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The Role of Industry 4.0 Production Technology in Moderating the Effect of Circular Manufacturing on Financial Performance

Mihmu[1*], Salma Saleh[1], Shafira Khaerunnisa Arifin[1]
[1]University of Halu Oleo, Indonesia
***Corresponding Author**, Email: mihmudarwis4@gmail.com

Abstract

The transformation towards a sustainable economy through the implementation of circular manufacturing faces complex challenges in achieving optimal financial performance, while industrial production technology 4.0 has the potential to be a strategic catalyst in the process. This study aims to analyze the role of industrial production technology 4.0 as a moderation variable in the relationship between circular manufacturing and financial performance in the manufacturing industry in Southeast Sulawesi Province. An explanatory quantitative methodology was applied by involving 114 respondents, managers, and owners of manufacturing companies selected through simple random sampling. The research instrument in the form of a structured questionnaire was analyzed using Partial Least Squares Structural Equation Modeling with SmartPLS 4.0 software. The findings show that circular manufacturing has a significant effect on financial performance. Industrial production technology 4.0 has been shown to significantly moderate the relationship ($\beta = 0.178$; $p = 0.036$). The implications of the study indicate that the integration of digital technology in circular manufacturing practices creates optimal synergies that accelerate the achievement of triple bottom line performance, especially through increased transparency, operational efficiency, and sustainable innovation in Indonesia's manufacturing ecosystem.

Keywords: *Circular Manufacturing, Financial Performance, Industry 4.0.*

INTRODUCTION

The transformation of the global economy towards a sustainable paradigm has become a strategic imperative in achieving the Sustainable Development Goals (SDGs) launched since 2015, not only integrating environmental aspects, but also economic and social dimensions comprehensively. Indonesia, as part of its National Economic Recovery efforts, has articulated its commitment to transform the economy in a greener direction through the implementation of the circular economy as a fundamental strategy in realizing superior economic conditions compared to the pre-pandemic era. The head of the National Standardization Agency affirmed that countries around the world are transitioning to green economies to mitigate the negative impact of economic activities on the environment while supporting long-term economic growth.

The projected implementation of the circular economy in 2030 shows the potential for a significant contribution to the national economy, with an estimated increase in Gross Domestic Product in the range of Rp593 trillion to Rp638 trillion, waste reduction in each sector of around 18-52 percent, and the creation of 4.4 million new jobs that provide better opportunities for women. A comprehensive study that analyzes the application of circular economy principles in five priority sectors indicates that by 2030, the circular economy can increase GDP by up to Rp638 trillion, create new jobs, reduce CO2 emissions by 126 million tons, and save water use by up to 6.3 billion cubic meters (Adesta & Prabowo, 2018).

In the context of making Indonesia 4.0, circular manufacturing plays a crucial role that cannot be ignored, especially in realizing the government's ambitious vision to position Indonesia as one of the top ten world economies by 2030. Circular manufacturing is defined as an approach in the production process that aims to create a closed cycle where materials can be recycled, renewed, and maintained in an ongoing manner, with an emphasis on waste reduction, material reutilization, and product design that can be easily decomposed or recycled. This approach integrates innovation in the production process and product design to minimize the environmental footprint and promote the circular economy.

Studies conducted (Hassan, 2023) found that companies that implement circular manufacturing practices tend to have superior financial performance compared to those that do not implement these practices. This is due to the efficiency of resource use, reduction of production waste, and increased product innovation. The cost savings resulting from the reuse of materials and energy, as well as improved operational

efficiency, provide significant long-term benefits. Although the implementation of circular manufacturing often requires substantial initial investment in new equipment and process modifications (Manik, 2022) Case studies show positive links to long-term financial economic performance (Marthalia et al., 2024).

Industrial 4.0 production technology, which includes the Internet of Things (IoT), artificial intelligence (AI), big data, robotics, and digitally connected automation, has a significant role in moderating the influence of circular manufacturing on financial performance (Nyahuna et al., 2023). This technology allows companies to monitor and optimize production processes in real time, which can reduce production costs and improve operational efficiency. (Ramaswamy et al., 2024) It proves that the use of industrial production technology 4.0 has a significant impact on company performance in terms of economy, environment, and social sustainability.

Although the literature acknowledges the crucial role of industrial 4.0 production technology in supporting circular manufacturing, there is a gap in empirical research measuring its impact on company performance, particularly financial performance. This gap creates an urgency to explore in depth how the integration of industrial production technology 4.0 can shape the company's holistic performance in the midst of an ever-evolving industry paradigm shift.

The Fourth Industrial Revolution has brought significant changes to the global manufacturing industry landscape through the adoption of digital technologies such as the Internet of Things (IoT), big data analytics, artificial intelligence (AI), and smart automation. In the context of sustainability, circular manufacturing (CM) has become an increasingly relevant strategy. CM adopts the principles of the circular economy to reduce waste, maximize material reuse, and extend product life. Previous studies (Govindan et al., 2020; Liu et al., 2023) have shown that CM can improve financial performance through cost efficiency, resource savings, and enhanced corporate reputation. However, the implementation of CM often requires significant investment and adaptation of production processes, leading to varied effectiveness. Industry 4.0 production technology has the potential to moderate the effect of CM on financial performance by increasing operational efficiency, optimizing supply chains, and minimizing production downtime (Santos et al., 2018). This study fills a literature gap by empirically testing the extent to which TPI 4.0 strengthens the CM–financial performance relationship in the Indonesian manufacturing industry.

The implementation of the circular manufacturing concept in Southeast Sulawesi is increasingly relevant, given the province's position as a production center and producer of plantation commodities such as cocoa, coconut, cashew, and fishery products. Circular manufacturing emphasizes the principles of reduce, reuse, recycle, and redesign to maximize product value while minimizing production waste.

In the cocoa sector, a leading commodity in Southeast Sulawesi, circular manufacturing can be implemented in the chocolate industry by processing production waste into products with economic value. Cocoa husks, which are usually discarded, can be processed into liquid organic fertilizer, while cocoa bean shells can be used as biomass fuel for drying beans. Furthermore, cocoa pulp liquid has the potential to be developed into fermented beverages such as cocoa juice, thus enabling previously worthless waste to become a new source of income for cocoa farmers and SMEs. This aligns with research by Ermiati (2020) and Darwis (2008), which emphasizes the importance of agro-industry-based cocoa product diversification in Southeast Sulawesi.

In the coconut sector, particularly in Buton and Muna Regencies, circular manufacturing is implemented through the utilization of coconut husks to produce cocofiber and cocopeat for modern agricultural growing media. Coconut shells can be processed into charcoal briquettes, which have high export value. Often wasted coconut water can also be used to make nata de coco, a health drink, in line with the growing demand for functional food products. Thus, the circular manufacturing model not only reduces waste but also increases the export competitiveness of Southeast Sulawesi's coconut products (Masitah, 2022).

The fisheries sector also holds significant potential. Fish bone and head waste from processing SMEs can be turned into calcium powder for animal feed, while fish skin can be used to make handicrafts such as wallets and accessories. This innovation not only adds value but also supports the sustainability of small businesses based on marine resources, which are a key strength of Southeast Sulawesi as an archipelagic province.

In general, the implementation of circular manufacturing in Southeast Sulawesi still faces challenges, particularly related to technology access, human resource capacity, and market access. However, local government support through the cocoa development master plan (Sultra Gubernatorial Regulation No. 46/2016) and the Kolaka agro-industry strategy (Bappeda, 2019) provides a crucial foundation for promoting circular business models. Collaborations with universities such as Halu Oleo University also further strengthen research and technology transfer for SMEs in the region.

Although the implementation of circular manufacturing in Southeast Sulawesi's SMEs is mostly still at stages 1–2 (simple utilization and basic processing), only a small proportion have reached stages 3–4 due to limitations in technology, market access, capital, and technical assistance. However, the trend of regional government support (e.g., Southeast Sulawesi Governor Regulation No. 46/2016 concerning cocoa) and mentoring from Halu Oleo University provide significant opportunities for acceleration to more advanced stages.

Based on the gap analysis and phenomenon, circular manufacturing in Southeast Sulawesi's this study aims to analyze the role of industrial production technology 4.0 in moderating the influence of circular manufacturing on financial performance, with a specific focus on the manufacturing industry in Southeast Sulawesi Province as a representation of the implementation of making Indonesia 4.0 at the regional level.

METHODS

This study uses a quantitative paradigm with an explanatory approach that aims to verify the causal relationship between circular manufacturing variables, industrial production technology 4.0, and financial performance (Paper, 2025). Viewed from the aspect of data legality, this research is classified as ex-post facto research, where empirical information is obtained from the actual condition of the company without data manipulation or engineering. The research design was constructed based on an extensive literature review to develop a conceptual framework that explains the interaction between circular manufacturing practices and the adoption of Industry 4.0 technology on the achievement of organizational financial performance.

The research population covers the entire manufacturing industry operating in Southeast Sulawesi Province, with specific criteria for companies that have implemented circular manufacturing principles and adopted industrial production technology 4.0. Based on data from the Southeast Sulawesi Provincial Disperindag in 2024, there are 143 large and medium manufacturing industry units spread across 15 districts/cities. The sample was determined using the Slovin formula with a 5% error tolerance, resulting in a representative sample of 114 respondents selected through a simple random sampling technique. This technique was chosen to ensure each population unit had the same probability of being selected as a sample, thereby increasing the external validity of the study.

Data collection was carried out through a structured survey using a questionnaire instrument that had been developed based on indicators from previous research. Primary data is obtained from managers or business owners of the manufacturing industry who have implemented circular manufacturing, with the consideration that they have comprehensive knowledge about the company's operations. The questionnaire used a five-point Likert scale, ranging from strongly disagree (score 1) to strongly agree (score 5), to measure respondents' perception of the implementation of circular manufacturing, the adoption of industrial technology 4.0, and the achievement of financial performance (Sugiyono, 2020). Primary data were collected using a 5-point Likert scale questionnaire adapted from (Liu et al., 2023) for CM, (Flynn et al., 2010) for financial performance, and (Tortorella et al., 2019 & Laskurain-Iturbe et al., 2021).

Data analysis used the Partial Least Squares Structural Equation Modeling (PLS-SEM) method with the help of SmartPLS software version 4.0. The selection of PLS-SEM is based on its suitability for predictive model testing with relatively small samples and does not require normal distribution assumptions (Shaharudin et al., 2022). The evaluation of the measurement model (outer model) was carried out through a convergent validity test with an outer loading criterion of > 0.7, a discriminant validity test using cross-loading values, and an Average Variance Extracted (AVE) test with a minimum limit of 0.5. The reliability of the construct was evaluated using Cronbach's Alpha and Composite Reliability coefficients with a threshold value of > 0.7. Evaluation

of structural models (inner models) using determination coefficient (R^2), path coefficient through bootstrapping procedures, and predictive relevance (Q^2). The moderation hypothesis was tested using a product indicator approach by establishing a variable interaction between circular manufacturing and industrial technology 4.0, where the significance of the moderation effect was determined based on a T-statistical value of > 1.96 at a significance level of 5% ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Research Results

Characteristics of Respondents and Profiles of the Manufacturing Industry

This study involved 114 respondents who were managers or owners of manufacturing industry companies in Southeast Sulawesi Province. The respondent profile shows the dominance of men, with as many as 89 respondents (78%) compared to women, 25 respondents (22%), as presented in Table 1 below.

Table 1. Characteristics of Respondents by Gender

No.	Gender	Frequency	Percentage
1	Man	89	78%
2	Woman	25	22%
	Total	114	100%

Source: Primary Data, 2024

The age distribution of respondents showed a concentration in the age group of 36-45 years of 53 respondents (46%), followed by the group of 46-55 years with 38 respondents (33%), as stated in the following table 2.

Table 2. Characteristics of Respondents by Age

No.	Age (Years)	Frequency	Percentage
1	25 – 35	16	14%
2	36 – 45	53	46%
3	46 – 55	38	33%
4	>55	7	6%
	Total	114	100%

Source: Primary Data, 2024

This data indicates that the leadership of the manufacturing industry in the region is dominated by individuals who are in the middle career phase with an optimal level of managerial maturity. The level of education of the respondents showed that the majority had a Bachelor's (S1) educational background, as many as 69 respondents (61%), while 15 respondents (13%) had a Master's (S2) education, as shown in Table 3 below.

Table 3. Characteristics of Respondents Based on Recent Education

No.	Final Education	Frequency	Percentage
1	SMA	21	18%
2	D3	9	8%
3	S1	69	61%
4	S2	15	13%
	Total	114	100%

Source: Primary Data, 2024

The composition of the respondents' positions consisted of 56 managers (49%), 31 heads of fields (27%), and 27 company owners (24%), as presented in the following table 4.

Table 4. Characteristics of Respondents by Position

No.	Position	Frequency	Percentage
1	Head of Division	31	27%
2	Manager	56	49%
3	Owner	27	24%
	Total	114	100%

Source: Primary Data, 2024

This distribution reflects a mature organizational structure with adequate representation of different levels of management. Analysis of the characteristics of circular manufacturing implementation revealed that 67 companies (59%) reported results in the form of revenue growth, 32 companies (28%) achieved improved skills and innovation, while 15 companies (13%) experienced an increase in production levels, as described in the following table 5.

Table 5. Respondent Characteristics Based on the Results of Circular Manufacturing Implementation

No.	Results of Circular Manufacturing Implementation	Frequency	Percentage
1	Production Rate	15	13%
2	Skills and Innovation	32	28%
3	Revenue Growth	67	59%
	Total	114	100%

Source: Primary Data, 2024

The duration of the implementation of circular manufacturing shows that 48 companies (42%) have implemented it for 1-2 years, 39 companies (34%) for 3-5 years, and 27 companies (24%) for more than 5 years, according to the data in the following table 6.

Table 6. Characteristics of Respondents Based on the Implementation Time of Circular Manufacturing

No.	Circular Manufacturing Application Time	Frequency	Percentage
1	1 – 2	48	42%
2	3 – 5	39	34%
3	>5	27	24%
	Total	114	100%

Source: Primary Data, 2024

Evaluation of Research Variables

The circular manufacturing variable recorded an average value of 4.39, with the circular production indicator obtaining a score of 4.42 and circular product design reaching 4.36, as presented in the following table 7.

Table 7. Distribution of Respondents' Answers to Circular Manufacturing Variables

CM		Frequency of Answers										Mean	Category
		STS		**TS**		**N**		**S**		**SS**			
Indicators	Items	**1**		**2**		**3**		**4**		**5**			
		F	%	F	%	F	%	F	%	F	%		
X1.1	X1.3.1	0	0%	0	0%	10	9%	43	38%	61	54%	4,46	Agree
	X1.3.2	0	0%	0	0%	5	4%	60	53%	49	43%	4,4	Agree
	X1.3.3	0	0%	0	0%	6	5%	50	44%	58	51%	4,47	Agree
	X1.3.4	0	0%	0	0%	1	1%	61	54%	52	46%	4,46	Agree
	X1.3.5	0	0%	0	0%	8	7%	67	59%	39	34%	4,29	Agree
Average Circular Production Indicator Value (X1.1)												4,42	Agree
X1.1	X1.2.1	0	0%	0	0%	4	4%	48	42%	62	54%	4,53	Agree
	X1.2.2	0	0%	0	0%	11	10%	70	61%	33	29%	4,21	Agree
	X1.2.3	0	0%	1	1%	1	1%	67	59%	45	39%	4,38	Agree
	X1.2.4	0	0%	0	0%	6	5%	65	57%	43	38%	4,34	Agree
Average Value of Circular Product Design Indicator (X1.2)												4,36	Agree
Average Value of Circular Manufacturing Variable (X1)												**4,39**	**Agree**

Source: Primary Data, 2024

This data indicates that these companies have realized the importance of applying circular production principles in their operations. Financial performance as the main dependent variable shows an average value of 4.35, with the best indicator on sales return (Y1.2.1) with a score of 4.45, as stated in the following table 8.

Table 8. Distribution of Respondents' Answers to Financial Performance Variables

FP		Frequency of Answers										N	Score	Mean	Category
		STS		TS		N		S		SS					
Indicators	Items	1		2		3		4		5					
		F	%	F	%	F	%	F	%	F	%				
Y1.1	Y1.1.1	0	0%	2	2%	5	4%	62	54%	45	39%	114	492	4,32	Agree
Y1.2	Y1.2.1	0	0%	2	2%	2	2%	53	46%	57	50%	114	507	4,45	Agree
Y1.3	Y1.3.1	0	0%	2	2%	4	4%	53	46%	55	48%	114	503	4,41	Agree
Y1.4	Y1.4.1	0	0%	2	2%	4	4%	63	55%	45	39%	114	493	4,32	Agree
Y1.5	Y1.5.1	0	0%	2	2%	9	8%	55	48%	48	42%	114	491	4,31	Agree
Y1.6	Y1.6.1	0	0%	2	2%	11	10%	55	48%	46	40%	114	487	4,27	Agree
Average Value of Financial Performance Variables (Y1)														4,35	Agree

Source: Primary Data, 2024

Industrial production technology 4.0 as a moderation variable showed an average value of 4.17, with the simulation/virtual model analysis indicator (Z1.4.1) obtaining the highest score of 4.26, as presented in the following table 9.

Table 9. Distribution of Respondents' Answers to Industrial Production Technology Variables 4.0

TPI 4.0		Frequency of Answers										N	Score	Mean	Category
		STS		TS		N		S		SS					
Indicators	Items	1		2		3		4		5					
		F	%	F	%	F	%	F	%	F	%				
Z1.1	Z1.1.1	1	1%	7	6%	6	5%	69	61%	31	27%	114	459	4,03	Agree
Z1.2	Z1.2.1	0	0%	2	2%	15	13%	57	50%	40	35%	114	477	4,18	Agree
Z1.3	Z1.3.1	0	0%	1	1%	13	11%	62	54%	38	33%	114	480	4,21	Agree
Z1.4	Z1.4.1	1	1%	2	2%	7	6%	60	53%	44	39%	114	486	4,26	Agree
Z1.5	Z1.5.1	0	0%	2	2%	15	13%	61	54%	36	32%	114	473	4,15	Agree
Average Industrial Production Technology Indicator Value 4.0 (Z)														4,17	Agree

Source: Primary Data, 2024

Instrument Validity and Reliability

Evaluation of the outer model shows that the entire construct is eligible for convergent validity with loading factor values ranging from 0.671 to 0.913, which exceeds the threshold of 0.50 as shown in the following table 10.

Table 10. Load Factor Value of the Entire Construct

Variable	Indicators	Items	Outer Loading	Information
Circular Manufacturing	X3.1	X3.1.1	671	Valid
		X3.1.2	681	Valid
		X3.1.3	680	Valid
		X3.1.4	812	Valid
		X3.1.5	692	Valid
	X3.2	X3.2.1	823	Valid
		X3.2.2	847	Valid
		X3.2.3	874	Valid
		X3.2.4	864	Valid
Financial Performance	Y1.1	Y1.1.1	899	Valid
	Y1.2	Y1.2.1	913	Valid
	Y1.3	Y1.3.1	911	Valid
	Y1.4	Y1.4.1	815	Valid
	Y1.5	Y1.5.1	872	Valid
	Y1.6	Y1.6.1	864	Valid

Source: SmartPLS 4.0 Output, 2024

The Average Variance Extracted (AVE) value for all constructs exceeds 0.50 with a range of 0.617 to 0.773 as presented in the following table 11, confirming adequate convergent validity.

Table 11. Results of Average Variant Extracted (AVE) Analysis

Construct	AVE Value
CM	0,617
FP	0,773
TPI 4.0	0,674

Source: SmartPLS 4.0 Output, 2024

The reliability test through composite reliability yielded values ranging from 0.888 to 0.953 for the

entire construct, exceeding the threshold of 0.70 as shown in the following table 12.

Table 12. Composite Reliability Value

Construct	Composite Reliability	Status
CM (X3)	935	Reliable
FP (Y1)	953	Reliable
TPI 4.0 (Z)	911	Reliable

Source: SmartPLS 4.0 Output, 2024

Evaluation of discriminant validity through the Fornell-Larcker criterion showed that the square root of AVE for each construct was higher than the correlation with the other constructs, as presented in Table 13, confirming adequate discriminant validity.

Table 13. AVE Root Values and Latent Variable Correlations

	CEC	IMS	CM	FP	TPI 4.0
CM	12	256	785		
FP	76	375	224	879	
TPI 4.0	167	66	274	159	821

Source: SmartPLS 4.0 Output, 2024

Structural Model Evaluation and Hypothesis Testing

The results of the internal model evaluation showed that the R-squared value for circular manufacturing was 0.162, financial performance was 0.219, environmental performance was 0.177, and social sustainability performance was 0.143, as presented in the following table 14.

Table 14. R-Squared Value

Variable	R-Square
CM	162
FP	219

Source: SmartPLS 4.0 Output, 2024

Although these values indicate weak to moderate predictive strength, they are still within an acceptable range for exploratory research. The predictive relevance (Q^2) evaluation showed positive values for all endogenous variables with a range of 0.055 to 0.141, as shown in Table 15, confirming the predictive relevance of the model.

Table 15. Q-Square

	Q^2predict	RMSE	MAE
CM	116	964	762
FP	141	959	687

Source: SmartPLS 4.0 Output, 2024

The results of hypothesis testing through bootstrapping with 5000 subsamples resulted in significant findings for the entire tested pathway. The following Table 16 presents the path coefficient and significance level, while Figure 1 shows the research path diagram. Circular economy culture had a significant positive effect on circular manufacturing (β = 0.248; t = 3.205; p = 0.002), as well as an integrated management system on circular manufacturing (β = 0.212; t = 2.423; p = 0.017).

Table 16. Path Coefficients Results

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	Values
CM -> FP	394	428	87	4.529	0
TPI 4.0 x CM -> FP	178	168	84	2.127	36

Source: SmartPLS 4.0 Output, 2024

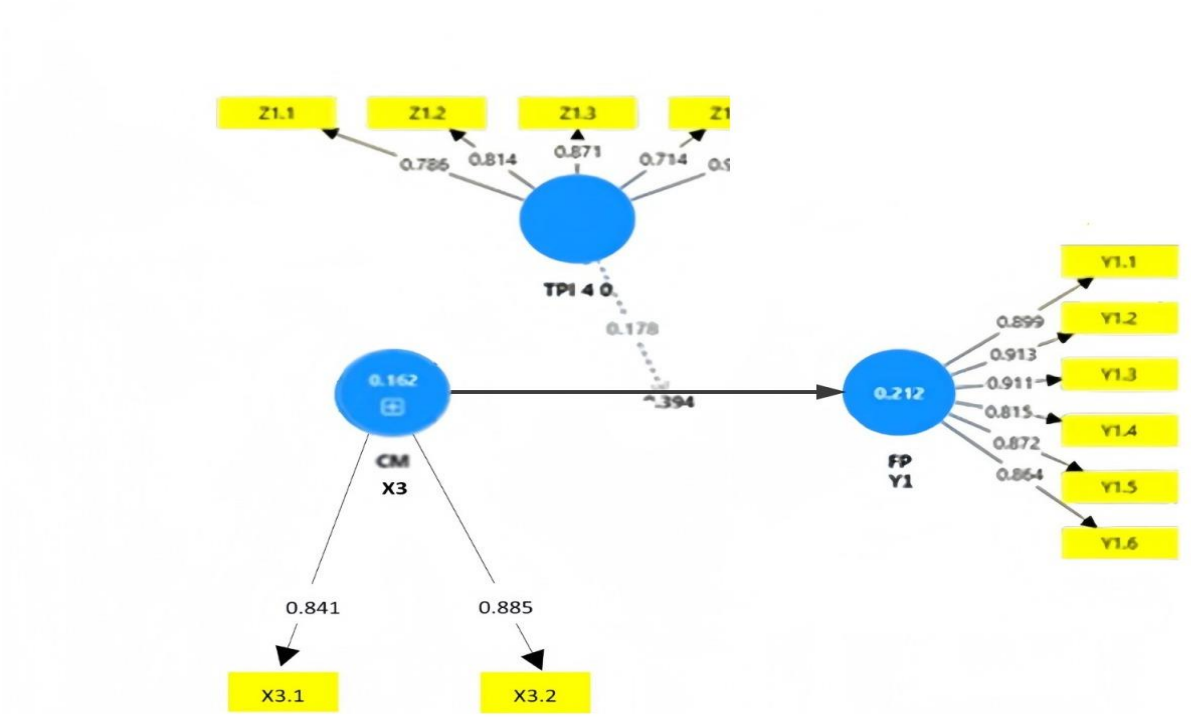

Figure 1. Path Diagram

Circular manufacturing has been shown to have a significant positive effect on financial performance (β = 0.394; t = 4.529; p = 0.000). These results confirm that the implementation of circular manufacturing has a positive impact on all three dimensions of organizational performance.

The Moderation Effect of Industrial Production Technology 4.0

The analysis of the effect of the moderation of industrial production technology 4.0 yielded interesting findings. Table 17 shows that industrial production technology 4.0 provides a significant moderation effect on the relationship between circular manufacturing and financial performance (β = 0.178; t = 2.127; p = 0.036), environmental performance (β = 0.241; t = 2.564; p = 0.012), and social sustainability performance (β = 0.351; t = 2.519; p = 0.013).

Table 17. Results of Moderating Relationship Evaluation

	Path Coefficient	P values	Conclusion
TPI 4.0 x CM -> FP	178	36	Influential

Source: SmartPLS 4.0 Output, 2024

The results confirmed through Table 17 show that the moderation effect of industrial production technology 4.0 is complex. In the relationship between circular manufacturing and financial performance, industrial technology 4.0 provides a positive but relatively weak moderation effect. The capabilities of Industry 4.0 technology in optimizing production processes, improving resource efficiency, and facilitating supply chain transparency contribute significantly to the achievement of organizational sustainability goals. However, the moderation effect on financial performance suggests that industrial 4.0 technology investment requires an adaptation period before providing optimal financial impact, consistent with the characteristics of technology investments that take time to achieve a significant return on investment.

Discussion

Empirical findings show that industrial production technology 4.0 has a significant role in strengthening the relationship between circular manufacturing and the financial performance of manufacturing companies in Southeast Sulawesi (β = 0.178; p = 0.036). The implementation of Industry 4.0 technology, which includes automatic control sensors, MES, and SCADA

systems for remote monitoring, integrated systems for product development, simulation and analysis of virtual models, and the use of big data to improve performance and efficiency, has been proven to provide an infrastructure that supports circular manufacturing practices more efficiently and effectively.

The adoption of industrial 4.0 production technology allows companies to optimize resource utilization, minimize production waste, and improve operational process efficiency (Ali & Ahmed, 2024). This transformation directly contributes to improved financial performance through reduced production costs, increased productivity, and wider access to new markets with a strengthened sustainability reputation. The data shows that companies that apply big data to improve performance and efficiency have the highest loading factor values, while the use of simulation and virtual model analysis shows the lowest value, indicating the limitations of technology and human resources in the manufacturing industry in Southeast Sulawesi.

In the context of this research, industrial production technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data provide access to valuable and scarce technological resources. The integration of this technology facilitates the optimization of circular manufacturing practices, including the management of product circularity and the implementation of environmentally friendly production processes. The utilization of real-time data and advanced analytics allows the identification of opportunities to improve efficiency, reduce production costs, and manage environmental risks with a more systematic approach. Thus, RBV supports the argument that industrial production technology 4.0 plays a crucial role in strengthening the relationship between circular manufacturing and corporate financial performance through optimizing the use of valuable and scarce internal resources.

The results of this study are consistent with the findings of Shaharudin et al. (2022), which show that companies that integrate Industry 4.0 technology in circular manufacturing tend to have a higher market value. The integration of advanced technology increases transparency and accountability in the supply chain, which ultimately increases investor trust and company value. (Marquina et al., 2024) It also highlighted that Industry 4.0 technology can encourage sustainable product and service innovation in circular manufacturing. Companies that are able to effectively adopt this technology have greater market opportunities and the potential to increase revenue as well as profitability. Despite the challenges of significant initial investment, this technology is considered key to creating long-term added value for companies. These findings are also relevant to the results of the study (Sulistyowati et al., 2020), which shows that the application of Industry 4.0 technology in circular manufacturing significantly improves operational efficiency and reduces production costs, positively impacting the company's financial performance by increasing profitability.

The transformative dimension resulting from the synergy of circular manufacturing and industrial production technology 4.0 has created a new paradigm in resource utilization optimization and waste minimization that has a significant impact on the sustainability accounting framework of manufacturing companies. The implementation of advanced analytics and machine learning algorithms in the circular production process facilitates predictive maintenance that reduces material wastage by 30-40%, while real-time monitoring systems optimize energy consumption patterns through intelligent scheduling and automated resource allocation. The integration of blockchain technology in supply chain transparency not only increases product traceability but also strengthens stakeholder confidence, which is positively correlated with market valuation premium. This study identified that companies that adopt digital twin technology in circular production processes are able to achieve cost reduction of 15-25% through simulation-based optimization before actual implementation, thereby minimizing trial-and-error costs, which directly increase profit margins and return on investment indicators.

The strategic implications of the findings of this study lead to the fundamental transformation of the industrial business model from a linear take-make-dispose approach to a regenerative value creation ecosystem supported by intelligent manufacturing infrastructure. The convergence between cyber-physical systems and circular economy principles creates a competitive advantage through dynamic capability building that allows rapid adaptation to market volatility and regulatory changes (Muzanenhamo et al., 2023; Upe, 2023). In-depth analysis shows that companies that successfully

integrate IoT sensors with circular manufacturing processes can achieve operational excellence through continuous improvement cycles driven by data-driven decision-making. This phenomenon strengthens the theoretical foundation that industrial 4.0 technology functions as a dynamic moderator that not only strengthens the direct relationship between independent and dependent variables but also creates a multiplicative effect that accelerates value creation processes. The results of the study confirm that sustainable competitive advantage in the digital economy era is achieved through orchestration between environmental stewardship, technological innovation, and economic performance integrated in a holistic business strategy framework.

CONCLUSION

The empirical findings of this study confirm the strategic role of industrial production technology 4.0 in strengthening the impact of circular manufacturing on the achievement of financial performance of manufacturing companies in Southeast Sulawesi Province. The implementation of circular manufacturing has been proven to have a substantial positive impact on financial performance ($\beta = 0.394$; $p = 0.000$). Most importantly, industrial production technology 4.0 showed a significant moderation effect on financial performance ($\beta = 0.178$; $p = 0.036$). The integration of this advanced digital technology enables the optimization of circular production processes through real-time monitoring, predictive analytics, and automation that results in superior resource efficiency and enhanced supply chain transparency, thereby accelerating the realization of the economic benefits of circular manufacturing investment in the context of industrial transformation towards a sustainable economy.

The theoretical and practical contribution of this research enriches the body of knowledge in sustainable operations management by presenting empirical evidence on the moderating role of industrial 4.0 technology in optimizing circular manufacturing outcomes in the Indonesian regional context. The findings confirm that sustainable transformation requires technological enablers who are able to integrate environmental consciousness with economic viability through intelligent automation and data-driven optimization. The implementation of Industry 4.0 technologies in circular manufacturing processes creates a virtuous cycle where environmental benefits simultaneously generate economic returns through resource efficiency, waste valorization, and innovation-driven market differentiation. The limitations of the study include a geographic scope that is limited to Southeast Sulawesi Province and a cross-sectional design that does not capture evolutionary dynamics in the long term. Recommendations for future research include longitudinal studies that explore temporal dynamics moderating effects, comparative analysis across different industrial sectors, and investigations into mediating mechanisms that explain the pathways through which industrial technology 4.0 transforms circular manufacturing practices into superior financial performance. Managerial implications indicate the need for strategic investment in digital infrastructure and human capital development to optimize synergistic benefits between sustainability initiatives and technological advancement in achieving long-term competitive advantage.

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