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## Investigating Sustainable Food Business Ecosystems: A Cluster Analysis

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**Abstract:** The sustainability of the food industry in Indonesia requires a comprehensive understanding of operational dynamics and inter-agency interactions within the national food supply chain. This study aims to model the governance of a sustainable food ecosystem in Indonesia by examining the roles of collaboration, sustainability commitment, knowledge sharing, and innovation as key factors in risk mitigation and performance enhancement within an inclusive and adaptive system.

A mixed-methods approach was employed using both primary and secondary data. Primary data were collected through a survey of 80 organizations involved in the Indonesian food ecosystem, with variables measured using a 10-point Likert scale to capture levels of collaboration, knowledge transfer, innovation, and sustainability commitment. Secondary data were obtained from BPS, the Global Innovation Index, the World Bank, and FAO for the period 2020 to 2024 to provide macro-level context and support the interpretation of results.

The analysis combined K-means clustering with the Elbow method to determine the optimal number of clusters, Principal Component Analysis (PCA) for dimensionality reduction, and multiple linear regression to examine relationships between variables. To enhance interpretability, variable values were categorized into low, medium, and high levels based on the measurement scale.

The results identified three types of food ecosystems in Indonesia: (1) knowledge-based innovative ecosystems with high levels of collaboration and knowledge sharing, predominantly in Java, Bali, and Nusa Tenggara; (2) relatively balanced and sustainability-oriented ecosystems in Sumatra and Sulawesi; and (3) ecosystems in Kalimantan characterized by strong sustainability commitment but limited knowledge transfer.

Regression analysis shows that knowledge collaboration ( $\beta = 0.46$ ;  $p < 0.01$ ) and knowledge transfer ( $\beta =$



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0.39;  $p < 0.05$ ) have a significant positive effect on innovation, with an  $R^2$  value of 0.74. PCA results further confirm the dominant role of collaboration and knowledge-based innovation in shaping sustainable food ecosystems.

These findings indicate that knowledge sharing and inter-agency collaboration are critical drivers in the transition toward sustainable food systems. However, the results should be interpreted with caution when generalizing at the national level, and further research with broader data coverage is recommended.

**Keywords:** Food Industry Sustainability; Indonesia; Knowledge Sharing; Inter-agency Collaboration; Innovation; Cluster Analysis; Food Systems Governance.

## 可持续食品商业生态系统研究：基于聚类分析的方法

**摘要：**印度尼西亚食品产业的可持续发展需要全面理解国家食品供应链中的运行动态及跨机构互动机制。本研究旨在通过分析协作、可持续发展承诺、知识共享与创新在风险缓解及绩效提升中的作用，对印度尼西亚可持续食品生态系统的治理进行建模。

本研究采用混合研究方法，结合一手与二手数据。一手数据通过对80家参与印度尼西亚食品生态系统的组织开展问卷调查获取，采用10点李克特量表测量协作程度、知识转移、创新水平及可持续发展承诺。二手数据来源于印度尼西亚统计局（BPS）、全球创新指数、世界银行及联合国粮农组织（FAO），涵盖2020年至2024年，用于提供宏观背景并支持结果解释。

研究方法包括K均值聚类分析，并通过肘部法确定最优聚类数量，采用主成分分析（PCA）进行降维处理，同时运用多元线性回归分析变量之间的关系。为提高结果解释性，将变量值根据量表范围划分为低、中、高三个水平。

研究结果识别出三类食品生态系统：（1）以知识驱动的创新型生态系统，具有较高的协作与知识共享水平，主要分布在爪哇、巴厘及努沙登加拉地区；（2）相对均衡且以可持续发展为导向的生态系统，主要分布在苏门答腊和苏拉威西；（3）以可持续发展承诺为主但知识转移较为有限的生态系统，主要分布在加里曼丹。

回归分析结果表明，知识协作（ $\beta = 0.46$ ； $p < 0.01$ ）与知识转移（ $\beta = 0.39$ ； $p < 0.05$ ）对创新具有显著正向影响，模型拟合度 $R^2$ 为0.74。主成分分析结果进一步验证了协作与知识驱动创新在构建可持续食品生态系统中的关键作用。

研究表明，知识共享与跨机构协作是推动食品系统向可持续发展转型的核心驱动力。然而，在进行国家层面的推广时需谨慎解释研究结果，未来研究应扩大数据范围以增强结论的稳健性。

**关键词：**食品产业可持续性；印度尼西亚；知识共享；跨机构协作；创新；聚类分析；食品系统治理

### 1. Introduction

The transformation of the global food system is currently one of the strategic issues in the Sustainable Development agenda, along with increasing pressure on food production, distribution and consumption systems. The food system is no longer understood as a linear chain, but rather as a complex ecosystem

involving multidimensional interactions between economic, social, and environmental actors. In this context, the sustainability of the food system is determined not only by increased productivity, but also by the system's ability to maintain a balance between economic efficiency, social justice, and environmental sustainability [1][2][3]. Therefore, a holistic and integrative approach is very important to understand

the dynamics of the food system as a whole.

In developing countries such as Indonesia, the challenges of building sustainable food systems are becoming increasingly complex. Rapid population growth, climate change, land degradation, and limited infrastructure are the main factors affecting the stability of national food security [4][5]. In addition, disparities between regions in terms of production capacity, access to technology, and the quality of Human Resources also exacerbate inequality in the food system. This condition shows that conventional approaches that focus on increasing production alone are no longer sufficient, so a strategy is needed that is able to integrate various actors and resources in an adaptive, collaborative, and knowledge-based ecosystem framework.

In this context, the concept of Food Business Ecosystem (FBE) emerged as a relevant approach to understanding and managing the complexity of food systems. The FBE views the food system as an interdependent network of various actors, including producers, distributors, industry players, governments, academics, and consumers, who interact with each other through mechanisms of exchange of resources, information, and knowledge [6][7]. This approach emphasizes that value is not only created individually, but also through collaboration and synergy between actors in the ecosystem. Thus, the success of a food system transformation depends largely on the quality of interaction, coordination, and collective learning capacity within the ecosystem.

Numerous empirical studies show that cross-sector collaboration and knowledge transfer are key determinants in driving innovation and sustainability in food ecosystems [8][9][10]. Collaboration enables the integration of different resources and competencies, while knowledge transfer accelerates the learning process as well as the diffusion of innovation. In the context of developing countries, where limited technological and infrastructural resources are still a major challenge, interagency collaboration is a strategic mechanism to increase innovation capacity [11][12][13]. Nevertheless, the effectiveness of collaboration is determined not only by the intensity of interaction, but also by the characteristics of the organization, the level of trust, as well as commitment to the principles of sustainability [14][15][16].

In Indonesia, various policies and programs have been initiated to encourage the transformation of the food system towards sustainability, such as smart agriculture programs and strengthening region-based food security [17][18]. These programs aim to improve integration between the production, research, and public policy sectors. Despite this, its implementation shows variable results between regions, which indicates a heterogeneity in the characteristics and behavior of organizations involved in food ecosystems

[19][20]. This confirms the importance of an analytical approach that is able to identify patterns and typologies of organizations in a more systematic and data-based manner.

Although the literature on sustainable food ecosystems continues to evolve, there are some research gaps that still need to be addressed. First, empirical studies that simultaneously examine the relationship between collaboration, knowledge transfer, sustainability commitment, and innovation within a single analytical framework are still relatively limited, particularly in the context of developing countries in Southeast Asia [21][22]. Second, a data-based approach to identify organizational heterogeneity through cluster analysis techniques is still rarely applied in the study of food ecosystems in Indonesia [23][24]. Third, the integration between micro data based on organizational perception and macro data sourced from secondary indicators is still not widely explored in a comprehensive manner [25][26]. To fill this gap, this study proposes an analytical approach that integrates K-means clustering, Principal Component Analysis (PCA), and multiple linear regression to map the structure of food ecosystems and examine the relationship between key variables. The clustering approach used in this study is data-driven, where the formation and interpretation of clusters is based on differences in quantitative characteristics between organizational groups. This approach allows for a more objective and systematic classification, thereby reducing the potential for subjectivity in naming and cluster interpretation [27][28].

Primary Data was collected through a survey of 80 organizations involved in the food ecosystem in Indonesia, which includes industry players, government agencies, and research institutions. Measurement of variables was conducted using a 10-point Likert scale to capture an organization's perception of the level of collaboration, knowledge transfer, innovation, and sustainability commitment. Meanwhile, secondary data obtained from various sources such as BPS, World Bank, and FAO are used to provide macro context and strengthen the interpretation of the analysis results.

The main contribution of this research lies in several aspects. First, this study identifies the typology of food ecosystems based on organizational characteristics through a data-based cluster analysis approach. Second, the study provides empirical evidence on the strategic role of collaboration and knowledge transfer in driving innovation in sustainable food ecosystems. Third, this study integrates micro and macro approaches in a comprehensive analytical framework. Fourth, this study increases objectivity in the interpretation of ecosystem typology through the use of data-based classification approach. Thus, this research is expected to not only contribute to the development of academic

literature, but also generate practical implications for policy makers, industry players, and academic institutions in designing strategies to strengthen inclusive, adaptive, and sustainable food ecosystems in Indonesia.

## 2. Materials and Methods

### 2.1 Research Design

This study uses a quantitative approach to analyze the interaction patterns and relationships between variables in sustainable food ecosystems in Indonesia. This study aims to examine the relationship between four main variables, namely the intensity of collaboration, knowledge transfer, commitment to sustainability, and the level of innovation in various organizations involved in the food ecosystem.

The approach used combines exploratory and explanatory analysis. In the explorative stage, cluster analysis is used to identify patterns of organizational heterogeneity in food ecosystems. Cluster analysis is considered appropriate to process heterogeneous data, especially in the context of ecosystems that involve various actors such as businesses, academics, governments, and communities. This heterogeneity arises from different levels of collaboration, knowledge exchange, and sustainability practices between actors in ecosystem networks [29].

Furthermore, PCA is used for dimension reduction and visualization of data structures, while multiple linear regression is used to test the relationship between variables empirically. This approach allows the identification of latent patterns before testing the relationship between variables.

This study utilized a combination of primary and secondary data. Primary Data is used as the main basis of quantitative analysis, while secondary data is used to provide macro context in the interpretation of results.

### 2.2 Population and Sampling

The population in this study includes organizations involved in the food ecosystem in Indonesia, including agribusiness companies, food producers, academic institutions, and government agencies. The study sample consisted of 80 organizations selected using the purposive sampling technique based on the following criteria: (a) have an active involvement in food production, distribution, or innovation, (b) participate in cross-sector collaboration, and (c) have a commitment to the implementation of sustainability practices.

Primary Data were collected through structured surveys to representatives of organizations. The use of a sample size of 80 organizations is considered adequate for exploratory multivariate analyses such as K-means clustering and PCA, which focus on pattern identification and data segmentation, rather than population-wide generalization.

In addition, secondary data sourced from the Central Statistics Agency, FAO, World Bank, and Global Innovation Index are used to provide macro context related to the condition of Indonesia's food system in the period 2020-2024. These secondary Data are not used in the measurement of the main variables, but rather to support the interpretation of the results.

### 2.3 Research Variables

This study used four main variables, namely the intensity of collaboration, knowledge transfer, level of innovation, and commitment to sustainability. Each variable was measured using several indicators adapted from previous literature and adapted to the context of the food ecosystem. Measurement of variables was conducted using a 10-point Likert scale to capture the organization's perception of the actual conditions they are experiencing. This scale was chosen to provide a higher level of sensitivity in capturing perceptual variations than a narrower scale. The value of each variable is calculated as the average of all indicators representing it. Table 1 presents the operational definition and scale of measurement of variables used in this study.

**Table 1. Operational definitions and measurement scales of research variables**

| No | Variable                  | Operational Definition  | Scale       | Reff.        |
|----|---------------------------|---|-------------|--------------|
| 1  | Collaboration Intensity   | The degree of inter-organizational cooperation in joint projects, R&D, and policy initiatives.                | Likert 1–10 | [30]<br>[30] |
| 2  | Innovation Level          | The organization's ability to develop new products, production processes, or technologies based on knowledge. | Likert 1–10 | [31]<br>[32] |
| 3  | Sustainability Commitment | The extent to which sustainability principles are used in both strategic planning and operations.             | Likert 1–10 | [22]<br>[33] |
| 4  | Knowledge Transfer        | The level of knowledge exchanged between organizations and research institutions.                             | Likert 1–10 | [34]<br>[35] |

### 2.4 Data Analysis Procedures

Data analysis is carried out through several systematic stages. First, all variables were normalized using Z-score standardization to ensure scale equality between variables before cluster analysis.

Second, cluster analysis was conducted using the K-means method to group organizations based on the similarity of characteristics in the four main variables. The optimal number of clusters was determined using

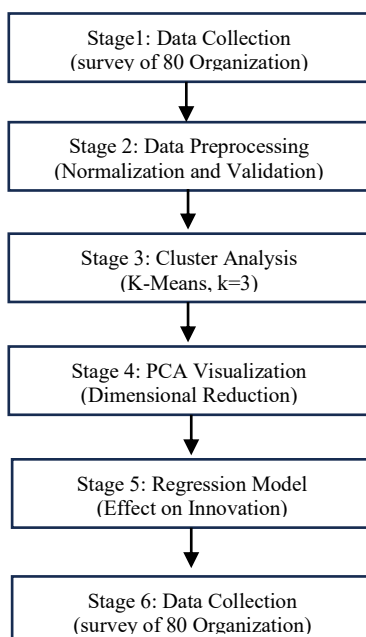
the Elbow and Silhouette methods. The results of the analysis showed that the optimal number of clusters is three ( $k = 3$ ), with a silhouette score of 0.62, which indicates an adequate level of separation and cluster cohesion) [36][37]. To increase the objectivity of the interpretation, the mean values of the variables in each cluster were classified into low, medium, and high categories based on a 10-point Likert scale range. This approach allows for a more systematic and transparent interpretation of clusters.

Third, PCA is used to reduce data dimensions and visualize the structure of relationships between organizations. The number of main components retained is determined based on the Kaiser criterion (eigenvalue  $> 1$ ) and the cumulative variance. In this study, the two main components are retained because they are able to explain about 78% of the total variances, which is considered sufficient to represent the data structure [38][39].

Fourth, multiple linear regression analysis was used to examine the effect of collaboration intensity, knowledge transfer, and sustainability commitment on the level of innovation. The test was conducted using F test (simultaneous), t test (partial), and coefficient of determination ( $R^2$ ) [40]. To ensure the reliability of the model, classical assumption tests were carried out, which included multicollinearity, normality, and heteroscedasticity tests. All analyses were performed using Python 3.12 with pandas, scikit-learn, matplotlib, and stats models libraries.

## 2.5 Research Workflow

The workflow of this study is shown in Figure 1, which illustrates the stages of research ranging from data collection, data processing, statistical analysis, to interpretation of the results. This approach ensures that the analysis process is carried out systematically and can be replicated.



**Figure 1. Workflow of the sustainable food business ecosystem analysis research methodology**

## 2.6 Validity and Reliability

The validity of the instrument in this study was evaluated through construct validity test using item-total correlation, with a minimum threshold value of 0.60. All measurement items show correlation values above these thresholds, so they are valid in representing the measured construct.

The reliability of the instrument was tested using Cronbach's Alpha coefficient, with a threshold value of 0.70. The test results showed that all variables have a value of 0.70, which indicates a sufficient level of internal consistency [41].

This research instrument is adapted from the relevant previous literature and has been adapted to the context of sustainable food ecosystems, thus ensuring conceptual conformity between the indicators and the measured constructs.

In addition to instrument testing, evaluation of regression models is performed to ensure that the results of the analysis meet the necessary statistical assumptions. These tests include multicollinearity, normality, and heteroscedasticity tests to ensure the reliability and accuracy of model estimates [42].

## 2.7 Summary of Methodological Approach

This study integrates exploratory and explanatory approaches within the framework of multivariate analysis to understand the dynamics of sustainable food ecosystems. Cluster analysis and PCA were used to identify patterns and data structures, while linear regression was used to empirically test the relationships between variables. This approach provides a comprehensive understanding of how collaboration, knowledge transfer, and sustainability commitments contribute to innovation in the food ecosystem.

## 3. Results and Discussion

### 3.1 Overview of Data and Analytical Framework

This study used a dataset consisting of 80 organizations operating in the sustainable food ecosystem in Indonesia, including the agribusiness sector, food industry, academic institutions, government agencies, and non-governmental organizations. The variety of characteristics between organizations reflects the complexity and heterogeneity of actors in national food systems. The analytical approach used integrates K-means clustering, PCA and multiple linear regression methods to identify latent patterns, group organizations, and evaluate the relationship between the main variables. All numerical variables have gone through a standardization process (z-score normalization) before cluster analysis to ensure that each variable has a balanced contribution in the calculation of distance. In addition, the regression

assumption test showed that the data met the normality criteria ( $p > 0.05$ ) and there was no multicollinearity ( $VIF < 3$ ), making it eligible for further analysis [43].

**3.2 Descriptive Statistics and Preliminary Analysis**

Descriptive statistics show that in general organizations have a relatively high level of commitment to sustainability, followed by the intensity of collaboration, knowledge transfer, and level of innovation. To improve comparability, all variables are transformed into an index scale (0-100) as shown in Table 2.

**Table 2. Descriptive Statistics of Key Variables in Indonesia’s Sustainable Food Ecosystem**

| Variable                  | Mean  | Std. Dev. | Min   | Max   |
|---------------------------|-------|-----------|-------|-------|
| Collaboration Intensity   | 72.14 | 11.23     | 42.51 | 94.82 |
| Innovation Level          | 68.47 | 13.15     | 37.25 | 96.83 |
| Sustainability Commitment | 76.98 | 10.72     | 49.18 | 97.66 |
| Knowledge Transfer        | 70.35 | 11.42     | 45.36 | 95.28 |

Correlation analysis showed a significant positive relationship between the intensity of collaboration and innovation ( $r = 0.61, p < 0.01$ ), as well as between knowledge transfer and innovation ( $r = 0.58, p < 0.01$ ). This confirms that inter-organizational interactions play an important role in driving innovation in the food ecosystem [44].

**Table 3. Organizational clusters**

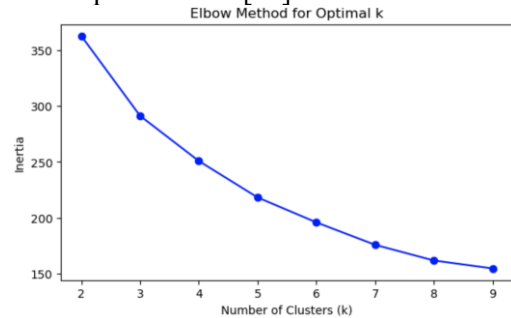
| Cluster | Collaboration | Innovation | Sustainability | Knowledge Transfer | Interpretation  |
|---------|---------------|------------|----------------|--------------------|---|
| 0       | 60.87         | 58.95      | 70.61          | 59.78              | Adaptive Followers – moderate collaboration, low innovation, weak knowledge linkages          |
| 1       | 76.42         | 74.31      | 79.18          | 73.85              | Collaborative Innovators – strong synergy across all sustainability and innovation dimensions |
| 2       | 70.15         | 63.52      | 83.74          | 68.44              | Sustainability-Oriented Traditionalists – strong sustainability commitment, modest innovation |

Cluster 1 demonstrates a strong integration of collaboration, innovation, and knowledge transfer, thus acting as the main motor of innovation in the ecosystem. Cluster 2 has a high commitment to sustainability, but it has not been fully offset by innovation. Meanwhile, cluster 0 showed a relatively lower level of adaptation. This threshold-based categorization approach increases transparency in cluster interpretation and ensures consistency of analysis.

**3.5 Organizational Composition by Cluster**

**3.3 Determining the Optimal Number of Clusters**

Determination of the optimal number of clusters was carried out using a combination of Elbow method and Silhouette analysis. The results show that the optimal number of clusters is three ( $k = 3$ ). Silhouette score value of 0.62 indicates that the cluster structure has a good level of internal cohesion and separation between clusters. This value indicates that the objects in each cluster are relatively homogeneous and sufficiently separated from the rest of the cluster, so that the configuration of the three clusters can be considered representative [45].

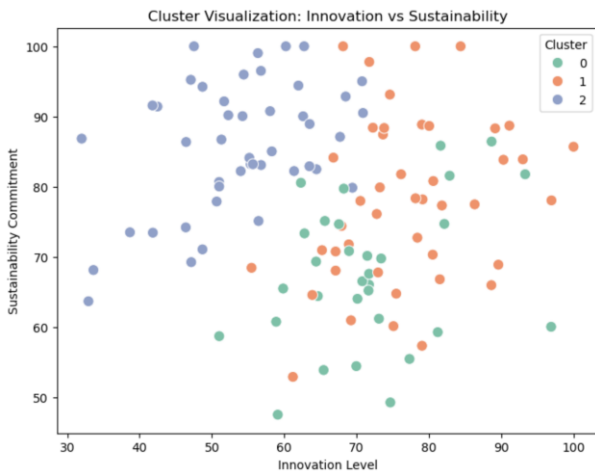


**Figure 2. Elbow Method for Optimal k (k=3)**

**3.4 Cluster Formation and Profiles**

The results of clustering with K-means (Table 3) resulted in three organizational clusters with different characteristics. To increase the objectivity of the interpretation, the variable values were classified into low (0-59), medium (60-74), and high ( $\geq 75$ ) categories. This threshold-based approach helps reduce subjectivity in cluster naming and interpretation.

The distribution of organizations within each cluster shows different sectoral patterns (Figure 3). Cluster 1 is dominated by academic institutions and innovative SMEs that are active in research-based collaborations. Cluster 2 is dominated by large agribusiness companies and government agencies with a focus on sustainability policies. Meanwhile, cluster 0 consists mostly of private companies with relatively limited collaborative involvement. These findings show that the type of organization influences the position in the cluster, and underscore the importance of cross-sector collaboration in driving food system innovation.



**Figure 3. Cluster Visualization by Organization Type**

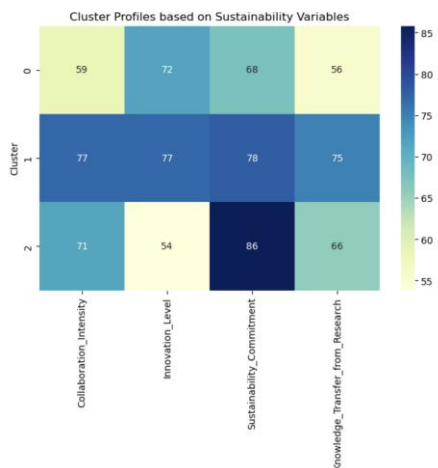
These results confirm that innovation will flourish when academics and industry players connect through research-based collaboration mechanisms, reinforcing Xiaolan Fu's findings [46].

**3.6 PCA Visualization and Interpretation**

Plotting PCA as shown in Figure. 4 identifies two main components, namely:

1. PC1 (Innovation–Collaboration Axis) which explains 61.8% of the total variance,
2. PC2 (Sustainability–Knowledge Axis) which explains 23.7%.

The upper right quadrant is occupied by Cluster 1, in this cluster shows the innovation and collaboration performance that has high value. Low integration is occupied by cluster 0 which is in the lower left position. Cluster 2 is in the upper left quadrant position which has high sustainability but innovation is still limited. Based on the Quadrant position, it can be concluded that sustainability that is not accompanied by active collaboration will not result in an increase in innovation as expected.



**Fig. 4. PCA Biplot of Organizational Clusters**

**3.7 Regression Analysis**

The results of regression analysis (Table 4) provide

empirical validation of the relationship between variables in the food innovation ecosystem.

**Table 4. Organizational clusters**

| Variable                  | $\beta$ Coeff. | t-Stat. | p-Value | Significance |
|---------------------------|----------------|---------|---------|--------------|
| Collaboration Intensity   | 0.48           | 6.11    | <0.001  | ***          |
| Sustainability Commitment | 0.29           | 3.69    | 0.001   | **           |
| Knowledge Transfer        | 0.37           | 4.08    | 0.002   | **           |

These results show that collaboration has the strongest influence on innovation followed by knowledge transfer, as well as sustainability commitments Cluster distribution shows that Cluster 1 (38.75%) is the largest group and acts as a collaborative innovator. Cluster 2 (35%) reflects an organization with a strong sustainability orientation, while cluster 0 (26.25%) shows a lower level of adaptation. This pattern reflects that innovation in Indonesia's food ecosystem tends to be concentrated in organizations with strong cross-sector connectivity, such as universities and agricultural technology-based companies, which serve as key links in the flow of knowledge and collaboration [47].

**3.8 Discussion and Implications**

The results demonstrate that innovation thrives within collaborative, knowledge-intensive ecosystems. Cluster 1 organizations—collaborative innovators—represent Indonesia’s emerging innovation leaders, effectively integrating research collaboration with sustainability objectives. In contrast, cluster 2 organizations prioritize sustainability compliance but lack adaptive innovation mechanisms, while cluster 0 firms show limited ecosystem engagement. The innovation framework in an ecosystem is, in a theoretically way, seen as a cooperation carried out in a systematic way with knowledge content as a trigger for sustainable transformation [48]. Based on managerial and policy frameworks: (a) innovations resulting from collaboration between universities and industry should be adopted by companies in order to accelerate product development, (b) Institutional Relations of policy makers should be carried out through digital collaboration infrastructure in order to link research and its application. This understanding means that the sustainability transition in Indonesia depends on strengthening the sharing of knowledge and trust among the entities involved, not only on investment in the use of technology.

**3.9 Summary of Key Findings**

Important information in the data of sustainable development ecosystem in Indonesia can be analyzed using cluster analysis, PCA, and regression methods.

An important finding that can be generated from this data set is the existence of organizational innovation formed by the close relationship between collaboration and the level of knowledge transfer. Commitment to sustainability is an important foundation for the development of innovation, but this commitment does not independently guarantee strong innovation performance. On the contrary, synergistic collaboration and well-conducted research cooperation will encourage innovation in the ecosystem. These results indicate that the food ecosystem in Indonesia is in the process of structurally transitioning from an institutional order to an interconnected and innovation-oriented system.

**Table 5. Summary of Key Findings**

| Key Insight                          | Empirical Evidence        | Implication   |
|--------------------------------------|---------------------------|---|
| Collaboration drives innovation      | $\beta = 0.48, p < 0.001$ | Building cross-sector partnerships enhances innovation capacity |
| Knowledge transfer is essential      | $\beta = 0.37, p < 0.01$  | Research collaboration accelerates organizational learning      |
| Sustainability alone is insufficient | $\beta = 0.29, p < 0.01$  | Integration with innovation systems is required                 |
| Optimal ecosystem typology           | 3 clusters identified     | Enables targeted strategies and policy design                   |

### 3.10 Interpretation Summary

The sustainable food ecosystem in Indonesia is undergoing three evolutionary paths, ranging from isolated private companies to collaborative networks oriented to innovation. Empirical evidence suggests that sustainable transformation emerges through systemic collaboration, shared institutional learning, and shared innovation practices, positioning the ecosystem as a cornerstone of national food security and economic goals as a whole

## 4. Conclusion and Policy Implications

### 4.1 Conclusion

This study analyzes the structure and dynamics of sustainable food ecosystems in Indonesia by integrating K-means clustering, PCA, and multiple linear regression approaches. The analysis was conducted on 80 cross-sector organizations—industry, academia, and government—that represent interactions within national food systems. All variables have been standardized prior to the clustering process to ensure the balance of contributions in the formation of clusters, while the validity of the cluster structure is supported by the silhouette score value that indicates good separation quality.

The results of the analysis identified three main typologies of organizations in the ecosystem, namely:

(a) Collaborative Innovators, who show high levels of collaboration, knowledge transfer, and innovation; (b) Sustainability-Oriented Traditionalists, who have a strong sustainability commitment but relatively limited innovation; and (c) Adaptive Followers, which are characterized by low levels of collaboration and knowledge exchange. This classification is reinforced through a threshold-based approach (low, medium, high), thereby increasing the transparency and consistency of cluster interpretation.

The results of the PCA show that two main components are able to explain most of the data variance, representing the main dimensions of interaction between innovation, collaboration, sustainability and knowledge transfer. These visualizations confirm that organizations with high innovation performance tend to be in a space defined by a strong intensity of collaboration and knowledge exchange. Furthermore, the regression results showed that the intensity of collaboration ( $\beta = 0.48, p < 0.001$ ) and knowledge transfer ( $\beta = 0.37, p < 0.01$ ) were the most significant predictors of innovation performance, while sustainability commitment ( $\beta = 0.29, p < 0.01$ ) played a supporting factor. This Model is able to explain about 72% variance (Adjusted  $R^2 = 0.72$ ) in Organizational Innovation, which shows the strength of the relationship between variables within the framework of the ecosystem.

These findings confirm that innovation in sustainable food ecosystems does not develop in isolation, but rather through collaborative networking mechanisms and learning between organizations. A commitment to sustainability, while important, does not automatically result in innovation in the absence of integration with active collaboration and effective knowledge transfer systems.

Theoretically, this study reinforces the innovation ecosystem perspective by showing that sustainable transformation is the result of systemic interactions between actors facilitated by Knowledge Exchange and collaborative governance. Methodologically, this study also shows that the combination of clustering, PCA, and regression can provide a comprehensive understanding of the structure and dynamics of ecosystems. Nevertheless, the results of this study need to be interpreted in the context of limited sample size ( $n = 80$ ), which, although adequate for exploratory analysis, still has limitations in generalization to the national level. Therefore, these findings are more correctly positioned as an initial empirical basis for the development of more extensive and in-depth follow-up studies. Overall, this study makes an important contribution to understanding how collaboration, knowledge, and sustainability interact to form an innovative and resilient food ecosystem in Indonesia.

### 4.2 Policy Implications

1. Improve collaborative governance; policies should be created to institute multi-actor coordination mechanisms through triple helix (industry–academia–government) and quadruple helix frameworks, which ensure systemic alignment between innovation, sustainability and policy objectives.
2. Developing regional food innovation centers; regional innovation and knowledge transfer centers need to be developed to bridge universities, SMEs, and local producers, so that they are expected to increase the influence of sustainable technology and can foster cross-sector learning networks.
3. Implement incentives for collaboration that impact knowledge enhancement; government programs should prioritize fiscal and regulatory incentives including sustainability innovation financing, innovation grants, and tax breaks for organizations that demonstrate measurable inter-organizational learning and collaboration outcomes.
4. Developing a digital ecosystem platform; developing a data-driven collaboration platform with a sustainability framework can improve transparency, monitor performance, and facilitate real-time policy feedback across ecosystem actors.
5. Implementing sustainable learning in the policy cycle; research-based feedback mechanisms in national and regional food governance will encourage adaptive policy making, aligning innovation efforts with the goals of food security, green economy, and circular economy.

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