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iJOE International Journal of Online and Biomedical Engineering

iJOE | eISSN: 2626-8493 | Vol. 22 No. 8 (2026) | OPEN ACCESS

https://doi.org/10.3991/ijoe.v22i08.62317

PAPER

Improving Palm Oil Supply Chain Resilience and Bioprocess Skills to Enhance SME Competitiveness: Evidence from South Sulawesi's Palm Oil Biorefinery Sector

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ABSTRACT

This study examines how supply chain resilience (SCR) can improve sustainable business performance for small and medium enterprises in the palm oil biorefinery sector in South Sulawesi, Indonesia. It focuses on the roles of Green Competitive Advantage and Bioprocess Skills in influencing this relationship. The research uses survey data from 150 owners and managers of micro and small enterprises (MSE) in Makassar City, Gowa Regency, and Pare-Pare City. The data were analysed with structural equation modelling (SEM) using IBM SPSS and AMOS 25. The findings show that SCR has a strong impact on green competitive advantage and bioprocess skills, but it does not directly improve sustainable SME business performance. Both green competitive advantage and bioprocess skills play a key role in boosting SME performance and fully explain how SCR affects business results. This means that having a resilient supply chain is not enough to improve SME performance unless it is combined with environmental competitiveness and strong bioprocess skills. The study points out that integrating resilient logistics, green operations, and technical engineering skills is important for improved sustainable performance in the palm oil biorefinery sector.

KEYWORDS

supply chain resilience (SCR), green competitive advantage, bioprocess skills, structural equation modelling (SME) performance, palm oil biorefinery

1 INTRODUCTION

According to Alkatiri and Wardhana, [1], the OECD (2026) and the Indonesian Ministry of cooperatives and micro, small, and medium enterprises (MSMEs) sector is still the main driver of Indonesia's economy. It contributes more than 61% to the

Pono, M., Sabbar, S. D., Munizu, M., Mugableh, M. I. (2026). Improving Palm Oil Supply Chain Resilience and Bioprocess Skills to Enhance SME Competitiveness: Evidence from South Sulawesi's Palm Oil Biorefinery Sector. *International Journal of Online and Biomedical Engineering (iJOE)*, 22(8), pp. 25–35. https://doi.org/10.3991/ijoe.v22i08.62317

Article submitted 2026-03-14. Revision uploaded 2026-04-05. Final acceptance 2026-04-12.

country's gross domestic product (GDP). In South Sulawesi, many SMEs are moving from traditional trade to higher-value agro-industrial sectors. One important area of growth is biorefinery engineering, where waste from palm oil mills, such as palm oil mill effluent (POME) and empty fruit bunches, is turned into products such as bio-fertilizers, biogas, and bio-plastics.

Indonesia is actively pursuing its net zero emission 2060 targets and the B50 Biodiesel mandate [2]. Consequently, the palm oil supply chain has evolved into a complex biological value chain. However, small and medium-sized enterprises (SMEs) in South Sulawesi continue to experience considerable uncertainty. Bio-feedstock supply is often disrupted by seasonal climate changes [3] and logistical challenges in the Makassar-Gowa-Parepare corridor [4]. Supply chain resilience (SCR), which is the ability to handle and recover from disruptions, and bioprocess skills, meaning the technical know-how to manage living microbial systems, have become essential for modern SMEs sized businesses to survive [5].

Despite the abundance of palm oil waste in South Sulawesi, most SMEs struggle to convert this "waste" into consistent "wealth". Previous research has long suggested that supply chain management (SCM) directly improves performance. However, empirical facts on the ground often contradict this: many SMEs with stable supply chains still fail to achieve a competitive edge. The core problem lies in a structural disconnect. A resilient supply chain provides the raw material, but without specialized Bioprocess Skills, the SME cannot handle the biochemical volatility of palm oil waste. Furthermore, traditional SCM models often ignore the "biological" nature of the product, leading to high spoilage rates and inefficient yields. There is a pressing need to understand why SCM alone fails to drive performance and how technical engineering competence acts as the missing link in the SME performance equation.

Although previous studies by Pono and Munizu [5] and Munizu et al. (2024) [6] have examined SCM and organizational competence in general manufacturing, a gap remains. Few researchers have examined how SCM and bio-engineering interact in Indonesian SME biorefineries. Most research treats competence as a broad managerial skill rather than a specific technical ability in bioprocessing. Earlier models often fail to capture the full mediation effect of technical skills. They usually assume SCM leads directly to profit, but in bio-industries, the conversion process is actually the main source of value.

This study evaluates a performance improvement model that integrates logistical resilience with engineering capabilities. It analyses the impact of SCR on green competitive advantage and bioprocess skills, examines the influence of bioprocess skills on the overall business performance of biorefinery SMEs, and determines whether SCR affects performance directly or indirectly through the mediating roles of competitive advantage and technical competence. Additionally, the study provides a strategic framework for SMEs in South Sulawesi to optimize their bio-based value chains and enhance sustainable business performance. This research includes 150 SME entrepreneurs and managers from the bio-refinery and Agro-processing sectors in South Sulawesi. It covers the industrial clusters in Makassar City, Gowa Regency, and Pare-Pare City. The study examines the upstream and midstream parts of the palm oil bio-value chain and uses structural equation modelling (SEM) to examine relationships among key variables.

2 RELATED REVIEW

As the Indonesian palm oil industry shifts from a commodity-based sector to a bio-based industrial ecosystem, SCR and technical bioprocess skills have become

more important for SMEs. In South Sulawesi, especially in the Makassar-Parepare industrial corridor, bio-refinery SMEs use palm oil residues, such as POME, empty fruit bunches, and biomass fibres to produce value-added products, including biogas, organic fertilizers, biochar, and biodegradable materials.

2.1 Supply chain resilience in the palm oil bio-economy

Supply chain resilience refers to the ability to adapt to unexpected events, handle disruptions, and keep running smoothly [6]. South Sulawesi's biorefinery sector's resilience goes beyond logistics and includes managing the unpredictable nature of palm oil by-products. Modern supply chains in the agro-industrial sector experience "ripple effects" when disruptions in upstream biomass collection, often caused by seasonal floods or changes in harvest timing, lead to production stoppages [7–8]. Within palm oil biorefineries, supply chain resilience serves two primary functions. It ensures uninterrupted access to biological feedstock necessary for production and facilitates sustainable operational planning by minimizing waste accumulation and enhancing material flow efficiency.

2.2 Bioprocess skills as a technical competence

Unlike traditional manufacturing, biorefinery engineering requires specific bioprocess skills. These include monitoring and controlling microbial growth, enzymatic reactions, and the stability of biochemical conversions [8]. For SMEs, this means being skilled in anaerobic digestion for biogas production and in thermochemical methods for biochar production.

The resource-based view (RBV) theory suggests that a firm's competitive advantage stems from resources that are valuable, rare, inimitable, and non-substitutable (VRIN). In the South Sulawesi context, while raw POME is widely available, the tacit knowledge required to manage its high acidity and chemical oxygen demand (COD) constitutes a unique technical competence [9–10]. In the absence of these skills, SMEs experience higher spoilage rates and inconsistent product quality, undermining the logistical benefits of a resilient supply chain [11].

2.3 Green competitive advantage

Green competitive advantage means a company can outperform its competitors by using environmentally friendly products, processes, and operations. In bio-based industries, sustainability is now closely tied to market acceptance, regulatory compliance, and long-term profitability. Small and medium-sized businesses that use palm oil waste to create renewable products can stand out by reducing their environmental impact, using resources efficiently, and supporting a circular economy.

Sustainable supply chain practices positively influence green innovation and eco-competitive positioning [12]. A resilient supply chain enables SMEs to secure continuous biomass input and reduce operational waste, thereby supporting greener production systems. In turn, green competitive advantage enhances customer trust, institutional support, and market expansion opportunities [10–12]. Biorefinery SMEs, environmental positioning is particularly important because national policies such as Indonesia's Net Zero Emission 2060 roadmap and biodiesel mandates increasingly prioritize low-carbon industrial practices.

2.4 Business performance in biorefinery SMEs

An organization achieves operational and financial objectives such as profitability, productivity, market growth, innovation capability, and sustainability outcomes. For SMEs in emerging bio-industrial sectors, performance also includes environmental efficiency, resource utilization, and production stability [13]. This study addresses the identified theoretical gap by introducing an integrated framework that unites logistical resilience, engineering capability, and green competitive positioning within a comprehensive performance model. The framework acknowledges that, within biological industries, value creation predominantly takes place during the conversion process rather than solely through raw material acquisition.

2.5 Conceptual framework

Figure 1 presents the conceptual framework for this study. The framework posits that resilient supply chain systems improve operational continuity and feedstock availability. These improvements subsequently enhance technical competence and sustainable competitive positioning, which ultimately result in improved business performance for small and medium-sized enterprises.

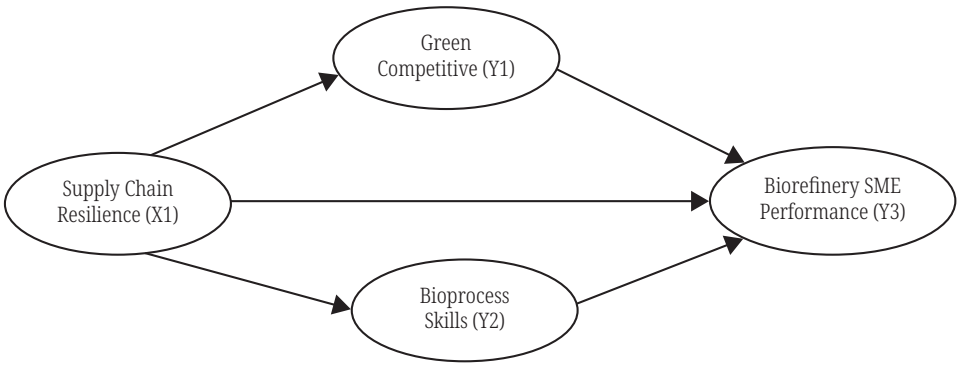

Fig. 1. Research conceptual model

In accordance with the literature review and empirical review of previous research, the following research hypotheses can be formulated:

H1: Supply chain resilience has a significant positive effect on Green Competitive Advantage among palm oil biorefinery SMEs in South Sulawesi.
H2: Supply chain resilience has a significant positive effect on Bioprocess Skills among palm oil biorefinery SMEs in South Sulawesi.
H3: Green competitive advantage has a significant positive effect on sustainable SME business performance.
H4: Bioprocess skills have a significant positive effect on sustainable SME business performance.
H5: Supply chain resilience has a significant positive effect on sustainable SME business performance.
H6: Green competitive advantage mediates the relationship between supply chain resilience and sustainable SME business performance.
H7: Bioprocess skills mediate the relationship between SCR and sustainable SME business performance.

3 METHODOLOGY

This study used a quantitative approach to explore how SCR, green competitive advantage, bioprocess skills, and sustainable SME business performance are connected in the palm oil biorefinery sector in South Sulawesi, Indonesia. The research took place in Makassar City, Gowa Regency, and Pare-Pare City, which are key centres for SME and agro-industrial development in the region. These locations were chosen because they are actively involved in palm oil processing, using biomass, and supporting bio-based SME activities.

The study focused on micro and small enterprise (MSE) entrepreneurs working in the bio-refinery and agro-processing sectors. Researchers used purposive sampling to select respondents who aligned with the study's objectives, especially those from SMEs involved in waste valorisation, bioenergy production, and similar agro-industrial activities. In total, 150 SME owners and managers participated.

A questionnaire is valid when each question or statement measures the concept it is meant to assess. In this study, item validity was assessed using the Pearson product-moment correlation. A high correlation coefficient indicates that the indicator aligns with the overall measurement construct, confirming the instrument's validity. An indicator is valid if the correlation coefficient is greater than 0.30 ($r > 0.30$).

Reliability testing was conducted to assess the questionnaire's consistency and stability. An instrument is reliable if it yields consistent results when used repeatedly. In this study, internal consistency was assessed using Cronbach's alpha (α). Hair et al. [14] state that a variable is reliable when the Cronbach's alpha value is above 0.60 ($\alpha > 0.60$). Table 1 shows the results of the reliability test.

Table 1. Cronbach's alpha (α)

Variable	Cronbach's Alpha (α)
Supply Chain Resilience (X1)	0.856
Green Competitive Advantage (Y1)	0.765
Bioprocess Skills (Y2)	0.710
Sustainable SME Business Performance (Y3)	0.734

The data analysis methods used in this study included descriptive statistics and SEM. Research data were processed using IBM SPSS and AMOS version 25 software. Descriptive statistical analysis described respondent profiles and the characteristics of research variables using mean scores and percentage distributions. SEM examined the direct and indirect relationships among study variables simultaneously. SEM was chosen for its capacity to analyse complex causal relationships involving multiple dependent and mediating variables within a single integrated model.

4 RESULTS AND DISCUSSION

4.1 Descriptive statistics

Table 2 shows that most respondents were male (65.3%) and that females accounted for 34.6%. More than half of the respondents were aged 36 to 45 (54.0%), which suggests that most SME operators are in their most productive years.

Regarding education, most had finished high school or vocational training (41.3%), and 30.6% held a bachelor's degree. Makassar City accounted for the largest proportion of SMEs (46.6%), followed by Gowa Regency (30.0%) and Pare-Pare City (23.3%). Most businesses had been operating for 11 to 20 years (41.3%), indicating that the majority of respondents had significant entrepreneurial and operational experience in the Agro-processing and biorefinery sectors.

Table 2. Respondents profile (N = 150)

Category	Classification	Frequency	Percentage (%)
Gender	Male	98	65.3
	Female	52	34.7
Age	25–35 years	24	16.0
	36–45 years	81	54.0
	46–60 years	35	23.3
	>60 years	10	6.7
Education Level	High School/Vocational School	62	41.3
	Diploma	30	20.0
	Bachelor's Degree	46	30.7
	Postgraduate Degree	12	8.0
Business Location	Makassar City	70	46.7
	Gowa Regency	45	30.0
	Pare-Pare City	35	23.3
Business Experience	<5 years	20	13.3
	5–10 years	38	25.3
	11–20 years	62	41.3
	>20 years	30	20.0

Table 3 shows that Sustainable SME Business performance achieved the highest mean score at 4.1, followed by green competitive advantage and bioprocess skills at 4.0, and SCR at 3.8. These findings suggest that SMEs in the palm oil biorefinery sector in South Sulawesi demonstrate robust operational resilience, technical proficiency, environmental competitiveness, and business performance.

Table 3. Descriptive statistic mean value

Variable	Mean Score	Category
Supply Chain Resilience (X1)	3.8	Good
Green Competitive Advantage (Y1)	4.0	High
Bioprocess Skills (Y2)	4.0	Good
Sustainable SME Business Performance (Y3)	4.1	High

4.2 Confirmatory factor analysis

Table 4 presents the results of the confirmatory factor analysis (CFA), demonstrating that the analysis was performed to evaluate the validity and contribution of each indicator in explaining the study's latent constructs: Supply Chain Resilience (X1), Green Competitive Advantage (Y1), Bioprocess Skills (Y2), and Sustainable SME Business Performance (Y3). Indicators are deemed significant when the probability value is less than 0.05, and the Critical Ratio (C.R.) exceeds 1.96. Table 4 shows that all indicators represent their constructs well, with factor loadings above 0.40, p-values below 0.05, and Critical Ratio values above 1.96. X1.1 had the strongest effect on Supply Chain Resilience (0.743). Y1.1 had the highest loading for Green Competitive Advantage (0.686). Y2.1 was the top indicator for Bioprocess Skills (0.733), and Y3.2 had the highest loading for Sustainable SME Business Performance (0.810). These findings confirm that all indicators are valid and suitable for measuring the study variables.

Table 4. Summary of confirmatory factor analysis results

Variables	Factor Loading	C.R.	p-Value	Information
Supply Chain Resilience (X1)	0.743	Fixed	–	Significant
	0.488	5.239	0.000	Significant
	0.732	7.421	0.000	Significant
	0.673	7.003	0.000	Significant
	0.576	6.122	0.000	Significant
Green Competitive Advantage (Y1)	0.686	Fixed	–	Significant
	0.619	4.981	0.000	Significant
	0.575	4.838	0.000	Significant
	0.502	4.455	0.000	Significant
Bioprocess Skills (Y2)	0.733	Fixed	–	Significant
	0.728	6.655	0.000	Significant
	0.628	6.184	0.000	Significant
	0.548	5.538	0.000	Significant
Sustainable SME Business Performance (Y3)	0.620	Fixed	–	Significant
	0.810	5.806	0.000	Significant
	0.590	5.444	0.000	Significant
	0.498	4.791	0.000	Significant

4.3 Structural equation modelling analysis

Table 5 shows that four goodness-of-fit criteria (CMIN/DF, RMSEA, CFI, and TLI) reached acceptable values within the recommended thresholds, while three criteria (Chi-Square, Probability, and GFI) were rated as marginal. Still, based on the parsimony principle in SEM analysis, a structural model is acceptable if several key fit indices meet the recommended standards. As a result, the proposed structural model

in this study is considered fit and ready for further hypothesis testing and analysis of structural relationships.

Table 5. Goodness-of-fit test results

Criterion	Recommended Value	Result	Category
Chi-Square	Expected to be small	150.39	Marginal
Probability	≥0.05	0.01	Marginal
CMIN/DF	≤2.00	1.32	Good
GFI	≥0.90	0.89	Marginal
RMSEA	≤0.08	0.05	Good
CFI	≥0.90	0.92	Good
TLI	≥0.90	0.91	Good

The SEM results in Table 6 show that SCR significantly influences green competitive advantage ($\beta = 0.951$; $p < 0.05$) and Bioprocess Skills ($\beta = 0.868$; $p < 0.05$), supporting H1 and H2. However, Supply Chain Resilience does not directly affect Sustainable SME Business Performance ($\beta = -0.852$; $p > 0.05$), leading to the rejection of H3. Green Competitive Advantage ($\beta = 0.867$; $p < 0.05$) and Bioprocess Skills $= 0.532$; $p < 0.05$) both significantly improve SME performance, supporting H4 and H5. The indirect effects are also significant, where Supply Chain Resilience improves performance through Green Competitive Advantage (0.824) and Bioprocess Skills (0.461), supporting H6 and H7. These findings indicate that supply chain resilience enhances SME performance indirectly through environmental competitiveness and technical bioprocess capability.

Table 6. Hypothesis testing results

Hypothesis	Path	Path Coefficient	C.R.	p-Value	Decision
Direct Effects					
H1	Supply Chain Resilience (X1) → Green Competitive Advantage (Y1)	0.951	3.910	0.000	Supported
H2	Supply Chain Resilience (X1) → Bioprocess Skills (Y2)	0.868	4.822	0.000	Supported
H3	Supply Chain Resilience (X1) → Sustainable SME Business Performance (Y3)	–0.852	–0.507	0.612	Not Supported
H4	Green Competitive Advantage (Y1) → Sustainable SME Business Performance (Y3)	0.867	2.034	0.049	Supported
H5	Bioprocess Skills (Y2) → Sustainable SME Business Performance (Y3)	0.532	2.422	0.021	Supported
Indirect Effects					
H6	Supply Chain Resilience (X1) → Green Competitive Advantage (Y1) → Sustainable SME Business Performance (Y3)	0.824	0.951 × 0.867	Significant	Supported
H7	Supply Chain Resilience (X1) → Bioprocess Skills (Y2) → Sustainable SME Business Performance (Y3)	0.461	0.868 × 0.532	Significant	Supported

The complete structural model and the relationships among the research variables are presented in Figure 2.

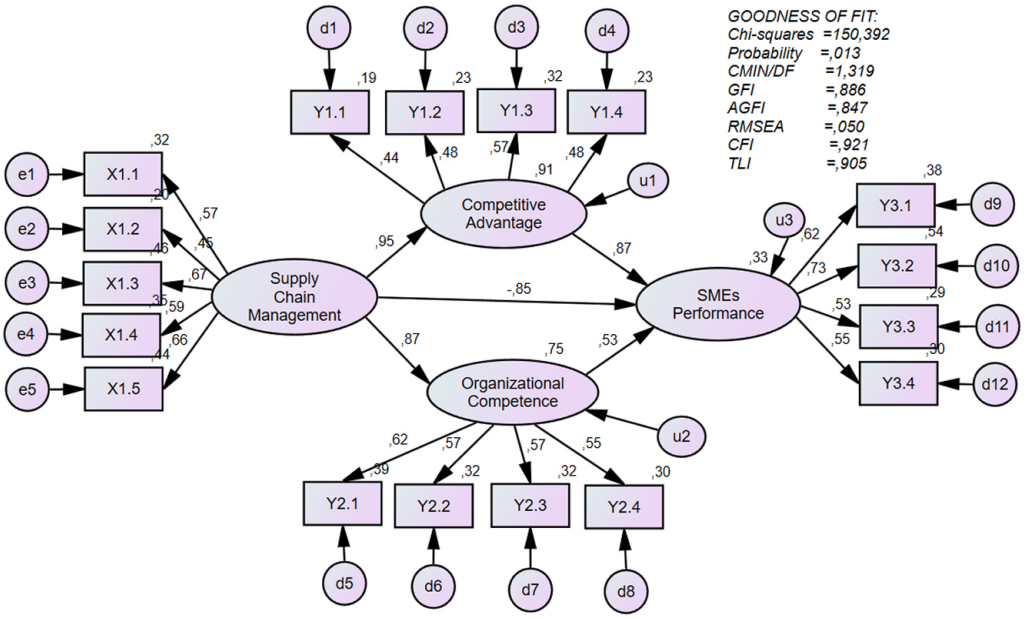

Fig. 2. SEM-measurement model

4.4 Discussion

This study looked at how SCR helps palm oil biorefinery SMEs in South Sulawesi improve their Green Competitive Advantage and Bioprocess Skills. The results show that SCR has a strong positive effect on both, suggesting that strong logistics, teamwork, and digital coordination boost environmental competitiveness and technical skills in these businesses. These results align with earlier research showing that resilient and sustainable supply chains make agro-industrial firms more capable and competitive [4], [5], [8].

However, supply chain resilience does not directly lead to better sustainable business performance for SMEs. This means that simply having operational resilience is not enough to boost performance in the palm oil biorefinery sector. SMEs also need strong technical processing skills and a focus on environmentally friendly competitive strategies to turn biomass resources into sustainable economic value [13]. This result aligns with other studies that emphasize the roles of technological capability, innovation, and sustainable bioprocess development in bio-based industries [15–16].

The study shows that green competitive advantage and bioprocess skills play a key role in improving SME performance. SMEs that are more environmentally competitive, manage costs effectively, and have strong technical skills and innovation tend to achieve better sales growth, higher productivity, and more sustainable operations. The findings also reveal that these two factors fully mediate the link between Supply Chain Resilience and SME performance. In other words, supply chains only add value when combined with green market strategies and technical skills, especially in the biological and circular-economy context of palm oil biorefineries in South Sulawesi.

5 CONCLUSION AND FUTURE STUDIES

This study finds that Supply Chain Resilience helps improve Green Competitive Advantage and Bioprocess Skills for palm oil biorefinery SMEs in South Sulawesi. However, it does not directly boost Sustainable SME Business Performance. Instead, business performance improves indirectly when Green Competitive Advantage and Bioprocess Skills are stronger. These results show that having a resilient supply chain is not enough on its own. SMEs also need strong environmental competitiveness and technical bioprocess skills. To improve long-term competitiveness and performance, SMEs should focus on building technological expertise, better biomass processing, and sustainable operations. Future research should cover a wider range of regions in Indonesia and examine additional factors, such as digital innovation, circular economy practices, green technology adoption, and government policy support, to better understand how to improve bio-based SME performance.

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