Boosting the Yellow River Basin's Green Efficiency through Sustainable Silk Production

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ABSTRACT This study analyzes the green economic efficiency (GEE) of the silk industry in China's Yellow River Basin using panel data from 2014 to 2024 across nine provinces. A resource–environment–economy evaluation framework integrating the super-efficiency SBM model and Tobit regression is employed to investigate regional performance and driving mechanisms. The results show that basin-wide GEE increased at an average annual rate of 2.7%, with technological progress contributing more substantially than technical efficiency improvement. Pronounced regional heterogeneity is observed, where downstream provinces achieve higher efficiency through intelligent manufacturing and cleaner production technologies, whereas upstream regions remain constrained by ecological vulnerability and insufficient environmental investment. Tobit regression further identifies technological innovation and environmental expenditure as significant positive determinants of GEE, while excessive industrial specialization negatively affects efficiency. The proposed zoned governance strategy provides differentiated pathways for coordinated ecological and industrial development. Beyond promoting sustainable transformation in the traditional silk industry, the established evaluation framework offers methodological insights for resource-efficient manufacturing systems that support environmentally sustainable infrastructure and intelligent industrial environments relevant to advanced electromagnetic engineering applications, including sensor-enabled monitoring and smart production networks.

INDEX TERMS green economic efficiency, sustainable silk production, intelligent manufacturing, electromagnetic sensing, resource-efficient systems

I. INTRODUCTION

THE Yellow River Basin, which spans nine provinces and regions, including Qinghai, Sichuan and Gansu, is an important ecological barrier and economic corridor in China that also serves multiple functions, such as soil and water conservation and energy supply [1]. As the core area of the Belt and Road Initiative (BRI), its ecological protection and high-quality development have been incorporated into the national strategy (The Outline of the Yellow River Basin Ecological Protection and High-Quality Development Plan, 2021). Meanwhile, the silk industry, the history of which can be traced back to the ancient Silk Road period, is a traditional pillar industry in the Yellow River Basin. Today, Nanyang, Henan, Jining, Shandong, and other provinces remain important bases for sericulture and silk processing in China [2]. Based on statistics, the total output value of the silk industry in the Yellow River Basin in 2020 exceeded 120 billion yuan, accounting for 28% of the total output value of the national silk industry. This industry employs over 1.5 million people and earns foreign exchange through exports that account for 35% of the national total.

However, this traditional industry is facing severe challenges of sustainable development [3]. For example, its production mode has long relied on high energy consumption equipment (e.g., unit energy consumption of traditional silk reeling machines reaches 0.8 tons of standard coal/10000 meters) and synthetic chemical dyes (utilization rate exceeding 70%), resulting in the consumption of water resources per unit output value of 50 m^3/10000 yuan, far exceeding the average level of the textile industry (30 m^3/10000 yuan). At the same time, the concentration of COD in the industrial wastewater generated from the printing and dyeing process is as high as 200 mg/L, while the total annual discharge of wastewater from the silk industry in the basin exceeds 120 million tons, accounting for about 12% of the industrial wastewater discharge in the Yellow River Basin.

Such extensive production has exacerbated existing problems, including the shortage of water resources (e.g., the runoff of the Yellow River decreased by 40% compared with the 20th century rate [4–6]) and soil heavy metal pollution [7] (e.g., the area of mulberry fields with excessive cadmium and lead content account for 15% of the total). At the same time, it is in direct conflict with the dual carbon goal of the government [8,9], especially because the carbon emission intensity of the silk industry has reached 2.3 tons of CO_2/10000 yuan, which is significantly higher than the average value of the textile industry (1.8 tons of CO_2/10000 yuan). In this context, green economic efficiency (GEE) [10,11] has become the core indicator to measure the effectiveness of silk industry transformation. GEE emphasizes minimizing resource consumption and environmental pollution to maximize economic output through technological innovation and resource allocation optimization [12,13]. For the Yellow River Basin, improving GEE in the silk industry has dual significance. On the one hand, ecological pressure can be alleviated by promoting water-saving reeling technology [14] (e.g., the automatic circulating water treatment system can reduce water consumption by 30%), the use of bio-based dyes to reduce COD emissions by more than 50%, and clean energy substitution (every 10% increase in the popularity of solar drying technology, the carbon emission intensity will decrease by 1.2%).

On the other hand, upgrading the industrial chain (e.g. , the proportion of high value-added silk products increased from 20% to 35%) can enhance international competitiveness [15,16] and facilitate the construction of the "green silk road." However, most of the existing studies focus on the whole industry or on energy-intensive industries (e.g., steel and chemical industry). There remains a significant gap in the research on the green efficiency of the silk industry, a traditional labor-intensive industry, along with a lack of consideration on the heterogeneity of regional resource endowment. For example, Qinghai Province has a single industrial structure, lacks diversified development, and shows insufficient development of high value-added industries. Thus, some enterprises in traditional high-carbon emission industries may be at a disadvantage in the competition [17]. Together, Shandong and Henan in the lower reaches account for 63.6% of the total economic output value of relevant provinces and regions in the Yellow River Basin. This level of industrial structure is low, and some regions still have extensive economic development mode and low energy utilization rates [18].

With the global emphasis on sustainable development, the green transformation of the silk industry in the Yellow River Basin has become an inevitable trend. Therefore, the current paper constructs a GEE evaluation system that covers the multidimensional resource environment economy of the silk industry and reveals the dynamic evolution of efficiency by combining the super-efficiency SBM model and Malmquist index. The Tobit model is also used to quantify the differential impacts of technological progress, environmental protection investment, and industrial structure on GEE. Based on the regional comparison, this paper proposes the transformation path of implementing policies in different regions, which provides theoretical support for solving the problem of the efficiency equity trade-off in the green transformation of traditional industries. The research results not only help promote the construction of ecological civilization and the coordinated development of industries in the Yellow River Basin but also provide a practical paradigm for the green upgrading of traditional industries in similar basins around the world.

II. LITERATURE REVIEW

A. THEORETICAL EVOLUTION OF GEE

According to Zhao, the so-called Silk Road not only promoted the exchange of commodities but also promoted the spread of textile technology, in which the textile technologies and products from Central Asia, West Asia, and Europe were absorbed and integrated by the East [19]. The Silk Road is not only a trade route but also a platform for the interaction of different cultures, languages, religions and ideas, thus promoting cultural exchanges between the East and the West [20]. While China's silk industry has had an important impact on foreign countries in terms of technological innovation and brand building, problems of environmental pollution and resource consumption during production have become increasingly prominent. For example, discarding sericin as a waste product in the silk industry has caused environmental pollution [21]. In this regard, GEE is an important indicator in evaluating the coordinated development of economic growth and environmental protection, which, in turn, are significantly affected by industrial structure, technological innovation, environmental regulation and other factors [22].

The concept of "green economic efficiency" originates from the school of ecological economics [23]. Subsequent scholars introduced data envelopment analysis (DEA) into efficiency measurement. For example, Renbian Mo introduced polar coordinate theory into the epsilon measure model (EBM), constructed the ray epsilon measure model (REBM), and used the DEA method to evaluate China's GEE [24]. Liu Fangmei argues that the traditional three-stage DEA model does not consider the function form and multicollinearity. Thus, the author proposed a new three-stage DEA model based on the stochastic semiparametric frontier and used the empirical analysis method to evaluate the efficiency of China's green economy [25]. Considering that the traditional DEA cannot sort and analyze the effective units, Shen Zhifeng improved the DEA model by using BP neural network and conducting in-depth research and analysis on the GEE evaluation method of resource-based cities [26]. Based on the DEA model, Qiang Sun comprehensively evaluated China's agricultural green ecological efficiency from 2002 to 2021, and then analyzed its efficiency characteristics from multiple perspectives [27]. In view of the limitations of the existing definition of "energy efficiency," the current study proposed the redefinition of energy efficiency under the framework of sustainable development and used the super-efficiency SBM–DEA model to evaluate the energy efficiency of 168 economies in the world from 2000 to 2017. Then, we conducted a detailed investigation of the spatiotemporal patterns and inequalities [28].

In the face of global warming, Xu Yebiao used the super-efficiency SBM model to accurately measure the carbon emission efficiency of the construction industry in each province, determine the influencing factors, and formulate reasonable emission reduction policies for the construction industry [29]. Gan Lu evaluated the tourism ecological security level of the urban agglomeration from 2011 to 2020 using the dynamic superefficiency network SBM (slow based measure) model, and discussed the driving factors of tourism production stage and tourism ecological protection stage by using the geographical detector [30]. However, current research has mainly focused on urban resources and other aspects; thus, there remains a gap in terms of specific research conducted on the silk industry in the Yellow River Basin [31].

B. STUDIES ON THE SUSTAINABLE DEVELOPMENT OF SILK INDUSTRY

China's traditional silk industry has a long history; thus, as an ancient traditional industry, there are some "bottleneck" factors restricting its development. Generally speaking, the plight of the development of traditional industries is mainly reflected in the rise of an emerging industry—the chemical industry. Over the years, several products that use chemical fibers and weaving and blending technologies grew rapidly, and the proportion of silk consumption decreased. The silk industry's development not only faces the general problems of traditional industries but also those that are unique to the industry, such as environmental pollution and high energy consumption [32]. Thus, research on the sustainable development of the silk industry has a more urgent practical significance. One aspect of the silk industry's sustainable development is the ecological direction that pursues ecological balance, resource reproduction, and sustainable utilization. All of these goals require the industry to achieve green transformation and follow the path of "green, environmental protection, ecology, energy conservation and emission reduction, and comprehensive development and utilization," in line with the concept of "sustainable development" [33].

The silk industry's green transformation involves sericulture, silk reeling, weaving, printing and dyeing, and end product manufacturing [34,35]. Based on the background of modern economic environment, Shen Li deeply analyzed the important impact and effective path of the digital transformation of Adlay silk on the high-quality development of Xinjiang's silk industry. Based on the results, the author revealed the mechanism and path of how digital transformation can significantly improve production efficiency, expand market coverage, enhance brand awareness, and stimulate the high-quality development of Xinjiang's silk industry [36]. Investigating the cooperative of professional silkworm farmers in Nanyang Village, Gula Town, Binyang County, Liyan Fei systematically analyzed the three silkworm ecological cycle planting and breeding modes and their corresponding benefits through field research and experimental demonstration, and promoted the ecological planting and breeding modes [37].

Some scholars have made contributions to sustainable textile processing by comparing the effectiveness of innovative heating methods used in natural and synthetic dyes [38]. For example, Huchun Mei studied the effects of live pupa reeling on the economic traits of silkworm hybrids and parents, providing theoretical support for the creation of new silkworm materials and the cultivation of new silkworm varieties [39]. C.B. Abla used a variety of plant dyes to conduct dyeing experiments and tie-dyed designs on silk. Through dyeing and color fastness experiments, he found that the combination of Sappan dye and alum mordant was suitable for clothing applications and had good dye uptake, which increased the realizable product pattern [40]. Liu Huaping discussed the use of water resources in silk enterprises, combined these with water-saving technologies at home and abroad, and proposed different ways and measures to save water based on the characteristics and problems of silk production [41].

Due to the wide distribution of the silk industry and the lack of unified market rules, management confusion and intellectual property infringement issues have also emerged. To promote the stable and high-quality development of the silk industry, Tu Ling put forward legal suggestions on this phenomenon [42]. Taking as an example Zhejiang Province, also known as the "Silk City," Fang Ping explored the current situation of the use of digital communication in the silk industry, based on the BRI's vision, he focused on the shortcomings in thinking, expression and connotation, and proposed a digital communication development model of "government education, industry guidance, market guidance and cultural guidance" from four dimensions [43]. Despite the publication of these studies, most of the existing works have focused on individual technological improvements and the lack of systematic evaluations of the whole industrial chain's efficiency [44–46]. Thus far, many have not yet considered the impact of regional resource endowment differences on the transformation path.

C. CURRENT RESEARCH LIMITATIONS AND INNOVATIONS OF THIS ARTICLE

The existing research on the GEE of the silk industry in the Yellow River Basin has significant limitations. First, the literature mostly focuses on the green transformation of macro industries or high-energy consuming industries (e.g., steel and chemical), with a serious lack of attention to labor-intensive traditional industries (e.g., silk) and systematic analyses of regional resource endowment heterogeneity. Second, existing evaluation methods often adopt a single perspective of technological improvement (e.g., water-saving processes or emission reduction equipment), neglecting the systematic evaluation of the entire industry chain's GEE. Finally, policy recommendations generally lack quantitative support for cost-effectiveness, making it difficult for the "one size fits all" governance plan to adapt to the diverse ecological and economic conditions within the watershed.

In response to the abovementioned shortcomings, the present article has achieved multidimensional innovation at the theoretical and methodological levels. On a theoretical level, this study breaks through the traditional one-dimensional perspective of research. Through the integration of Tobit regression, we analyzed the relationship between technological progress, environmental investments, industrial structure, environmental regulation intensity, dual carbon policy variables, and GEE, thereby revealing the deep constraints of different factors on green transformation. At the methodological level, the integration of microlevel data, such as intelligent silk reeling coverage and biological enzyme COD emission reduction intensity, fills the gap of traditional macro indicators (e.g., energy consumption per unit output value) in characterizing industry characteristics. At the same time, the introduction of multidimensional ecological constraints, such as vegetation coverage (NDVI) and water resource pressure (WSI) overcomes the limitations of relying on individual pollution indicators (e.g., excessive soil cadmium). At the practical level, by combining net present value (NPV) and investment payback period to evaluate the technical and economic feasibility, the above innovations can fill the theoretical gap in the research of green efficiency in the silk industry. At the same time, these innovations can provide a replicable evaluation paradigm and practical path for the green upgrading of traditional industries in similar watersheds around the world.

III. METHODS

A. RESEARCH METHOD

This paper used the super SBM model and Malmquist index model [47,48] in the DEA method to measure the GEE of the silk industry in the Yellow River Basin. At the same time, the Tobit model was used to empirically analyze the factors affecting the industry's GEE, thereby revealing the mechanism of each influencing factor on cocoon production efficiency [49,50].

B. SUPER-EFFICIENCY SBM MODEL

DEA is a nonparametric evaluation method used to evaluate the relative effectiveness of multiple production decision-making units (DMUs) with the same production nature, input, and output [51]. The super-efficiency SBM model (also known as the super SBM model) is an improved DEA method that is specially used to deal with the efficiency evaluation problems with unexpected outputs (e.g., pollution emissions) [52]. Compared with the traditional DEA model, the super SBM model can distinguish effective DMUs, consider unexpected output, and calculate the super-efficiency value [53]. For the kth DMU, the objective function of super SBM model is given by [54,55]:

$$\rho' = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^*}{z_i}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{n-1} \frac{s_r^*}{y_r} + \sum_{q=1}^{n} \frac{s_q^*}{z_q}\right)}. \quad (1)$$

The constraints are given by:

$$\sum_{j=1, j\neq i}^{n} \lambda_j x_{ij} \leq x_{ik} - s_i,\ \forall i, \quad (2)$$

$$\sum_{j=1, j\neq k}^{n} \lambda_j y_{jr} \geq y_{kr} + s_i',\ \forall r, \quad (3)$$

$$\sum_{j=1, j\neq k}^{n} \lambda_j z_{jq} = z_{kq} + s_q^*,\ \forall q, \quad (4)$$

$$\lambda_j \geq 0, \quad s_i \geq 0, \quad s_i^* \geq 0, \quad s_q^* \geq 0, \quad \forall j, i, r, q. \quad (5)$$

The symbol descriptions are presented below:

x_{ik}: input i of the kth DMU
y_{rk}: the r-th expected output of the kth DMU
z_{kq}: the q-th unexpected output of the kth DMU
s_i: input relaxation variable
s_i^*: expected output relaxation variable
s_q^*: undesired output relaxation variable
λ_j: weight vector
m: number of input indicators
n: number of decision making units
s_i: number of expected output indicators
s_q: number of unexpected output indicators

C. TOBIT MODEL

The Tobit model (truncated regression model) is a restricted dependent variable regression model that is applicable to the case of truncation or deletion of dependent variables [56]. In the study of GEE, the Tobit model is often used to deal with the truncation characteristics of efficiency values and estimate influencing factors. The basic form of the Tobit model is given by [57,58]:

$$y_i^* = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + \epsilon_i. \quad (6)$$

The observed values are given by:

$$y_i = \begin{cases} y_i^*, & \text{if } y_i^* > 0, \\ 0, & \text{if } y_i^* \leq 0. \end{cases} \quad (7)$$

The symbol descriptions are as follows:

y_i^*: potential dependent variable (unobservable)
y_i: actually observed dependent variable
$x_{i1}, x_{i2}, \ldots, x_{ik}$: argument
$\beta_0, \beta_1, \ldots, \beta_k$: regression coefficient
ϵ_i: error term, usually assuming normal distribution $\epsilon_i \sim N(0, \sigma^2)$

D. MODEL APPLICATION

This study followed the research paradigm of system science and used the two-stage econometric analysis method to deeply explore GEE and its influencing factors. In the first stage, a super SBM considering unexpected output was constructed based on the DEA framework. In the second stage, the restricted dependent variable model was used for attribution analysis. The specific methods are described below. The first step is to determine the input, the expected output, and the unexpected output indicators. The super SBM model is constructed to calculate the efficiency value of each DMU. The super SBM model is then used to calculate the GEE value. The Tobit model is constructed by taking the efficiency value as the dependent variable [59], and technological progress, environmental protection investment, and industrial structure as the independent variables. Next, we estimate the model parameters and analyze the impact of various factors on the efficiency of green economy [60,61].

E. DATA SOURCES

The data used in this study mainly come from the public data of the National Bureau of statistics, the China Silk Association, and other related enterprises. Other sources include the China Silk Yearbook (2014–2024) issued by the National Bureau of Statistics and the China Silk Association [62]; public annual reports of major silk enterprises in the Yellow River Basin (e.g., as Shandong Ruyi, Jiangsu Sunshine, etc.) [63,64]; and the statistical yearbooks of nine provinces throughout the Yellow River Basin (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong) [65].

IV. EMPIRICAL ANALYSIS RESULTS

A. MEASUREMENT OF GEE

Using the super SBM model and Malmquist index model in DEA, the GEE of the Yellow River Basin from 2014 to 2024 is dynamically calculated and then decomposed into technical efficiency change (effch) and technological progress change (tech).

B. INPUT–OUTPUT INDEX SYSTEM

When constructing the input–output index system of green technology in the silk industry, the input index is used to measure the allocation of resources, funds, manpower, and other aspects of the industry. It is also used to provide basic data for analyzing the development level of green technology. This paper uses four input indicators, and the change curve of input indicators (2014–2024) is shown in Figure 1.

Capital investment: This refers to the fixed asset investment in the silk industry (tens of millions of yuan), reflecting the capital investment intensity of the industry in green technology R&D, equipment transformation, environmental protection facilities construction, and so on.

Labor input: This refers to the number of employees in the silk industry (person), reflecting the industry's talent allocation in the field of green technology, including R&D personnel and environmental management personnel.

Energy input: This refers to the total energy consumption of the silk industry (the first ton of standard coal), thereby reflecting the industry's investment in energy consumption, including the consumption of electricity, natural gas, steam, and other forms of energy.

Equipment input: This refers to the total amount of equipment (10000 sets), thus reflecting the industry's investments in green technology and equipment, including energy-saving equipment, environmental protection equipment, and resource recycling equipment.

As shown in Figure 1, the capital investment has increased year by year, reflecting the industry's emphasis on green technology development. Furthermore, the total number of technical personnel invested in human resources has increased year by year, reflecting the industry's demand for green technical personnel. The investment in energy-saving, environmental protection, and resource recycling equipment has also increased year by year, reflecting improvements in the level of green technology and equipment in the industry. Finally, while energy consumption is increasing year by year, energy efficiency is also improving through technological progress.

Two output indicators are as follows:

Expected output: This refers to the added value of silk industry (100 million yuan). Specifically, it refers to the economic value created by the silk industry in a certain period of time, and the net output after deducting intermediate input, which is then used to measure the economic contribution and growth quality of the industry.

The unexpected output is the COD emission per unit output value (kg/10000 yuan), which reflects the water pollution intensity of production activities. In this case, the lower the value, the better the environmental performance. The SO_2 emission per unit output value (kg/10000 yuan) that measures the intensity of air pollution in the production process is closely related to the energy structure (e.g., proportion of coal). By quantifying resource consumption, economic output and environmental pollution, we have been able to define the input–output index system of GEE evaluation, which, in turn, provides standardized data basis for model calculation and serves as the core basis for studying the green transformation effect of the silk industry in the Yellow River Basin.

C. RESULT ANALYSIS

(1) Analysis of green technical indicators

Through statistics, we obtained the change chart of green technology indicators in the Yellow River Basin from 2014 to 2024. As shown in Figure 2, from 2014 to 2024, the energy utilization efficiency decreased year by year, reflecting the significant improvement of energy utilization efficiency in the silk industry through technological upgrading and

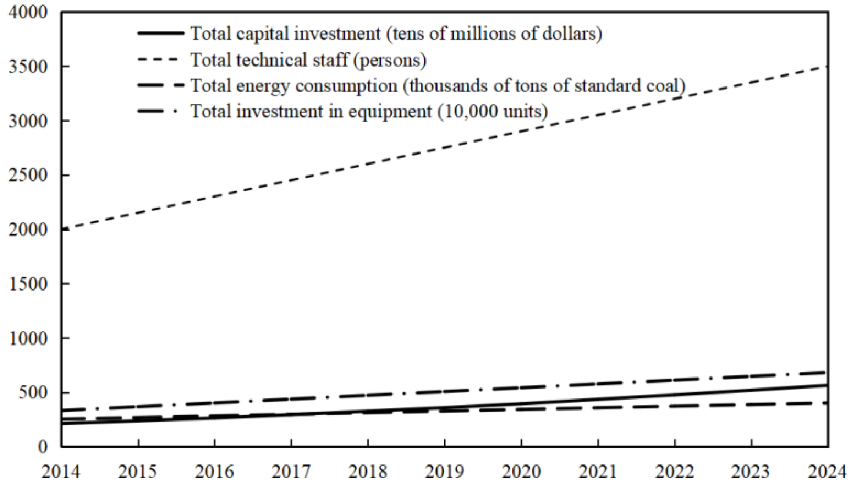

FIGURE 1. Input index (2014–2024) change curve

equipment transformation. Due to the importance of water resource management, the water resource recycling rate has also increased year by year, mainly because of the improvements of water resource utilization rate through such measures as reclaimed water reuse and water-saving technology. Furthermore, the comprehensive utilization rate of waste has increased year by year, indicating that the silk industry has made progress in waste treatment, such as waste silk and sludge after wastewater treatment, which have been more effectively utilized as resources. Waste water discharge per unit output value and waste gas discharge per unit output value also decreased year by year, indicating that the silk industry has achieved good results in waste water treatment and waste gas treatment.

(2) Analysis of GEE and environmental protection input and output

The super SBM model is used to calculate the GEE of the silk industry in the Yellow River Basin from 2014 to 2024, with the results shown in Figure 3. The input–output curve of environmental protection is shown in Figure 4. The results reveal that from 2014 to 2024, the average GEE of the Yellow River Basin increased from 0.62 to 0.81, with an average annual growth rate of 2.7%. In 2020, GEE significantly increased (0.72 to 0.81) due to the policy of "Yellow River Basin Ecological Protection and High-Quality Development Plan," which promoted technological upgrading in downstream provinces. Investments in environmental protection per unit output value also increased from 25 yuan to 75 yuan/10000 yuan, with an average annual growth rate of 18.2%. Furthermore, the COD emission per unit output value decreased from 15 to 7.5 kg/10000 yuan, with an average annual reduction rate of 4.5%, and SO_2 emission per unit output value decreased from 10 to 4.1 kg/10000 yuan, with an average annual reduction rate of 5.4%.

The average efficiency of the upstream regions (Qinghai, Sichuan, Gansu, Ningxia, and Inner Mongolia) increased from 0.58 in 2015 to 0.72 in 2025, with an average annual growth rate of 2.3%. The main constraints are the high investments in environmental protection per unit output value and the slow improvement of technical efficiency. Meanwhile, the average efficiency of the middle reaches (Shanxi and Shaanxi) increased from 0.64 to 0.83, with an average annual growth rate of 2.9%. The average efficiency of the downstream areas (Henan and Shandong) increased from 0.68 to 0.87, with an average annual growth rate of 2.8%. Its advantages are mainly due to the large-scale applications of green technology, the 50% decrease in COD emission per unit output value, and the 59% decrease in the SO_2 emission per unit output value.

(3) Analysis of technological progress contribution

The contribution of technological progress is divided into two aspects: technological progress index and technical efficiency index. The change curves of technological progress index (techch) and technical efficiency index (effch) in the Yellow River Basin from 2014 to 2024 are shown in Figures 5 and 6, respectively. The results reveal that within the same decade, the average annual growth rates of technical progress index and technical efficiency index in the Yellow River Basin are 3.3% and 1.2%, respectively. Furthermore, the upstream region is constrained by ecological fragility and insufficient R&D investments. Weak patent protection in the upstream leads to the prevalence of "reverse engineering" among enterprises, which then suppresses investments in original technology and results in slow technological progress.

Additionally, the average annual growth rate of the technological progress index is about 3.0%, and the improvement of technological efficiency is slow. The average annual growth rate of technological efficiency is 1.0%, and the resource utilization efficiency is relatively low. At the same time, the technological progress and technical efficiency in the middle reaches are growing faster than those in the middle reaches. The average annual growth

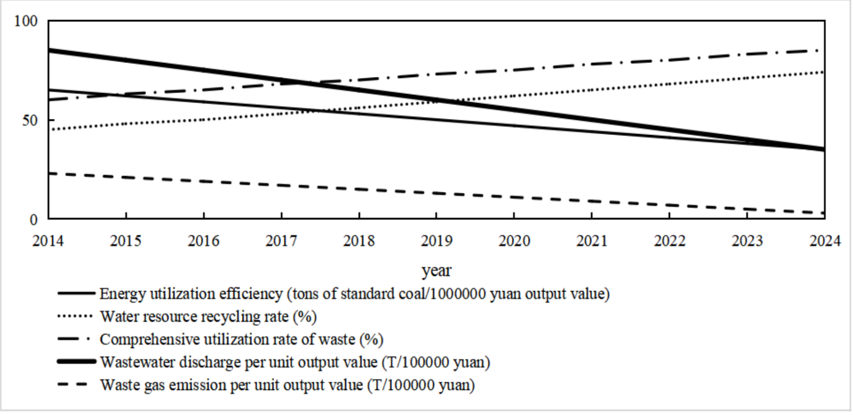

FIGURE 2. Change curves of green technology indicators in the Yellow River Basin (2014–2024)

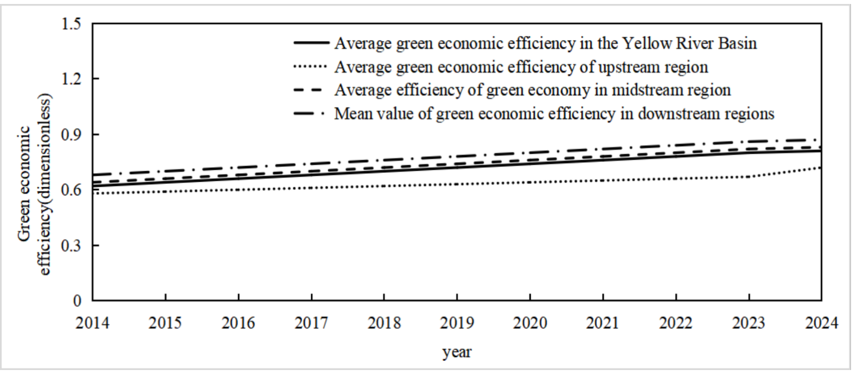

FIGURE 3. Change curves of the GEE in the Yellow River Basin (2014–2024)

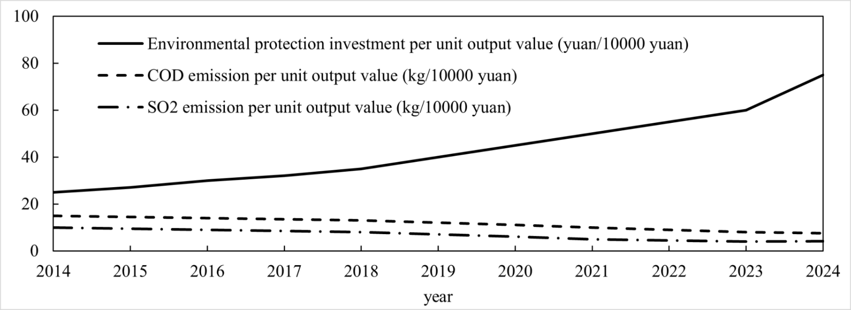

FIGURE 4. Change curves of the input and output of environmental protection in the Yellow River Basin (2014–2024)

rates of the technological progress and technical efficiency indexes are approximately 3.4% and 1.2%, respectively. The downstream regions rely on the economic foundation and industrial upgrading, resulting in technological progress. The average annual growth rates of the technical progress and technical efficiency indexes are 3.6% and 1.4%, respectively.

On the whole, investments in environmental protection in the Yellow River Basin continued to increase (average annual growth rate of about 18.2%), along with strengthened policy efforts. Apart from a 4.5% average annual decrease of COD emission, the sewage treatment and industrial upgrading of the surface silk industry have also achieved remarkable results. The annual average SO_2 emissions decreased by 5.4%, and the results of energy structure optimization and clean technology promotion were outstanding. Meanwhile, the upstream area is limited by ecology, and the technical efficiency and environmental protection investments are low. Relying on energy advantages, technological progress and environmental protection investment in the midstream region have increased simultaneously. Finally, the downstream region has a strong economic foundation, leading technology, and the optimal environmental protection input–output ratio.

D. TOBIT MODEL REGRESSION RESULTS

Taking nine provinces in the Yellow River Basin (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong) as the research objects, we con-

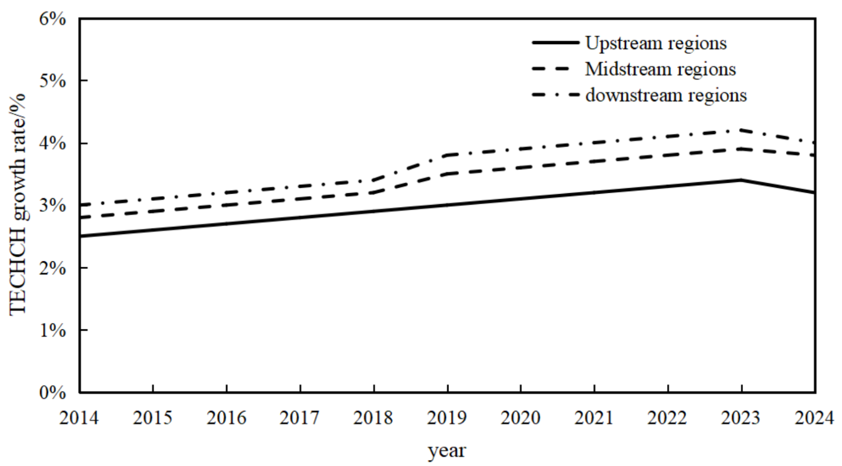

FIGURE 5. Change curves of technological progress index (techch) (2014–2024) in the Yellow River Basin

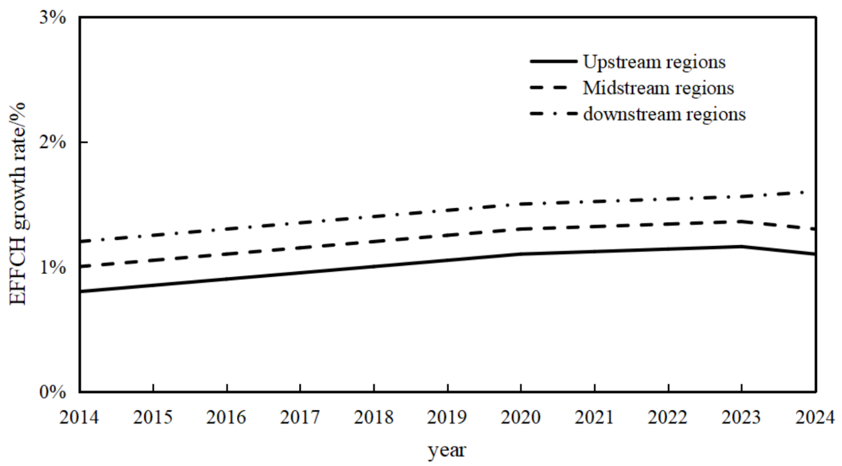

FIGURE 6. Variation curves of the technical efficiency index (effch) of the Yellow River Basin (2014–2024)

structed the model featuring GEE as the dependent variable. This is measured by the super SBM model, with a range of 0–1 in which the higher the value, the higher the efficiency [66]. The independent variables are discussed individually below. Technological progress (TP) refers to the ability of the silk industry to improve production efficiency and environmental friendliness through technological innovation, including process improvement, equipment upgrading, and new material R&D. It is comprehensively measured by the number of patent applications in the silk industry, investments in technological transformation and other indicators. The mechanism of "environmental regulation forces innovation" in Porter hypothesis is the core driving force of green transformation.

Environmental protection investment (EPI) refers to the capital investment of silk enterprises in pollution control, resource recycling and cleaner production. This is measured by the investment in environmental protection equipment and pollution control costs of silk enterprises and directly reflects the degree of internalization of enterprises' environmental externalities, which is the material basis for improving green efficiency.

Industrial structure (IS) reflects the proportion of silk industry in the regional economy and its impact on resource allocation. It is measured by the proportion of the added value of the silk industry in GDP. Furthermore, it reflects the impact of industrial structure on the efficiency of green economy, reveals the risk of industrial concentration and resource mismatch, and provides the basis for structural optimization aimed at better policymaking. The environmental regulation intensity (ERI) adopts the provincial-level "unit output value pollution fee collection amount" (yuan/10000 yuan GDP) as the core proxy variable, thus reflecting the economic constraints of local governments on corporate pollution behavior.

The dual carbon policy (DC) variable refers to China's goal of peaking carbon emissions (before 2030) and achieving carbon neutrality (before 2060), aimed at promoting low-carbon transformation of industries through policy guidance and market mechanisms. In this article, DC is reflected through the following indicators: dummy variables (1 for

2021 and beyond, 0 for before) corresponding to the implementation of the “Action Plan for Peak Carbon Emissions before 2030,” and the carbon quota trading volume (10000 tons of CO_2/year), which reflects the activity of the regional carbon market and the pressure on enterprises to reduce emissions.

As stated previously, regression analysis was conducted, with GEE as the dependent variable and the TP, EPI, IS, ERI, and DC as independent variables. The results showed that:

$$GEE_{it} = 0.55 + 0.32 \cdot TP_{it} + 0.25 \cdot EPI_{it} - 0.12 \cdot IS_{it} + 0.15 \cdot ERI_{it} + 0.1 \cdot DC_{it} + \epsilon_{it}. \quad (8)$$

The regression coefficient of TP is 0.32 ($p<0.01$), indicating that the GEE increased by 0.32% for every 1% increase in technological progress. This result is highly consistent with the theory of Porter hypothesis, which states that environmental regulation not only reduces pollution emissions but also improves resource utilization efficiency by forcing enterprises’ technological innovation. For example, Shandong Province has achieved a 1.2% reduction in carbon emission intensity/unit output value and a leap in GEE from 0.78 in 2014 to 0.88 in 2024 by promoting intelligent silk reeling technology (increasing the coverage of intelligent silk reeling equipment from 20% in 2014 to 85% in 2024) and biological enzyme dyeing and finishing processes (reducing COD emission intensity from 15 to 6 kg/10000 yuan and reducing COD by 60%). Such technological breakthroughs not only reduce dependence on traditional energy but also minimizes the waste of water resources through process optimization, thus reflecting the synergistic effect of promoting environmental protection through technological transformation.

The regression coefficient of EPI is 0.25 ($p < 0.05$), indicating that the GEE increased by 0.25% for every 1% increase in environmental protection investment. This result shows that the “real money and silver” investment in environmental governance has a direct contribution to efficiency improvement. Taking Henan Province as an example, its annual investment in environmental protection equipment has increased from 200 million yuan in 2010 to 800 million yuan in 2020, and these funds are mainly used for the construction of closed-loop water treatment systems (wastewater reuse rate $\geq$80%) and waste gas desulfurization devices (SO_2 emission reduction rate of 50%), reducing the COD emission per unit output value from 15 to 7.5 kg/10000 yuan. However, regional heterogeneity is observed in the marginal benefit of environmental protection investment. In particular, the intensity of environmental protection investment in Qinghai, Gansu, and other places in the upper reaches is insufficient (<45 yuan/10000 yuan), but every 10-yuan increase in investment can increase GEE by 0.3%, which is significantly higher than that in the lower reaches (0.2%). Therefore, the policy should be inclined to the upstream, and its capital and technology weakness must be alleviated through an ecological compensation fund and cross-regional technology transfer.

The regression coefficient of IS is -0.12 ($p < 0.1$), indicating that unreasonable industrial structures (e.g., excessive reliance on silk industry) will inhibit the improvement of GEE. This phenomenon is particularly prominent in downstream Shandong and Henan (IS > 15%). Its resources are excessively concentrated in silk processing, squeezing the development space of green industries, such as new energy and eco-tourism. For example, the concentration of the silk industry in Shandong Province is as high as 18.1%, resulting in the mismatch of land, labor, and other factors, which, in turn, limits the cultivation of emerging industries, such as photovoltaic agriculture and cultural tourism integration.

The ERI coefficient is significantly positive, indicating that strict environmental regulations can enhance GEE through the “forcing effect.” As for the DC, its significant positive coefficient indicates that the Chinese government’s dual carbon policy has institutional dividends for green transformation.

TP and EPI are in direct proportion to GEE. This means that TP and EPI will promote the improvement of GEE. IS is inversely proportional to GEE, indicating that unreasonable industrial structures (e.g., excessive reliance on the silk industry) will inhibit the improvement of GEE.

The characteristics of the silk industry in each province of the Yellow River Basin (average value from 2014 to 2024) are shown in Table 1. The EPI in Ningxia, Gansu, and other upstream provinces is low (35–45 yuan/10000 yuan), but there is significant room for efficiency improvement (GEE increased from 0.68 to 0.75), indicating that the marginal efficiency of EPI is high. For the upstream region, the ecological compensation mechanism can guide the upstream region to increase environmental protection investments and strengthen the diffusion of pollution control technology in the middle and downstream regions. The IS of Shanxi, Shaanxi, and other midstream provinces is reasonable (11.7%–12.3%), and the GEE has improved significantly (GEE reached 0.79–0.82), indicating that moderately reducing the proportion of the silk industry and extending the industrial chain (e.g., developing silk culture tourism) can improve efficiency. The upstream regions can promote the integration of the silk industry, cultural creativity, and ecological agriculture, as well as build a “Silk+” industrial ecosystem.

The TP of Shandong, Henan, and other downstream provinces is relatively high (2.7%–3.0%), and the GEE range is 0.85–0.88, thus verifying the leading role of technological progress in improving efficiency. For downstream provinces, we can increase R&D investments in the silk industry; promote low-carbon technologies, such as intelligent silk reeling and biological enzyme dyeing and finishing; and improve total productivity.

TABLE 1. Silk industry characteristics of provinces in the Yellow River Basin (average value from 2014 to 2024)

Province	GEE	TP (%)	EPI (yuan/10000 yuan)	IS (%)	ERI (yuan/10000 yuan)	DC (virtual variable/carbon quota in 10000 tons)
Qinghai	0.68	1.2	35	8.5	28	0.5
Gansu	0.71	1.5	40	10.2	32	0.6
Ningxia	0.75	1.8	45	9.8	38	0.7
Shaanxi	0.79	2.1	50	12.3	45	1.2
Shanxi	0.82	2.4	55	11.7	50	1.5
Henan	0.85	2.7	60	15.4	65	2.0
Shandong	0.88	3	65	18.1	75	2.8

V. CONCLUSIONS AND SUGGESTIONS

A. CONCLUSIONS

1. Dynamic improvement of GEE From 2014 to 2024, the average GEE of the silk industry in the Yellow River Basin increased from 0.62 to 0.81, with an average annual growth rate of 2.7%. Among these, the contribution rate of technological progress (3.3%) is significantly higher than that of technical efficiency (1.2%), indicating that technological innovation is the core driving force to improve efficiency. This finding verifies the applicability of the Porter hypothesis in the green transformation of traditional industries.

2. Significant regional heterogeneity

Downstream (Shandong and Henan): Here, GEE reached 0.85–0.88, with high technology intensity (patent applications account for more than 40%). However, high industrial concentration (silk industry account for over 15% of the GDP) led to resource mismatch.

In the middle reaches (Shanxi and Shaanxi): GEE reached 0.79–0.82, relying on the cascade utilization of coal and electricity waste heat (thermal efficiency increased by 25%) to achieve energy substitution. However, the added value of the industrial chain is low (the value-added rate of silk culture and tourism is only 15%).

Upstream (Qinghai and Gansu): GEE only reached 0.68-0.75, limited by insufficient investment in environmental protection (<45 yuan/10000 yuan) and ecological vulnerability, as evidenced by the following: the cadmium content in Sangtian soil is 1.2 mg/kg; NDVI and WSI in Qinghai are 0.41 and 0.65, respectively; and NDVI and WSI in Gansu are 0.22 and 1.5, respectively.

Key influencing factors: The Tobit model shows that technological progress (β = 0.32) and environmental protection investment (β=0.25) have a significantly positively effect on GEE, while the simplification of industrial structure (β=-0.12) inhibits the improvement of efficiency. These findings verify the applicability of the Porter hypothesis in traditional industries.

B. SUGGESTIONS FOR ZONING DEVELOPMENT

(1) Downstream: Technology integration and industrial chain upgrading

R&D of low-carbon technology: Efforts should be done to promote intelligent silk reeling [67] (energy consumption $\leq$0.5 tons of standard coal/10000 meters) and biological enzyme dyeing and finishing technology [68] (COD reduction rate $\geq$60%), as well as to reduce the carbon emission intensity per unit output value to 1.5 tons of CO_2/10000 yuan by 2030.

The Ozone advanced oxidation+nanofiltration membrane two-stage wastewater treatment process (GB/t 31962-2025) must be adopted to achieve $\geq$80% wastewater reuse rate and $\leq$30 mg/L effluent COD, meeting the class IA standard of the discharge standard of water pollutants for textile dyeing and finishing industry (GB 4287-2012). After the process investment, the NPV and investment payback period should be 43.25 million yuan and 2.15 years, respectively.

High added value transformation: To achieve this, stakeholders must develop silk materials with special functions, such as silk products with antibacterial and UV resistance functions, and exert efforts to reduce industrial concentration.

(2) Middle reaches: Resource coupling and industrial integration

Collaborative utilization of energy: A coal and electricity waste heat silk drying cogeneration system (thermal efficiency $\geq$85%) must be built to replace gas-fired boilers (SO_2 30% reduction). After the process investment, the NPV should be 26.4 million yuan, and the investment payback period would be 1.79 years.

Solid waste recycling: Coal gangue must be used to prepare porous adsorbent (Pb^{2+} removal rate $\geq$95%), and the comprehensive utilization rate of solid waste must be increased to 75%.

Digitalization of "Silk+culture and tourism" [69]: AR/VR interactive platform must be developed, the conversion rate of tourists must be improved, and the integration of intangible cultural heritage technology and ecological manor must be promoted, thereby enabling the value-added of the industrial chain [70].

(3) Upstream: Ecological compensation and green transfer

Cross-regional coordination mechanism: The water quality and quantity compensation model [71] must be implemented to ensure that the upstream environmental protection investment intensity reaches 65 yuan/10000 yuan;

Layout of the "enclave economy": The upstream must focus on ecological sericulture bases (output $\geq$ 1.5 tons/hectare), and the highly polluting printing and dyeing links must be transferred to the downstream industrial parks, thus supporting carbon quota trading.

Finally, the mulberry field soil must be restored to reduce the cadmium content in mulberry field soil from 1.2 mg/kg to 0.8 mg/kg by 2030 (GB 15618-2018).

AUTHOR CONTRIBUTIONS

All work in this study was independently completed by Meng Zhang.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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