

Multidimensional and PCA-based analysis of seaweed industry cluster development in Bombana, Indonesia

¹Akhmad Mansyur, ²La Sara, ³Bahari, ²Andi I. Nur

¹ Study Program of Fisheries Agribusiness, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Kendari, Southeast Sulawesi, Indonesia; ² Study Program of Aquatic Resource Management, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Kendari, Southeast Sulawesi, Indonesia; ³ Study Program of Agricultural Agribusiness, Faculty of Agriculture, Halu Oleo University, Kendari, Southeast Sulawesi, Indonesia. Corresponding author: A. Mansyur, akhmadmansyur@uho.ac.id

Abstract. This study analyzes the development of seaweed industry clusters in Bombana Regency, Southeast Sulawesi, Indonesia, using an integrated multidimensional and Principal Component Analysis (PCA) approach. A mixed-methods design combining descriptive analysis and PCA was applied to identify latent structures across ecological, economic, social, institutional, and technological dimensions. The results reveal significant spatial heterogeneity, with ecological capacity as the primary strength, while economic, institutional, and technological capacities remain uneven. PCA identifies two principal components - productivity and competitiveness - that explain more than 50% of total variance. This study offers a novel integration of multidimensional analysis and PCA to reveal latent cluster structures. The findings emphasize the need to integrate environmental capacity, economic systems, and innovation to achieve sustainable competitiveness.

Keywords: aquaculture systems, cluster-based development, coastal sustainability, macroalgae cultivation, multivariate analysis.

Introduction. Research on the development of seaweed industries and aquaculture clusters has largely been dominated by partial approaches, with separate emphasis on ecological, economic, or social aspects. As a result, these studies have been unable to explain the systemic interconnections among dimensions that shape cluster structure and performance (Gephart et al 2021; Dentoni et al 2022). The methods commonly employed are predominantly descriptive or based on simple scoring techniques, which are limited in their ability to capture complex relationships and latent structures among variables within multidimensional cluster systems. This limitation becomes particularly critical in the context of Bombana Regency, where high ecological potential has not been effectively translated into optimal economic performance due to constraints in technology, institutional capacity, and infrastructure, reflecting a structural imbalance between resource potential and utilization capacity.

On the other hand, although multivariate methods such as Principal Component Analysis (PCA) have advanced in the analysis of complex systems, their application in aquaculture cluster studies remains relatively limited and has not been fully utilized to identify the key factors shaping cluster structures in depth (Abdi & Williams 2010; Hair et al 2019). Moreover, most previous studies tend to stop at factor identification or regional classification, without linking these findings to latent structures and multidimensional interactions that drive cluster dynamics within regional development contexts.

Therefore, a significant research gap remains in the absence of an integrated analytical approach combining multidimensional analysis with PCA-based latent structure identification. This study addresses this limitation by proposing an integrated framework linking dimensional and principal identities of aquaculture clusters, providing deeper

insights into multidimensional interactions in seaweed cluster development in Bombana Regency.

Material and Method

Research location and duration. This research was conducted from March to October 2025 in 16 coastal and island subdistricts (North Rarowatu, Rumbia, Central Rumbia, Mataoleo, Masaloka Islands, East Poleang, Central Poleang, Southeast Poleang, South Poleang, Poleang, West Poleang, East Kabaena, Central Kabaena, North Kabaena, West Kabaena, South Kabaena) in Bombana Regency engaged in seaweed cultivation for eight months (Figure 1). Data were collected through questionnaires, interviews, field observations, and secondary data from relevant institutions. All indicators were measured using a Likert scale ranging from 1 to 5 to represent the relative conditions of each region (Hair et al 2019), and data validity was ensured through triangulation (Creswell & Creswell 2018).

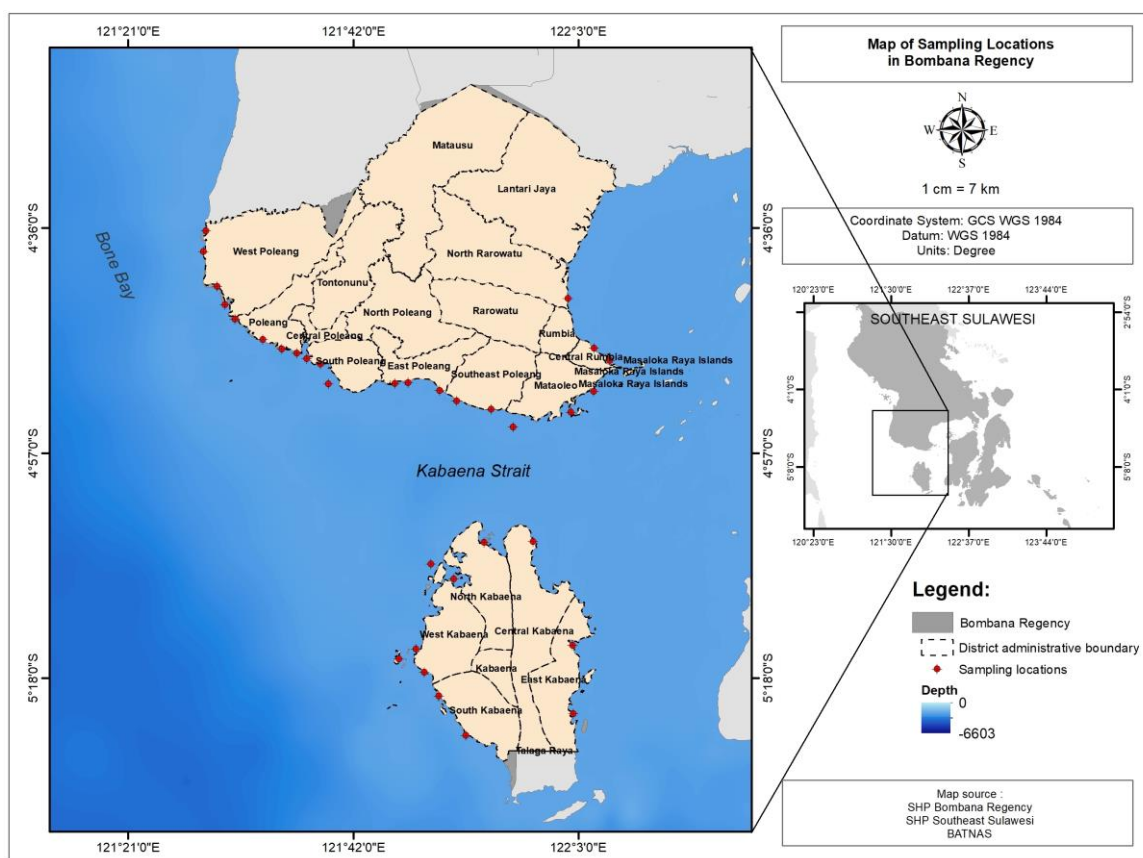


Figure 1. Map of Bombana Regency, Southeast Sulawesi, Indonesia, showing the spatial distribution of seaweed sampling locations across coastal and island sub-districts.

The research variables were grouped into five main dimensions: ecological (land suitability, cultivated area, productivity), economic (infrastructure, investment, capital, local economic activity), social (stakeholder support, community participation), institutional (organizational structure, monitoring), and technological (innovation, partnerships, and barriers to innovation).

This study employed a mixed-methods approach with a sequential explanatory design to analyze the development of seaweed industry clusters. The quantitative phase used PCA to identify key factors and latent cluster structure, while the descriptive phase interpreted the results in the context of regional characteristics (Gephart et al 2021; Dentoni et al 2022).

Data analysis was conducted in two stages. First, descriptive analysis was used to identify cluster profiles and classify regions. Second, PCA was applied to reduce variables and identify principal components, which can be mathematically expressed as:

$$Z_j = \alpha_{j1}X_1 + \alpha_{j2}X_2 + \dots + \alpha_{jp}X_p$$

where: Z_j represents the principal component and X_p denotes the standardized variables, α_{jp} is the variable multiplier.

The selection of components was based on eigenvalues greater than 1, cumulative variance explained of at least $\geq 60\%$, and loadings ≥ 0.5 (Jolliffe & Cadima 2016; Hair et al 2019).

Furthermore, biplot analysis was used to visualize the relationships among variables and the spatial distribution of regions, while cluster typology was determined based on PCA scores and classified into high, medium, and low categories (Gabriel 1971; Greenacre 2010).

Results and Discussion. The comparative analysis across sub-districts in Bombana Regency was conducted based on five key dimensions, namely ecological, economic, social, institutional, and technological aspects. The results reveal substantial spatial heterogeneity, indicating that cluster development is not uniform but shaped by multidimensional interactions among regions (Figure 2). This finding supports cluster theory, which emphasizes that regional competitiveness is influenced by differences in resource endowment, institutional quality, and market structure (Porter 1998).

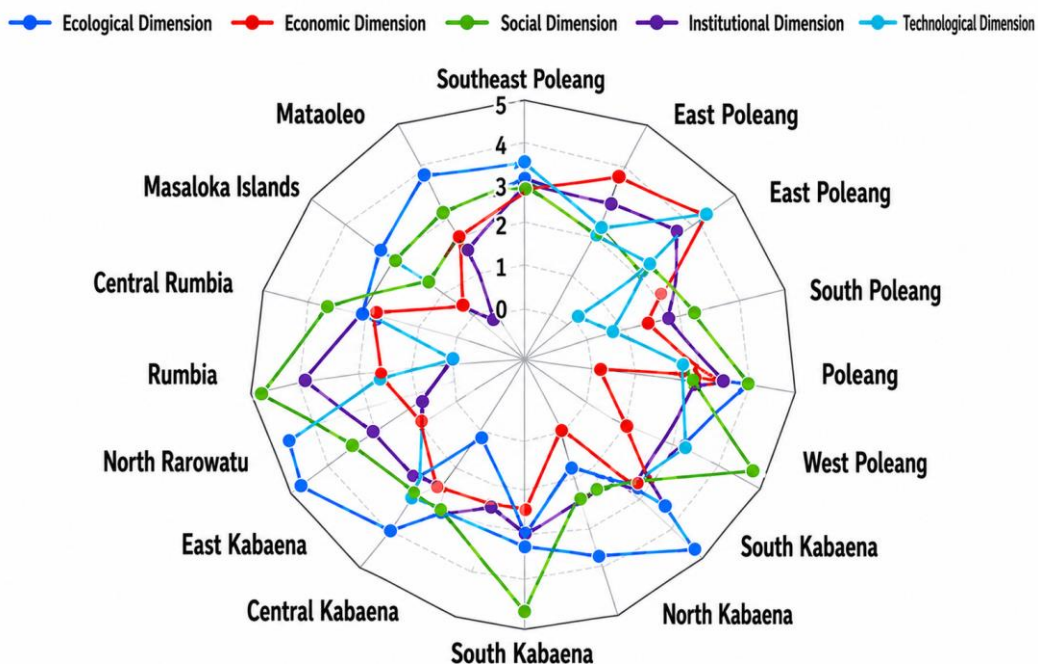


Figure 2. Radar chart illustrating the mean values of ecological, economic, social, institutional, and technological indicators across sub-districts in Bombana Regency, highlighting spatial variability and the multidimensional characteristics of seaweed cluster development.

Ecological capacity was consistently high in several areas, particularly Southeast Poleang, South Kabaena, and South Poleang, reflecting favorable environmental suitability for seaweed cultivation. These conditions align with global aquaculture studies showing that environmental suitability is a primary determinant of productivity and sustainability (Buschmann et al 2017; FAO 2018). However, economic capacity exhibited greater variability, with sub-districts such as South Poleang and Central Poleang demonstrating stronger performance due to better infrastructure, market access, and investment

conditions. This highlights the critical role of economic integration in enhancing value chains and regional competitiveness (Rodríguez-Pose 2013; World Bank 2021).

Social capacity was relatively strong in areas such as Rumbia and North Kabaena, where community participation supports sustainable production systems. This is consistent with findings that social capital is essential in small-scale aquaculture systems (Manlosa et al 2023; Nuryadi et al 2023). Meanwhile, institutional capacity remained moderate and uneven, suggesting differences in governance, coordination, and policy support. Strong institutions are widely recognized as key drivers of cluster efficiency and collective action (Schmitz 1995; Porter 1998). Technological capacity showed the highest variability, indicating uneven adoption of cultivation and post-harvest technologies, which are crucial for improving productivity and value addition (Ketels 2013; Geissdoerfer et al 2017).

Principal component analysis (PCA) results. The PCA results indicate that two principal components dominate the structure of the seaweed cluster system. The first principal component (PC1) has an eigenvalue of 6.21, explaining approximately 29.6% of total variance, and represents resource-based productivity factors, including land suitability, cultivation area, and productivity. The second principal component (PC2) has an eigenvalue of 4.35, explaining approximately 20.7% of total variance, and represents competitiveness-related factors, including economic capacity, institutional strength, and technological innovation (Figure 3).

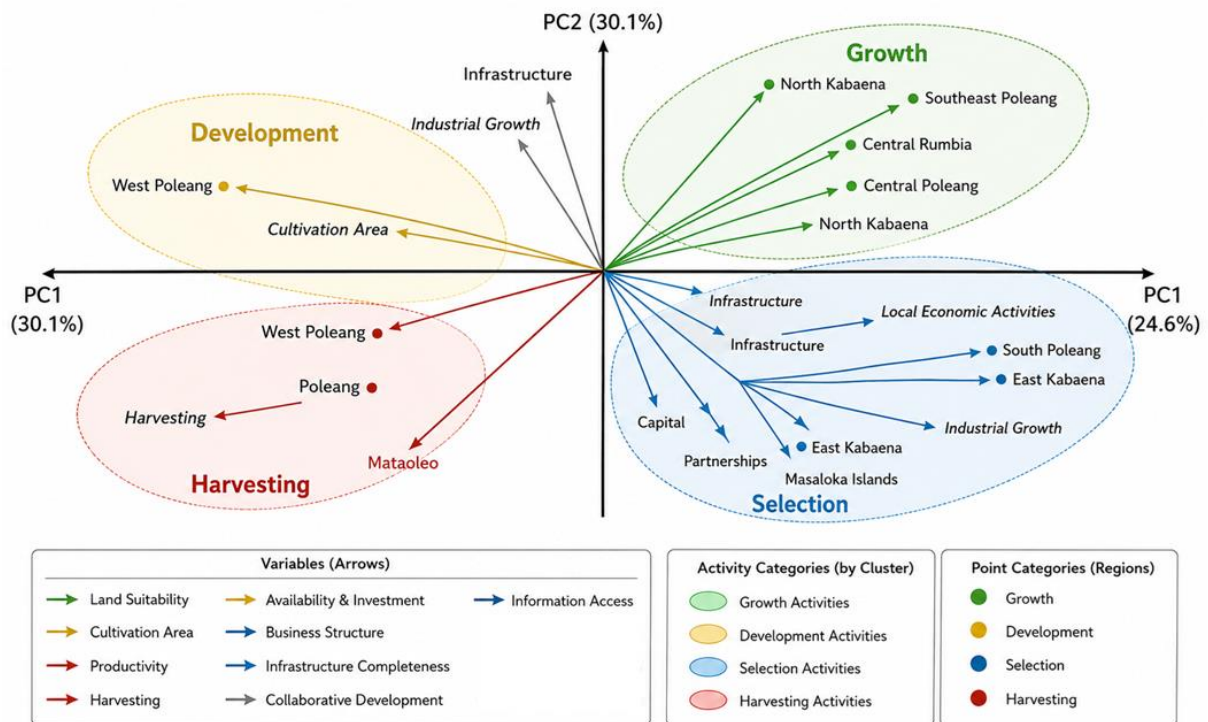


Figure 3. PCA biplot depicting the relationships among multidimensional variables and the distribution of sub-districts in Bombana Regency, where PC1 represents productivity-related factors and PC2 represents competitiveness-related factors, indicating cluster structure and spatial differentiation.

Together, PC1 and PC2 explain 50.3% of total variance, indicating that cluster development in Bombana is primarily driven by the interaction between ecological productivity and economic competitiveness. This finding is consistent with global studies highlighting that successful aquaculture clusters depend on the integration of environmental capacity and economic systems (Abdi & Williams 2010; Duarte et al 2017).

Spatial differentiation and cluster typology. At the sub-district level, distinct cluster identities emerge. Ecologically strong areas such as Southeast Poleang function as production bases but face limitations in economic and technological dimensions. In

contrast, South Poleang demonstrates strong economic performance, acting as a growth node within the cluster. South Kabaena shows balanced ecological and economic strength, indicating its potential as a priority development zone.

These variations form a spatial differentiation pattern consisting of ecological-based zones, economic growth zones, social-based zones, and technology-driven zones. Such differentiation suggests that cluster development strategies should be region-specific and based on comparative advantages, enabling the formation of a complementary and interconnected cluster system.

Biplot PCA interpretation. The PCA biplot analysis further illustrates the structural relationship among variables and regions (Figure 3). The distribution of variables shows two main clusters: (1) productivity-related variables forming the ecological axis, and (2) economic, institutional, and technological variables forming the competitiveness axis.

Regions located in the upper-right quadrant of the biplot demonstrate strong integration between productivity and competitiveness, indicating their role as potential growth centers. Conversely, regions located in other quadrants reflect imbalances between ecological capacity and economic performance.

This imbalance confirms that high ecological potential alone is insufficient to ensure cluster competitiveness. Similar patterns have been observed in global seaweed industries, where production capacity does not always translate into economic value due to limitations in market access, processing capacity, and innovation (Hurtado et al 2014; Buschmann et al 2017).

Strengthened global discussion. The findings of this study align with recent global research emphasizing that seaweed industry development requires the integration of ecological sustainability and economic competitiveness. Buschmann et al (2017) highlight that the global seaweed sector is transitioning toward a bioeconomy model, where value addition and innovation play a central role. Similarly, Duarte et al (2017) emphasize that aquaculture sustainability depends on balancing environmental capacity with economic and institutional systems.

However, the results also reveal a structural gap in Bombana, where ecological potential is relatively high but not fully translated into economic performance. This condition reflects a common challenge in developing regions, where resource-based industries remain underutilized due to limited infrastructure, weak institutions, and low technological adoption (Rodríguez-Pose 2013; Barrett et al 2022).

Therefore, strengthening cluster development requires an integrated approach that combines:

- ecological optimization (production efficiency);
- economic integration (market and value chain);
- technological innovation (processing and product diversification).

Such an approach is essential to transform resource-based advantages into sustainable competitive advantages in the global seaweed industry.

Conclusions. The development of seaweed industry clusters in Bombana Regency is characterized by significant spatial heterogeneity shaped by the interaction of ecological, economic, social, institutional, and technological dimensions. Ecological capacity constitutes the primary strength of the cluster, particularly in areas with high suitability and productivity. However, economic, institutional, and technological capacities remain uneven, resulting in a structural imbalance between resource potential and value creation. The PCA results confirm that cluster structure is mainly determined by two key components, namely ecological productivity and economic competitiveness, which together explain more than 50% of the total variance. This indicates that successful cluster development depends on the integration of environmental capacity with economic and innovation systems.

Furthermore, spatial differentiation across sub-districts reveals distinct cluster typologies, including production-based areas, growth centers, and transitional regions.

These findings highlight that cluster development strategies should be region-specific and based on comparative advantages.

Overall, the study emphasizes that high ecological potential alone is insufficient to ensure competitiveness. Therefore, strengthening economic integration, institutional capacity, and technological innovation is essential to transform resource-based advantages into sustainable competitive advantages in the seaweed industry.

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Authors contributions. AM conceptualized the study, conducted field surveys, performed data analysis, and prepared the original manuscript draft. LS contributed to research design, methodology development, supervision, and manuscript revision. B contributed to economic and agribusiness analysis, data interpretation, and critical review of the manuscript. AIN contributed to statistical analysis, interpretation of PCA results, and manuscript editing. All authors have read and approved the final version of the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Authors:

Akhmad Mansyur (AM), Study Program of Fisheries Agribusiness, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Green Campus Bumi Tridharma Anduonohu, 93231, Kendari, Southeast Sulawesi, Indonesia, e-mail: akhmadmansyur@yaho.ac.id

La Sara (LS), Study Program of Aquatic Resource Management, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Green Campus Bumi Tridharma Anduonohu, 93231, Kendari, Southeast Sulawesi, Indonesia, e-mail: lasara_unhalu@yahoo.com

Bahari (B), Study Program of Agricultural Agribusiness, Faculty of Agriculture, Halu Oleo University, Green Campus Bumi Tridharma Anduonohu, 93231, Kendari, Southeast Sulawesi, Indonesia, e-mail: baharihuo@gmail.com

Andi Irwan Nur (AIN), Study Program of Aquatic Resource Management, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Green Campus Bumi Tridharma Anduonohu, 93231, Kendari, Southeast Sulawesi, Indonesia, e-mail: andirwannur@uho.ac.id

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