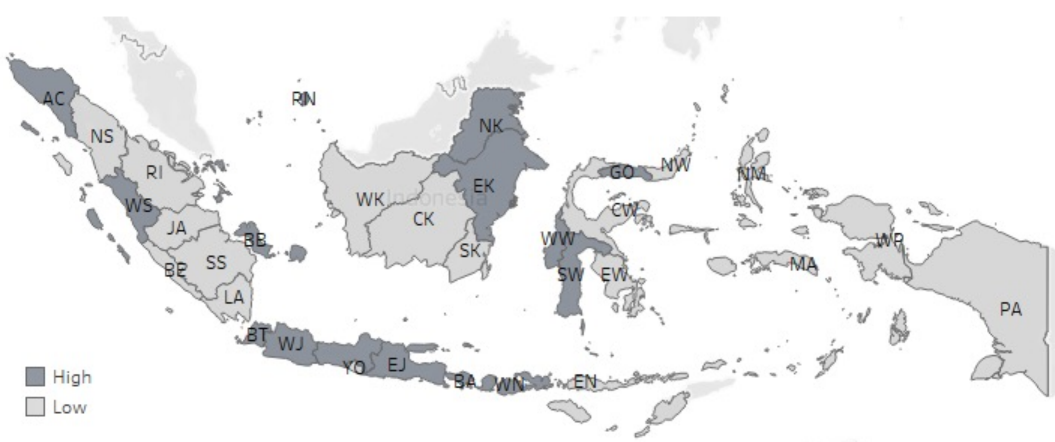

Figure 6. Map of social sustainability clusters in Indonesia.

Table 6. Mean scores of percentage coastal villages in each variable.

Sustainability	Variable	2023			2024		
		High (%)	Low (%)	p-value*	High (%)	Low (%)	p-value*
Environmental Sustainability	land pollution	**2.1**	1.4	0.162	**1.2**	0.8	0.353
	air pollution	**7.0**	5.0	0.161	**7.6**	5.7	0.337
	water pollution	**13.6**	8.7	0.073	**13.9**	8.4	0.048
	wood cooking	7.5	**31.2**	0.000	6.2	**28.4**	0.001
	gas cooking	**86.1**	44.4	0.000	**89.2**	43.3	0.000
Economic Sustainability	fish capture	**89.5**	89.2	0.931	**94.3**	92.0	0.507
	aquaculture	**35.4**	19.8	0.005	**39.0**	20.5	0.003
	maritime tourism	**22.9**	11.4	0.001	**25.4**	13.7	0.001
	food industry	**71.4**	47.5	0.000	**75.2**	52.3	0.000
	furniture industry	**63.6**	30.8	0.000	**64.4**	32.4	0.000
	beverages industry	**60.6**	33.8	0.000	**66.2**	37.4	0.000
	wood industry	**41.6**	24.4	0.002	**48.4**	28.8	0.002
	garment industry	**36.9**	12.9	0.000	**40.2**	14.6	0.000
Social Sustainability	wastewater installation	**82.7**	66.2	0.010	**91.0**	76.3	0.027
	household toilet	**97.8**	89.1	0.000	**100.5**	92.6	0.000
	gallon bottled water	**43.5**	18.8	0.003	**50.9**	22.4	0.002
	surface water	15.4	**49.3**	0.000	15.2	**48.4**	0.000
	drugstore	**36.6**	11.8	0.000	**15.2**	5.9	0.007
	private clinic	**34.3**	10.6	0.001	**24.4**	8.3	0.000
	Province	22	11		22	11	

* Non-significant at p-value <0.05

prominent than environmental sustainability. Economic and social sustainability measures in this analysis were part of the government development programs. In contrast, controlling the level of pollution is not a primary goal of the development program. The result showed that high economic sustainability aligns with high social sustainability. Economic and social progress can sometimes obscure underlying environmental issues, as rapid development, industrialization, and population growth often prioritize short-term gains and social welfare while diverting attention from rising pollution, resource depletion, and ecosystem damage. Pollution, as a popular measure for environmental aspects, does not differentiate between high and low-sustainability provinces. In contrast, prior studies in specific coastal regions indicate that the degradation of environmental conditions affects the economic and sociocultural aspects, as in Semarang (*Kurniati et al. 2024*) and Batam (*Suhardono et al. 2024*).

Furthermore, there are 22 provinces in the high-sustainability cluster and 11 provinces in the low-sustainability cluster (**Table 7**). Provinces in the eastern part of Indonesia and some provinces on the west side of Sumatra Island belonged to the low-sustainability cluster (**Figure 7**).

Sustainability and Macroeconomic Measures

The investigation used four macroeconomic measures related to the coastal communities: poverty rate in villages, life expectancy for males, life expectancy for females, and Human Development Index (HDI) in each province (**Figure 1**). The available data on those macroeconomic measures were from 2023; data from 2024 have not yet been released. A one-way ANOVA test was performed to investigate which measures differentiated the clusters. The life expectancy for males, life expectancy for females, and the Human Development Index significantly differentiate both clusters ($p<0.05$) (**Table 8**). The high-sustainability cluster denoted higher values for those three measures. The poverty rate in villages was higher for the low sustainability cluster but was not statistically significant ($p>0.05$). The result of the

Table 7. List of provinces in Indonesia in high and low sustainability clusters for 2023 and 2024.

High-Sustainability Cluster		Low-Sustainability Cluster
Aceh	Bali	North Sumatra
West Sumatra	West Nusa Tenggara	Riau
Bengkulu	West Kalimantan	Jambi
Lampung	South Kalimantan	South Sumatra
Bangka Belitung Isl	East Kalimantan	East Nusa Tenggara
Riau Islands	North Kalimantan	Central Kalimantan
West Java	Central Sulawesi	North Sulawesi
Central Java	South Sulawesi	Maluku
Yogyakarta	South East Sulawesi	North Maluku
East Java	Gorontalo	West Papua
Banten	West Sulawesi	Papua

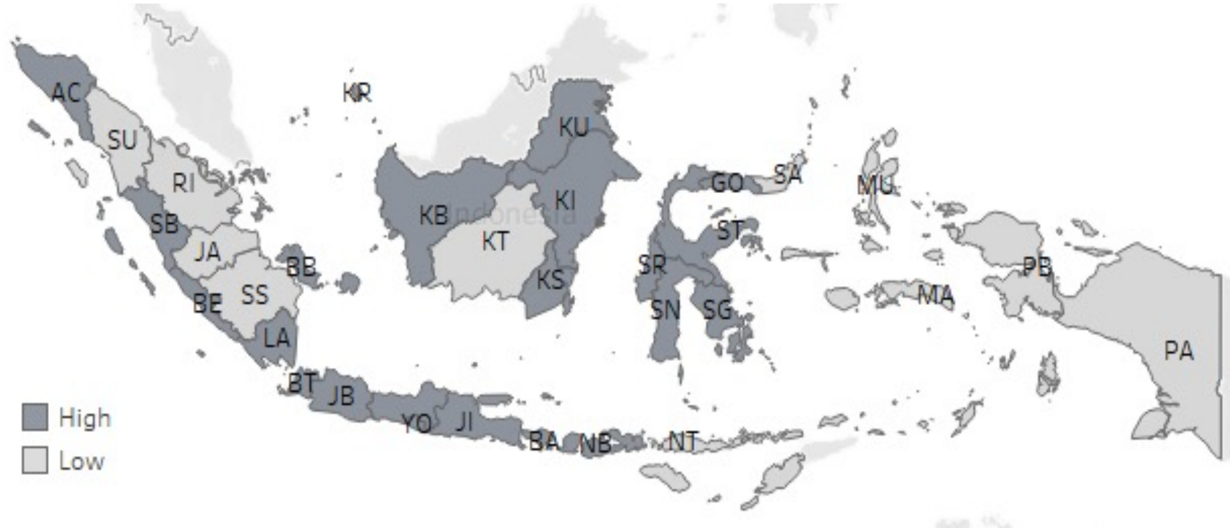

Figure 7. Overall sustainability mapping in Indonesia.

study was realistic, as high-sustainability provinces had higher HDI and life expectancy for males and females and lower poverty rates. These macroeconomic performance measures signify the result of regional and national development programs. Therefore, high-sustainability provinces were more developed than low-sustainable ones.

In addition to macroeconomic measures, the exploration was performed to discover the association between both clusters and the profile of coastal villages, which are the intensity of coastal villages per province and the length of coastline per village (**Table 1**). The result produced a non-significant association ($p>0.05$), implying that coastal villages' sustainability level was not associated with their geographic characteristics.

The blue economy in coastal villages

The Indonesian Government has made marine development a priority. The Ministry of Development Planning/ National Developing Planning Agency has released a document named "Indonesia Blue Economy Roadmap" (*Bappenas 2023*). The Indonesian Ministry of Marine Affairs and Fisheries executes five blue economy programs: expansion of marine conservation areas, quota-based measurable fishing, development of sustainable sea/coastal/land-based aquaculture, monitoring and control of coastal areas and small islands, and cleaning up plastic waste in the sea.

Economic activities related to a blue economy in coastal areas are capture fishery, aquaculture, and marine tourism. Figure 8 exhibits the capture fishery, aquaculture, and marine tourism plots for high-sustainability and low-sustainability provinces from Data 2023. Graphs were sorted based on the ascending order of aquaculture data. The figure shows that aquaculture and marine tourism were higher in high-sustainability than in low-sustainability provinces. Capture fishery seemed to be similar between both clusters. The data of sea use shows the high and low sustanability clusters in 2023 and 2024 (**Figure 8** and **Figure 9**).

The Government or other stakeholders should facilitate aquaculture development among coastal villages in the low-sustainability provinces. Aquaculture development has been determined as one of the priority programs in the blue economy. Aquaculture development targets five superior commodities: shrimp, lobster, crab, seaweed, and tilapia. The Ministry of Marine Affairs and Fisheries also formulates a strategy for accelerating aquaculture development in Indonesia, namely area-based aquaculture modeling. Some of its implementations are reported, such as the aquaculture of shrimp products in Kebumen Regency in Central Java, tilapia products in Karawang Regency in West Java, and seaweed in Wakatobi Regency in Southeast Sulawesi. Developing aquaculture villages managed by coastal communities is also important in the blue economy. Advanced

Table 8. Macroeconomic measures and sustainability clusters.

Cluster	Poverty Rate in Villages	Life Expectancy-Male (yrs)	Life Expectancy-Female (yrs)	HDI
High sustainability (22)	11.30	71.35	75.89	73.25
Low sustainability (11)	15.23	69.92	74.29	70.46
p-value	0.141	0.025	0.036	0.028

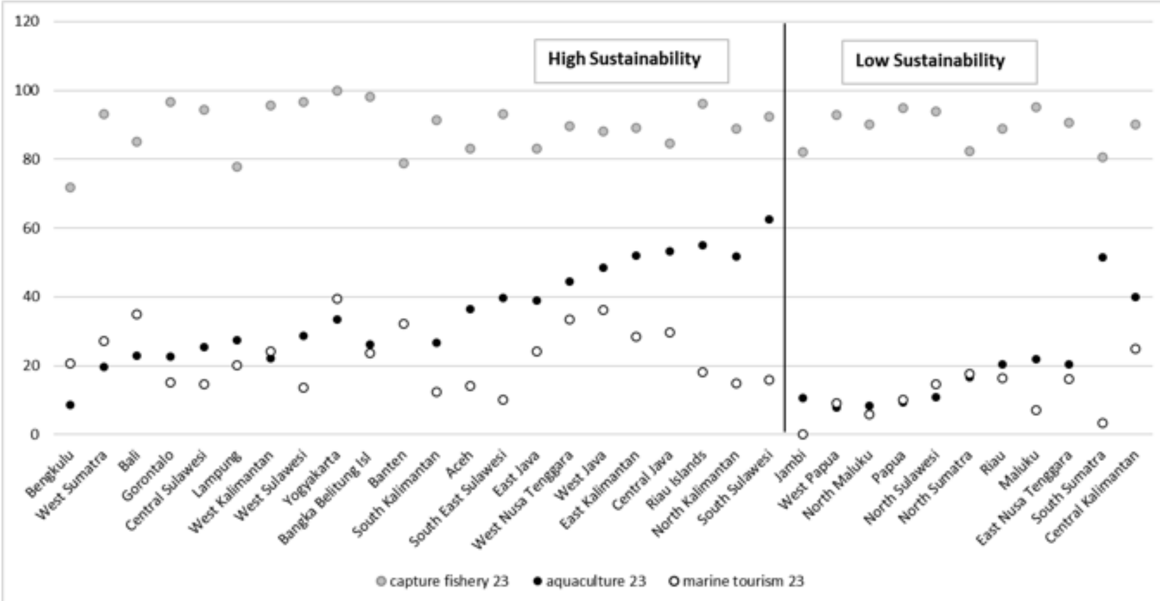

Figure 8. Sea use in sustainability cluster with Data 2023.
Note: Graphs are ordered in ascending order of aquaculture values for each cluster

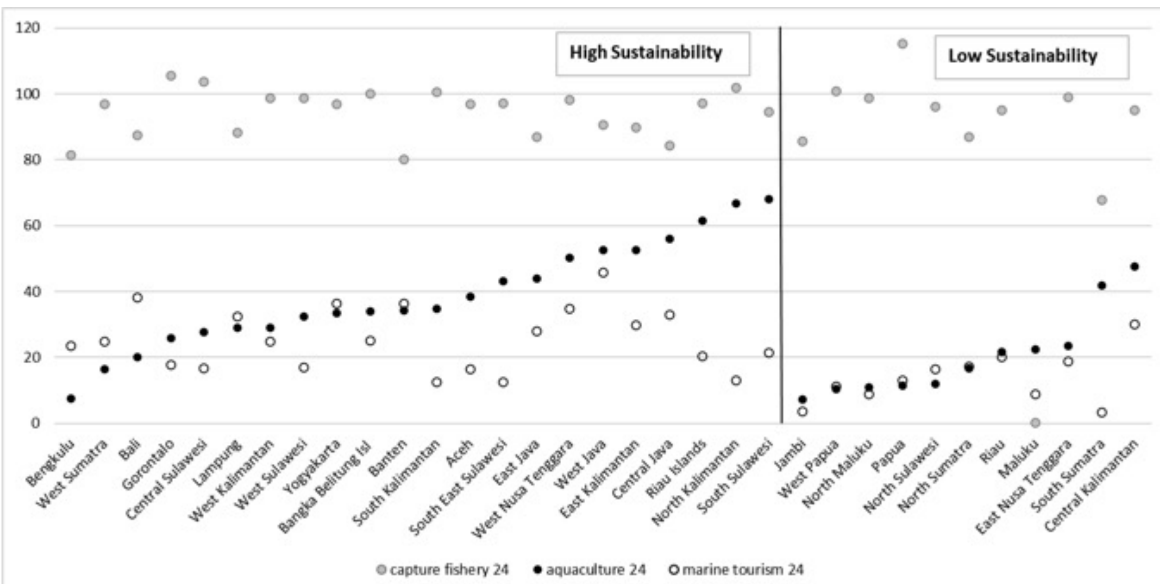

Figure 9. Sea use in sustainability cluster with Data 2024.
Note: Graphs are ordered in ascending order of aquaculture values for each cluster

technologies provide many solutions for aquaculture. For example, information technology for monitoring and control systems could support aquaculture development (*Muliani and Ujianti 2024*). The government should ensure that aquaculture development does not cause environmental damage by implementing sustainable practices. Here, the FAO's Guidelines for Sustainable Aquaculture can be used as a reference (*FAO 2025*).

With thousands of islands and a very long coastline, Indonesia has a huge potential for marine tourism. In addition to the potential for the natural beauty of its beaches and seas, marine tourism development needs to utilize various ecosystems on the coast. For example, coral reef ecosystems have the potential to become diving and snorkelling tourist destinations. Mangrove ecosystems with various types of plant diversity can be developed into ecotourism destinations and, at the same time, for ecosystem conservation. Likewise, seagrass beds, beds, which are underwater ecosystems, can be used for underwater tourism. Blue tourism is the right concept to implement as a sustainable marine tourism (*Supriyanto 2022*).

Developing a sustainable blue economy requires combining the local wisdom of coastal communities with advanced sustainable practices (*Suhardono et al. 2024*). Some local wisdom practices in terms of local tradition include Petik Laut, a ritual to preserve the marine environment practiced by coastal communities in Gili Island, and Jamu Laut, a ritual for fisherman safety practices by coastal society in East Sumatra (*Touwe 2020*). Additionally, the Sasi culture practiced by coastal communities in Maluku is a tradition of preserving natural resources (*Arismayanti 2021*).

In addition to local wisdom, advanced sustainable practices should be pursued through current technologies, such as renewable energy and smart marine aquaculture. Tidal energy as renewable energy could be implemented through the tidal barrage method or marine current method (*Masood Ahmad et al. 2022*). This renewable energy has the potential to be implemented in Indonesia (*Ikhwan et al. 2022*). Smart marine aquaculture has been developed using advanced digital technology such as Internet of Things (IoT)-enabled systems, cloud computing, and machine learning to monitor water quality, optimize feeding, and reduce waste (*Rodolfo W.L. Coutinho & Boukerche 2022*). Apart from new technology, established technology, such as coral reef rehabilitation to restore fish communities, still needs to be applied (*Samaniego et al. 2023*). These advanced technologies offer great potential benefits, so long as they are economically feasible.

CONCLUSION AND RECOMMENDATION

This study examined the level of sustainability of coastal villages in the provincial analysis unit of one country, Indonesia. Classifying provinces into each sustainability pillar, namely environmental, economic, and social, revealed which regions have higher or lower levels of sustainability. However, an analysis of the overall sustainability pillars showed a new understanding. This study exposed that in the analysis of overall sustainability, the level of sustainability in environmental aspects was not congruent with and was less prominent compared to the levels of economic and social sustainability.

Blue economy activities in coastal communities show the importance of using the sea for aquaculture and marine tourism. It is recommended that the Indonesian Ministry of Marine Affairs and Fisheries, provincial governments, and other stakeholders focus on developing aquaculture and marine tourism in low-sustainability provinces, while ensuring that these efforts use local knowledge and sustainable technologies to prevent environmental damage.

This study contributes knowledge to investigations on coastal areas at the country level, where most prior studies focused on specific coastal areas. The paper's contribution was also based on the data analytic method, as most studies employed case studies or survey methods. This study's generalization was limited to only one country and two years of data. Further studies may analyze data for extended periods to reveal coastal village changes toward sustainability. The research could be extended by implementing the method on other countries' data.

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