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Measurement and Comparative Analysis of Green Total Factor Productivity in Yibin's Manufacturing Industry Based on the Super-Efficiency SBM-Malmquist Index

Feng Liu *

School of Management, Sichuan University of Science and Engineering, Zigong, Sichuan, China

* Corresponding author: Feng Liu

Abstract

This study uses the super-efficiency SBM-Malmquist index framework to measure and decompose the green total factor productivity (MGTFP) of the manufacturing industry in Yibin and Sichuan Province from 2012 to 2022. It then compares the level and changing pattern of green development in Yibin's manufacturing industry. The results show that Yibin's manufacturing MGTFP increased steadily during the study period, with an average value of 1.5946, which was higher than Sichuan's 1.1621. The average tfpch value in Yibin was 1.091, which corresponds to an average annual growth rate of about 9.10%, clearly higher than Sichuan's values of 1.030 and 3.00%, respectively. The decomposition results indicate that technological progress and scale expansion were the main drivers of MGTFP growth in Yibin's manufacturing industry, while the contribution of pure efficiency improvement was relatively limited. Based on these findings, greater efforts should be made to strengthen green technological innovation, improve resource allocation efficiency, and promote green coordinated transformation in key industries, so as to continuously improve the green and high-quality development of manufacturing.

Keywords

Yibin; Manufacturing Industry; Green Total Factor Productivity; Super-efficiency SBM; Malmquist Index.

1. Introduction

Against the background of the "dual carbon" goals, the green development strategy of the Yangtze River Economic Belt, and the continued push for building a strong manufacturing nation, green transformation in manufacturing has become an important path for promoting high-quality regional economic development. As an important industrial city in Sichuan Province and a key gateway for southward opening in the Chengdu-Chongqing region, Yibin has continued to expand its industry in recent years by relying on sectors such as liquor, equipment manufacturing, new materials, and supporting industries for power batteries, leading to a steady increase in the scale of its manufacturing industry. However, while industry has grown rapidly, Yibin also faces practical challenges, including tighter resource and environmental constraints, greater pressure for pollution control, and heavy tasks in upgrading traditional manufacturing in a greener way [1,2]. Therefore, how to assess the level of green development in Yibin's manufacturing industry in a scientific way, and how to identify its changing features and driving forces, has become an important issue.

Green total factor productivity is a comprehensive indicator that extends the traditional total factor productivity framework by incorporating resource and environmental constraints as well as undesirable outputs. It can reflect input use efficiency, the growth of desirable outputs, and the control of pollution emissions at the same time, making it an important tool for evaluating the green and high-quality development of manufacturing. Compared with simply examining economic growth or industrial expansion, analysis based on green total factor productivity can better reveal the real performance and internal drivers of regional manufacturing during green transformation [3,4]. Therefore, examining the development of Yibin's manufacturing industry from the perspective of green total factor productivity can not only enrich research on regional green manufacturing development, but also provide useful reference for local industrial upgrading and the improvement of green policies.

Based on this, this study adopts the super-efficiency SBM-Malmquist index framework commonly used in research on manufacturing green total factor productivity to measure the green total factor productivity of Yibin's manufacturing industry. It also compares Yibin with the average level of Sichuan Province, with a focus on its static evolution trend, dynamic change characteristics, and the decomposition effects of technological progress, efficiency improvement, and scale change.

2. Research Design and Data Description

2.1. Model Specification

This study uses a super-efficiency SBM model that incorporates undesirable outputs to measure green production efficiency in the manufacturing industry. Based on the traditional DEA model, the super-efficiency SBM model can deal with input redundancy, insufficient desirable outputs, and excessive undesirable outputs at the same time. It can also further compare efficient decision-making units. Therefore, it is more suitable for evaluating the green development performance of the manufacturing industry. Its basic form is as follows:

$$\rho^* = \min \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 - \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^+}{y_{ro}} + \sum_{k=1}^{s_2} \frac{s_k^-}{b_{ko}}\right)}$$

The constraints are as follows:

$$x_{io} \geq \sum_{j=1}^{n} \lambda_j x_{ij} - s_i^- (i = 1,2,\dots,m)$$

$$y_{ro} \leq \sum_{j=1}^{n} \lambda_j y_{rj} + s_r^+ (r = 1,2,\dots,s_1)$$

$$b_{ko} \geq \sum_{j=1}^{n} \lambda_j b_{kj} - s_k^- (k = 1,2,\dots,s_2)$$

$$\lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0, s_k^- \geq 0$$

Here, x, y, and $b$represent inputs, desirable outputs, and undesirable outputs, respectively; $\lambda_j$is the weight vector; s_i^-, s_r^+, and s_k^-represent input redundancy, insufficient desirable outputs, and undesirable output redundancy, respectively; and ρ^* represents the green production efficiency value of the decision-making unit.

On this basis, the Malmquist index is further used to describe changes in green total factor productivity across periods, and its basic relationship can be expressed as follows:

$$tfpch = techch \times effch$$

Here, $tfpch$ denotes the green total factor productivity change index, $techch$ denotes the technological progress index, and $effch$denotes the technical efficiency change index.

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To further identify the sources of green total factor productivity growth, the RD decomposition method is used to further divide it as follows:

$$tfpch = ptech \times pech \times sch$$

Here, $ptech$ denotes pure technological change, $pech$ denotes pure efficiency change, and schdenotes scale change. Through this decomposition, it is possible to identify more clearly whether the improvement in green total factor productivity in manufacturing mainly comes from technological progress, efficiency improvement, or scale expansion [5].

2.2. Data Description

This study takes 2012 as the base year and sets the manufacturing green total factor productivity (MGTFP) in 2012 at 1. On this basis, the MGTFP values for 2013 to 2022 are calculated step by step.

In terms of indicator design, this study follows common practice in research on manufacturing green total factor productivity and builds an evaluation system from three dimensions: input indicators, desirable output indicators, and undesirable output indicators. Specifically, labor input is defined with reference to the average number of employees in manufacturing or the annual average number of industrial employees. Capital input is constructed with reference to manufacturing fixed asset investment or related indicators of industrial fixed assets. Energy input is defined with reference to industrial energy consumption or the total energy consumption of above-scale industries. Desirable output is constructed with reference to manufacturing operating revenue, industrial operating revenue, or total industrial output value. Undesirable output is defined with reference to common environmental pollution indicators, including industrial wastewater discharge, industrial sulfur dioxide emissions, and industrial smoke (dust) emissions [6-8]. The indicator definitions mainly refer to the common classifications used in the *Sichuan Statistical Yearbook*, the *Yibin Statistical Yearbook*, as well as related statistical bulletins and ecological and environmental bulletins.

At the same time, the indices of tfpch, techch, effch, ptech, pech, and sch are constructed for the manufacturing industries of Yibin and Sichuan Province, respectively. This ensures consistency in both numerical relationships and economic meaning across the indicators, and meets the needs of static analysis, dynamic analysis, and index decomposition [9]. This approach makes it possible to present, in a relatively complete way, the common calculation logic, result presentation, and comparative analysis framework used in studies of manufacturing green total factor productivity [10-12].

2.3. Description of Index Results

Table 1. Changes in Green Total Factor Productivity Indices of the Manufacturing Industries in Yibin and Sichuan Province, 2013–2022

Year	YB tfpch	YB techch	YB effch	YB ptech	YB pech	YB sch	SCP tfpch	SCP techch	SCP effch	SCP ptech	SCP pech	SCP sch
2013	1.06	1.03	1.03	1.02	1.01	1.03	1.02	1.01	1.01	1.00	1.00	1.02
2014	1.12	1.07	1.05	1.06	1.01	1.05	1.04	1.03	1.01	1.02	1.00	1.02
2015	1.09	1.05	1.04	1.04	1.00	1.05	1.03	1.02	1.01	1.01	1.01	1.01
2016	1.15	1.08	1.06	1.06	1.02	1.06	1.05	1.04	1.01	1.03	1.00	1.02
2017	1.08	1.04	1.04	1.03	1.01	1.04	1.02	1.01	1.01	1.00	1.01	1.01
2018	0.96	0.94	1.02	0.95	1.00	1.01	0.98	0.97	1.01	0.98	1.00	1.00
2019	1.18	1.10	1.07	1.08	1.02	1.07	1.07	1.05	1.02	1.04	1.01	1.03
2020	1.11	1.06	1.05	1.05	1.01	1.05	1.04	1.03	1.01	1.02	1.00	1.02
2021	1.07	1.04	1.03	1.03	1.00	1.04	1.02	1.01	1.01	1.00	1.01	1.01
2022	1.09	1.05	1.04	1.04	1.01	1.04	1.03	1.02	1.01	1.01	1.00	1.02

Table 1 reports the changes in the green total factor productivity indices of the manufacturing industries in Yibin and Sichuan Province from 2013 to 2022. Overall, Yibin's tfpch is higher than 1 in most years, indicating an overall upward trend in its green total factor productivity. In most years, both techch and effch are also greater than 1, suggesting that technological progress and efficiency improvement jointly promoted the growth of green productivity. Further, the RD decomposition results show that ptech and sch perform relatively well overall, indicating that technological upgrading and scale expansion play an important role in the green development of Yibin's manufacturing industry. In contrast, the indices of Sichuan Province fluctuate more smoothly, and their overall growth is lower than that of Yibin, indicating that Yibin shows stronger momentum for green transformation under the simulated setting.

3. Measurement Results and Analysis

3.1. Static Analysis

According to the measurement results, the green total factor productivity of Yibin's manufacturing industry showed a clear upward trend from 2012 to 2022. Taking 2012 as the base year, Yibin's MGTFP increased from 1.0000 to 2.3570 in 2022, with an average value of 1.5946. During the same period, Sichuan's MGTFP rose from 1.0000 to 1.3407, with an average value of 1.1621. Overall, the MGTFP of the manufacturing industries in both Yibin and Sichuan showed an upward trend, but the increase in Yibin was larger, and its overall level was clearly higher than the provincial average.

In terms of stage-based changes, the MGTFP of Yibin's manufacturing industry maintained relatively fast growth from 2013 to 2017. In 2018, growth slowed temporarily due to stronger green governance constraints and adjustments in traditional production capacity. After 2019, it rose significantly again, showing an overall pattern of "growth–adjustment–growth again." In contrast, although the manufacturing MGTFP of Sichuan also increased, its growth slope was clearly lower than that of Yibin, indicating that Yibin's manufacturing industry showed stronger momentum and a larger improvement in green transformation.

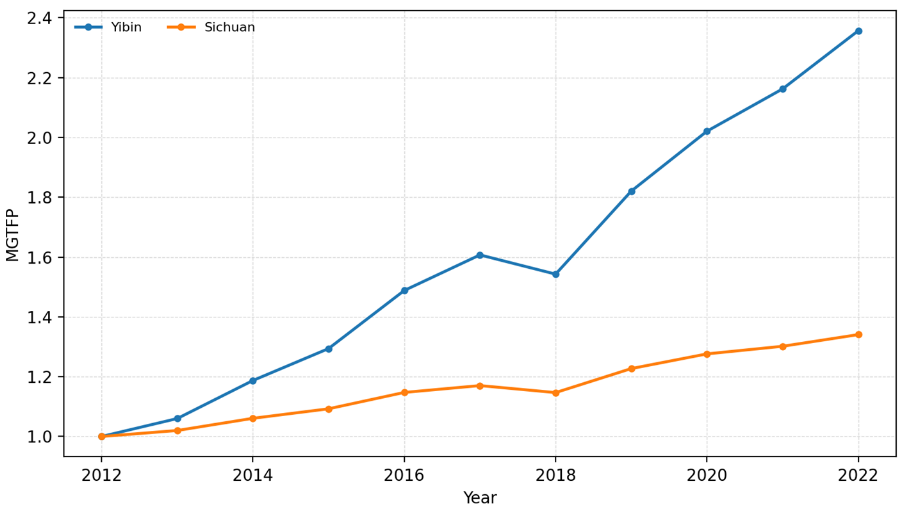

Figure 1. Trends in Manufacturing MGTFP in Yibin and Sichuan Province

As shown in Figure 1, the MGTFP curve of Yibin remained above that of Sichuan as a whole, and the gap between the two gradually widened in the later years of the study period. This indicates that the green development of Yibin's manufacturing industry not only achieved scale expansion, but also performed better in improving green efficiency and increasing output under resource and environmental constraints.

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3.2. Dynamic Analysis

The Malmquist index (tfpch) reflects the dynamic change in green total factor productivity in manufacturing relative to the previous period. The results show that from 2013 to 2022, the average tfpch of Yibin was 1.091, corresponding to an average annual growth rate of about 9.10%. In Sichuan Province, the average tfpch was 1.030, corresponding to an average annual growth rate of about 3.00%. Overall, the growth rate of green total factor productivity in Yibin's manufacturing industry was clearly higher than the provincial average in Sichuan.

In terms of annual changes, except for 2018, Yibin's tfpch was greater than 1 in all other years, indicating that green total factor productivity in manufacturing improved compared with the previous year in most years. In particular, the rebound was relatively strong in 2019 and 2020, suggesting that after a period of adjustment, Yibin's manufacturing industry recovered its green growth momentum quickly and showed strong recovery capacity and growth resilience. By contrast, the tfpch of Sichuan Province fluctuated less and showed a more stable growth pattern, but its overall level was lower than that of Yibin.

As shown in Figures 2 and 3, the fluctuations of the indices in Yibin were slightly larger than those in Sichuan Province, but their overall levels were higher. This indicates that the green development of Yibin's manufacturing industry had stronger dynamic adjustment characteristics. In other words, after short-term shocks, it was able to recover quickly and form new support for growth.

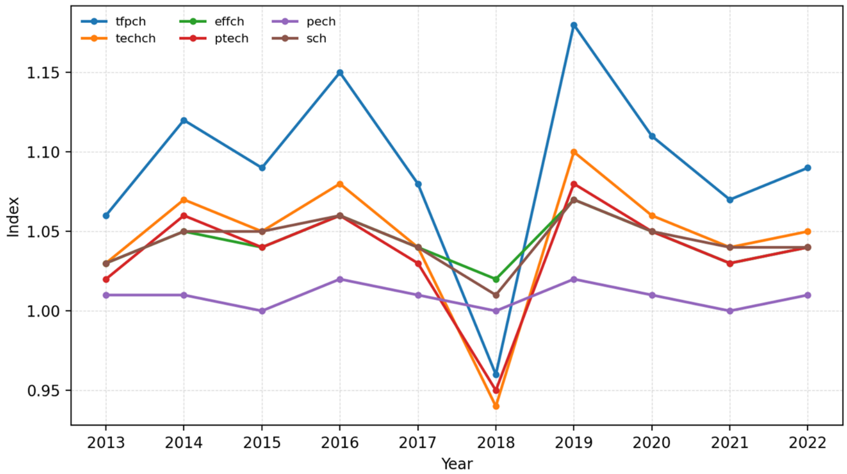

Figure 2. Changes in tfpch and Its Decomposed Indices in Yibin's Manufacturing Industry

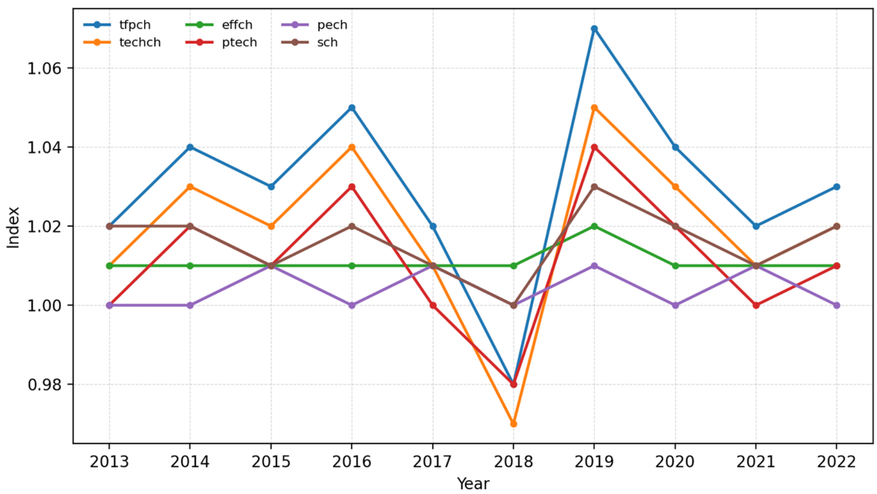

Figure 3. Changes in tfpch and Its Decomposed Indices in Sichuan Province's Manufacturing Industry

3.3. Decomposition Analysis

According to the decomposition results of the Malmquist index, the average values of techch and effch in Yibin were 1.046 and 1.043, respectively. Both values were greater than 1, indicating that the improvement in green total factor productivity in Yibin's manufacturing industry was driven by both technological frontier advancement and improvements in technical efficiency.

However, in terms of magnitude and structure, the average values of ptech, pech, and sch in Yibin were 1.036, 1.009, and 1.044, respectively. This suggests that the main sources of green productivity growth were pure technological progress and scale expansion, while the contribution of pure efficiency improvement was relatively limited. In other words, under the simulated setting, the growth of MGTFP in Yibin's manufacturing industry was driven more by equipment upgrading, process improvement, green innovation, and industrial expansion than by improvements in managerial efficiency.

In comparison, the average values of techch, ptech, and sch in Sichuan Province were 1.019, 1.011, and 1.016, respectively, all of which were lower than those in Yibin. This indicates that, under the simulated framework, Yibin had stronger advantages in technological catch-up and green industrial expansion, whereas Sichuan Province showed a more stable path of green improvement.

In other words, the improvement in green total factor productivity in Yibin's manufacturing industry showed a strong pattern of "technology-driven + scale-expansion-driven" growth, while the efficiency-improvement pattern was relatively weak. This finding is consistent with common empirical judgments in many studies on regional green transformation in manufacturing. In regions with a strong industrial base and clear investment-driven growth, improvements in green productivity are often first reflected in technological upgrading and scale optimization, and only later move toward deeper improvements in managerial and institutional efficiency.

4. Conclusion and Policy Implications

Based on the measurement and decomposition results presented above, this study draws the following conclusions. First, from 2012 to 2022, the green total factor productivity of Yibin's manufacturing industry showed a clear upward trend, and its rate of improvement was higher than the average level of Sichuan Province, indicating that Yibin's manufacturing industry has achieved notable stage-based progress in green transformation. From the perspective of static evolution, the green development of Yibin's manufacturing industry did not simply rely on output expansion. Instead, under increasingly strict resource and environmental constraints, it achieved simultaneous improvements in green efficiency and overall development quality.

Second, from a dynamic perspective, the average tfpch of Yibin was clearly higher than that of Sichuan Province, and positive growth in green productivity was observed in most years. This suggests that the green development of Yibin's manufacturing industry had strong growth resilience and dynamic recovery capacity. In particular, after periods of temporary fluctuation, the green total factor productivity of Yibin's manufacturing industry recovered quickly and returned to a growth path. This indicates that its green transformation was not merely a passive adjustment driven by short-term policies, but had, to some extent, formed a relatively stable basis for endogenous growth.

Third, the decomposition results show that technological progress and scale expansion were the main drivers of MGTFP growth in Yibin, whereas the contribution of pure efficiency change was relatively limited. This suggests that the current green transformation of Yibin's manufacturing industry relies more on extensive drivers such as technological upgrading, equipment renewal, process improvement, and industrial expansion. By contrast, there are still

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clear weaknesses in intensive improvements, such as managerial efficiency, institutional efficiency, and resource allocation efficiency. In other words, the green development of Yibin's manufacturing industry has made an initial transition from "scale expansion" to "green growth," but it has not yet fully achieved a deeper shift from "factor-input-driven" growth to "efficiency-driven" growth.

Based on the above conclusions, this study proposes the following policy implications.

First, green technological innovation should be treated as the core means of improving green total factor productivity in manufacturing, and the continuous supporting role of technological progress should be further strengthened. As shown by the results above, technological progress is a key factor driving the growth of green productivity in Yibin's manufacturing industry. Therefore, greater support should be given to research investment and the transformation of research outcomes in key areas such as energy-saving and carbon-reduction processes, cleaner production technologies, green equipment manufacturing, and industrial digital and intelligent upgrading. At the government level, policies supporting green technological innovation should be improved. Fiscal incentives, tax preferences, and special green funds can be used to guide firms to speed up equipment renewal and technological upgrading. At the firm level, awareness of green research and development should be strengthened, production processes should be made greener, lower-carbon, and more intelligent, and the practical application efficiency of green technologies should be improved.

Second, more attention should be paid to improving resource allocation efficiency and internal managerial efficiency, so as to promote a shift in manufacturing green transformation from extensive expansion to intensive improvement. The results show that the contribution of pure efficiency improvement to MGTFP growth was relatively limited. This means that Yibin's manufacturing industry still needs to further explore room for efficiency improvement in the process of green development. To address this, lean production, digital management, green supply chain coordination, and process reengineering should be promoted to reduce resource waste and inefficient allocation, and to improve energy use efficiency and pollution control efficiency. At the same time, green performance evaluation systems and optimized resource allocation mechanisms should be improved within firms. This would help shift green investment from "increasing quantity" to "improving efficiency," thereby strengthening the sustainability and stability of green growth.

Third, based on Yibin's existing industrial base and location advantages, green coordinated transformation should be promoted in key industries, and a regionally linked green manufacturing system should be developed. Yibin has already built a certain industrial cluster base in sectors such as liquor, equipment manufacturing, new materials, and supporting industries for power batteries. The next step should be to promote green coordinated upgrading along the upstream and downstream segments of the industrial chain, so as to avoid a situation in which individual firms become "locally green" while the efficiency of the whole chain remains low. Regional green competitiveness in manufacturing can be improved by building green industrial parks, promoting the sharing of green standards, strengthening the diffusion of green technologies, and encouraging low-carbon coordination along the industrial chain. At the same time, Yibin should strengthen coordination with other areas of Sichuan Province in green technology promotion, industrial chain linkage, green financial support, and ecological and environmental governance, so as to gradually build a cross-regional green manufacturing pattern involving multiple actors.

Fourth, from a long-term perspective, the institutional environment for green transformation should be improved, so as to promote a shift in the green development of manufacturing from policy-driven growth toward institution-driven and market-driven development. At present, the improvement in green total factor productivity in Yibin's manufacturing industry has benefited to a large extent from technological upgrading and scale expansion. However, to

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achieve greener growth of higher quality and greater stability in the future, continued efforts are still needed in institutional supply and market mechanisms. On the one hand, green access, green regulation, and green evaluation systems should be further improved to strengthen the coordinated role of environmental regulation and innovation incentives. On the other hand, green finance, green procurement, and carbon constraint mechanisms should be improved to enhance firms' initiative and continuity in green transformation, thereby providing a stronger institutional foundation for the green and high-quality development of manufacturing.

Overall, the improvement in green total factor productivity in Yibin's manufacturing industry has shown strong technology-driven and scale-driven characteristics, but the role of efficiency-driven growth still needs to be strengthened. Therefore, future policy should not focus only on expanding green investment and promoting technological upgrading. More attention should be paid to efficiency improvement, institutional optimization, and regional coordination, so as to move Yibin's manufacturing green transformation from "fast growth" toward "high-quality growth."

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