A Review of Research on the Influence Relationship Between Technological Innovation, Industrial Structure Optimization, and Water-use Efficiency

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ABSTRACT

This article systematically reviews the research literature on the relationship between technological innovation, industrial structure optimization, and water-use efficiency in China and foreign countries. Firstly, the authors summarizes the current research status of technological innovation, industrial structure optimization, and water-use efficiency evaluation index; Secondly, clarify the current research status of the relationship between technological innovation, industrial structure optimization, and water use efficiency; Then, summarize the current research status of technological innovation, industrial structure optimization, and water use efficiency evaluation methods. Finally, based on an in-depth analysis of the current research status, the authors conduct a review on the relationship between technological innovation, industrial structure optimization, and water-use efficiency.

Keywords: *Technological innovation, Industrial structure optimization, Water-use efficiency, Influence relationship.*

1. INTRODUCTION

Since the 21st century, the international community has continuously paid attention to how to use technological progress to restructure the global industrial chain to achieve steady and healthy economic development, and how to rely on technological innovation to improve resource utilization efficiency to achieve sustainable resource utilization. Among them, the restructuring of the industrial chain urgently requires optimizing the industrial structure, and improving resource utilization efficiency requires a focus on improving water resource utilization efficiency. The 2015 "Paris Climate Agreement" clearly emphasizes the important role of technological innovation in water resource management and utilization. The United Nations "Sustainable Development Goal 2030" prioritizes water resource management and emphasizes the crucial role of technological innovation in addressing water resource issues. The 2016 "Fourth Industrial Revolution Report", based on global economic and social development, clarifies the importance of the integration and innovation of emerging technologies in optimizing industrial structure. At the same time, the academic community continues to deepen research on scientific and technological innovation and industrial structure optimization, as well as the coordinated development of scientific and technological innovation and water resource utilization, and has constructed various distinctive evaluation index systems and methods. Therefore, deepening the research on the relationship between technological innovation, industrial structure optimization, and water-use efficiency is of great significance for promoting high-quality regional development, solving the obstacles to regional industrial upgrading and improving water resource utilization efficiency.

2. CURRENT STATUS OF RESEARCH ON TECHNOLOGICAL INNOVATION, INDUSTRIAL STRUCTURE OPTIMIZATION, AND WATER-USE EFFICIENCY EVALUATION INDEX

2.1 Evaluation Index of Technological Innovation Level

For the selection of indicators for technological innovation level, scholars often evaluate technological innovation capabilities from different dimensions based on their respective research focuses. Ludovico Alcorta et al. (1998) [1] studied and evaluated the innovation system performance of Latin American and Caribbean countries from the aspects of technological infrastructure, innovation organization interaction, innovation investment, human capital system, public policy, etc.; Hashimoto et al. (2008) [2] used R&D research and development expenditure as an indicator of technological innovation investment, and used patent numbers, sales revenue, and profits as indicators of technological innovation output. They constructed an input-output indicator system to measure the level of technological innovation in Japanese pharmaceutical enterprises; Mayor et al. (2012) [3] constructed an indicator system from three dimensions: innovation foundation (including infrastructure and human resources), innovation support (including government funding and enterprise support), and innovation output to evaluate the level of technological innovation in African countries; Christoph et al. (2018) [4] selected product innovators, service innovators, process innovators, new company product innovators, new product innovators entering the market, the revenue share of new company innovative products, the revenue share of newly launched innovative products, and the number of patent applications at the enterprise level to construct an indicator system for measuring regional innovation capability; Fan Hua et al. (2012) [5] measured the intensity of scientific and technological innovation investment using the relative indicators of scientific and technological personnel investment and funding investment, and measured the output of scientific and technological innovation using relevant indicators that characterize scientific and technological innovation achievements; Wu Fenghua et al. (2013) [6] measured regional independent innovation capability by the number of patent applications authorized and the number of new product development projects; Ye Tanglin et al. (2019) [7] selected appropriate indicators from three dimensions: factor input, market output, and environmental support to reflect the level of scientific and technological innovation; Huajian et al. (2019) [8] measured the level of scientific and technological innovation from five aspects: research and development investment, talent reserves, scientific and technological achievements, achievement transformation, and technology diffusion; Jia Hongwen et al. (2021) [9] selected a total of 10 indicators from three dimensions of innovation input, output, and innovation environment to construct a scientific and technological innovation indicator system; Cheng Pengfei et al. (2021) [10] selected adaptive indicators from three dimensions of innovation input, output, and environment to construct a regional innovation indicator system; Lu Zhaoyan et al. (2022) [11] selected a total of 26 indicators from three dimensions: industrial factors, resource factors, and environmental factors to construct an evaluation system for the potential of scientific and technological innovation.

2.2 Evaluation Index of Industrial Structure Optimization Level

For the selection of indicators for industrial structure optimization level, some scholars use a single dimension index to measure the level of industrial structure optimization, while most scholars construct a comprehensive evaluation index system from different dimensions based on the characteristics of industrial optimization to calculate the level of industrial structure optimization. On the one hand, scholars, based on past research experience, often construct formulas to calculate the industrial structure upgrading index, or use the industrial output ratio to measure the degree of industrial structure optimization. As Wu et al. (2021) [12] used the three-dimensional vector angle formula to calculate the industrial structure upgrading index covering the primary, secondary, and tertiary industries as well as high-tech industries; Pei et al. (2022) [13] used the ratio of the output value of the tertiary industry to the output value of the secondary industry to measure the degree of industrial structure optimization; Wu Fenghua et al. (2013) [6] measured the level of industrial upgrading by the proportion of regional secondary industry added value to GDP and the proportion of tertiary industry added value to GDP;

Zhang Zizhen et al. (2020) [14] used two indicators, the proportion of the added value of the tertiary industry to GDP and the ratio of the added value of the tertiary industry to the added value of the secondary industry, to characterize the level of industrial structure adjustment; Jia Hongwen et al. (2021) [9] constructed an industrial structure upgrading index covering the primary, secondary, and tertiary industries to characterize the level of industrial structure optimization.

On the other hand, some scholars have deeply grasped the connotation of industrial structure optimization and divided it into different dimensions to comprehensively evaluate the level of industrial structure optimization. As Wang et al. (2016) [15] decomposed industrial structure optimization into four parts: output value structure, employment structure, trade structure, and efficiency structure, to evaluate the level of comprehensive industrial structure optimization; Han et al. (2023) [16] used an improved Theil index to measure the level of industrial structure rationalization, and calculated the level of industrial structure advancement using a three-dimensional vector angle formula covering the primary, secondary, and tertiary industries; Ye Tanglin et al. (2019) [7] selected appropriate indicators from the perspectives of height and rationalization to reflect the level of industrial structure optimization; Cheng Pengfei et al. (2021) [10] selected adaptive indicators from three dimensions: efficiency, height, and rationalization of industrial structure to construct an indicator system for optimizing industrial structure; Wang Wenbin et al. (2020) [17] used the Theil index to calculate the degree of industrial rationalization, and used the ratio of the output value of the tertiary industry to the output value of the secondary industry to calculate the degree of industrial upgrading.

2.3 Evaluation Index of Water-use Efficiency

Scholars often construct a water-use efficiency evaluation index system based on input-output perspectives, mainly selecting input indicators from three aspects: water resource utilization, asset investment, and labor population, and using GDP output value as a key indicator to measure output efficiency. In addition, considering the water demand of industries, scholars often choose agriculture and industry for water-use efficiency evaluation. A small number of scholars conduct ecological water-use efficiency evaluation based on the characteristics of the research region and combined with international issues of sustainable development.

For the selection of agricultural water-use efficiency evaluation index, Yilmaz et al. (2009) [18] will select agricultural water supply and irrigation area as input indicators and agricultural gross output value as output indicators to calculate the agricultural irrigation water use efficiency of Türkiye's Buyuk Mendere basin; Manjunatha et al. (2011) [19] used agricultural water consumption, irrigation area, labor input, machine power, and fertilization as input indicators, and agricultural total output value as output indicator to calculate the agricultural irrigation water-use efficiency of groundwater in India; Zhao et al. (2022) [20] used agricultural water consumption, primary industry employment population, and grain sowing area as input indicators, and grain production as output indicators to calculate and evaluate the agricultural water-use efficiency in urban areas in the middle and lower reaches of the Yellow River; Zhu Lijuan et al. (2022) [21] used irrigation water consumption, crop sowing area, effective irrigation area, amount of agricultural fertilizer application, total power of agricultural machinery, and employment in the primary industry as input indicators, and agricultural output value as output indicators to calculate the water-use efficiency of agricultural irrigation in Chinese provinces.

For the selection of industrial water efficiency evaluation indicators, Zhao et al. (2022) [20] calculated the industrial water-use efficiency in the middle and lower reaches of the Yellow River by taking industrial water consumption, secondary industry employment population and fixed assets investment as input indicators and domestic GDP in the secondary industry as output indicators; Liu et al. (2020) [22] divided the input index system into two dimensions: input related to water resources and input unrelated to water resources, divided the output index system into two aspects: expected output and unexpected output, and selected appropriate indicators to measure the industrial water-use efficiency in Chinese mainland; Shen Manhong et al. (2015) [23] selected industrial fresh water intake as the input indicator and industrial total output value as the output indicator to improve the accuracy and suitability of the indicator system, in order to better measure industrial water-use efficiency; Zheng Le et al. (2020) [24] improved the general indicators for water use efficiency research by selecting fixed asset net value as a representative of capital investment to accurately evaluate the industrial water-use efficiency in Ningxia, in order to more accurately reflect capital consumption.

Regarding the selection of evaluation indicators for ecological water-use efficiency, Tupper et al. (2013) [25] selected labor cost, capital cost, and operating cost as input indicators, and water production and sewage treatment volume as output indicators to calculate the water use efficiency of Brazilian water companies; Liu et al. (2013) [26] selected three input indicators based on water consumption, capital investment, and labor, and considered ecological and environmental benefits. They selected 11 output indicators from five aspects: basic water engineering capabilities, soil and water conservation management, water pollution control, ecological environment, and economic benefits, to comprehensively measure the ecological efficiency of China's water system; Liu Yu et al. (2019) [27] considered the ecological benefits of water resources in Hubei Province and added indicators such as ecological water consumption, total investment in water conservancy funds this year, and small watershed soil erosion control area to the design of basic input indicators, constructing an ecological water-use efficiency evaluation index system.

3. CURRENT RESEARCH STATUS ON THE RELATIONSHIP BETWEEN TECHNOLOGICAL INNOVATION, INDUSTRIAL STRUCTURE OPTIMIZATION, AND WATER-USE EFFICIENCY

3.1 The Relationship Between Technological Innovation and Industrial Structure Optimization

Regarding the research on the relationship between technological innovation and industrial structure optimization, on the one hand, most scholars believe that technological innovation has significantly promoted the optimization and upgrading of regional industrial structure. Romer (1990) [28] pointed out, technological innovation can serve as one of the important driving forces for promoting industrial structure optimization; Nahm (2014) [29] found that technological innovation can serve as an effective means of industrial upgrading and enhancing national competitiveness; Wu et al. (2021) [12] pointed out that the optimization of regional industrial structure to a certain extent benefits from the promoting effect of technological innovation on economic growth; Ernst (2010) [30] studied the IT industry and found that the construction of production innovation networks can help reduce the cost of industrial upgrading; Kong Dandan et al. (2021) [31] found that the impact of technological innovation on industrial structure optimization shows a positive effect in the short term; Zhou Shulian et al. (2001) [32] found that one of the key factors in optimizing and adjusting industrial structure is that technological innovation promotes the improvement of labor productivity; Zhang Yinyin et al. (2013) [33] found that the transformation and upgrading of traditional industries cannot be achieved without the effective integration of new and industrial chains; Lu Yuanquan et al. (2022) [34] proposed that technological innovation can change the market demand structure, promote the flow of production factors from traditional industries and sectors to emerging industries and sectors, and adjust and optimize the industrial structure; Sun Yong et al. (2022) [35] found that digital technological innovation can promote digital industrialization and industrial digitization, thereby achieving industrial structure optimization and upgrading.

On the other hand, some scholars believe that the optimization and upgrading of regional industrial structure will promote technological innovation in the opposite direction, and there is a two-way interactive relationship between the two. Azadegan et al. (2011) [36] used 352 manufacturing enterprises as samples to explore the impact of industrial upgrading on innovation performance. The study found that the progress brought about by industrial upgrading can significantly promote enterprise innovation; Li et al. (2018) [37] used a systematic GMM model to examine the interaction between technological progress and industrial structure transformation, and verified the theory of mutual promotion between industrial structure transformation and technological progress in economics; Zhou Shulian et al. (2001) [32] proposed that industrial structure adjustment will affect market demand, thereby driving the pace of technological innovation; Zhao Qing (2018) [38] used the SBM model to calculate inter provincial technological efficiency and constructed a dynamic spatial econometric model to study and verify that industrial structure optimization and upgrading can significantly improve technological innovation efficiency; Li Zheng et al. (2017) [39] constructed a system of simultaneous equations, using economic growth, technological innovation level, and industrial structure upgrading as endogenous variables. Through empirical research, they verified the interactive relationship between technological innovation and industrial upgrading, which promotes and relies on each other; Wang Huiyan et al. (2019) [40] found through constructing a contribution rate model that technological innovation is the core driving force for industrial structure optimization, while also verifying that industrial structure optimization significantly drives technological innovation, and there is a positive two-way interaction between the two.

3.2 The Influence Relationship Between Technological Innovation and Water-use Efficiency

Based on the international strategy of innovative development and the global issue of water scarcity, scholars have studied and explored the impact of technological innovation on water resource utilization efficiency. On the one hand, most scholars have found that technological innovation is an important influencing factor when studying the efficiency of water resource utilization. Alvarez et al. (2013) [41] clarified the important role of technological innovation in achieving comprehensive water management and found that the innovation and development of nanotechnology can significantly improve the efficiency of water resource treatment; Liang et al. (2021) [42] used a two-stage DEA method to verify that technological progress is a key factor affecting the efficiency of water resource utilization in 11 provinces and regions of China; Pan et al. (2020) [43] used the super efficiency DEA method to calculate that the improvement in water resource utilization efficiency in Shandong Province is mainly attributed to technological changes; Zhang Leqin et al. (2018) [44] used partial least squares path analysis to calculate the marginal contribution of technological innovation to water resource utilization efficiency in Anhui Province. From this, it was found that the impact of technological innovation on water resource utilization efficiency can be divided into direct and indirect effects, with direct effects being greater than indirect effects that affect water resource utilization efficiency through intermediary factors such as economic development level, industrial structure, and regulatory policies; Wei Jie et al. (2022) [45] combined the SBM-DEA model and spatial econometric model to study and verify that there is a significant positive correlation between the level of scientific and technological innovation development in the middle and upper reaches of the Yellow River region and the degree of water-use efficiency improvement. However, it is necessary to be cautious of the negative spatial spillover effect of "benefiting oneself at others' expense".

On the other hand, some scholars have extended their research conclusions based on the significant improvement of water-use efficiency through technological innovation, and conducted in-depth research on the impact of technological innovation on the water resource utilization efficiency of different industries based on their characteristics. The research mainly focuses on agriculture and industry. First, in-depth research has been conducted on the application of water-saving technologies in agriculture. For example, Bjornlund et al. [46] (2009) found that regional financial constraints and farm conditions can affect the application of water-saving irrigation technologies, thereby affecting the improvement of regional water resource utilization efficiency; Xu Tao et al. (2018) [47] used structural equation modeling to analyze the willingness of farmers to adopt water-saving technologies, and found that farmers' technological awareness and policy subsidies are crucial for the application of agricultural water-saving technologies; Chen Jie et al. (2022) [48] learned from the analysis of the rebound effect of irrigation water use in the North China Plain that the investment in farmland irrigation water conservancy construction and the perfection of water rights market construction will affect the application of agricultural water-saving technology, resulting in the decline of agricultural irrigation water-use efficiency. Second, in-depth research has been conducted on the application of industrial water-saving technologies. For example, Trang et al. (2022) [49] found that the institutional environment can affect the application effect of water-saving technologies in Vietnam. For example, in important industrial parks, centralized systems provide strong support for the research and application of water-saving technologies; Du et al. (2022) [50] classified the clustering characteristics of polluting industries based on the industrial distribution in the Yellow River Basin, and used a geographically weighted regression model to calculate the water pollution intensity index of the Yellow River Basin. The study found that technological innovation significantly improved the water efficiency of heavily polluting industries; Miao Junyu et al. (2022) [51] combined the super efficiency EBM model, ML index, and Tobit model to calculate the dynamic trend of industrial water-use efficiency in

9 provinces and regions of the Yellow River Basin. They found that in recent years, the driving force of technological efficiency on the improvement of industrial water-use efficiency has weakened.

3.3 The Influence Relationship Between Industrial Structure Optimization and Water-use Efficiency

Based on the increasingly severe global water scarcity problem and the urgent need for restructuring of industrial and supply chains, the academic community is continuously deepening research on the impact of industrial structure optimization and water-use efficiency. On the one hand, most scholars believe that optimizing industrial structure significantly improves the efficiency of regional water resource utilization. Li Gao et al. (2008) [52] used the IWCPA model to simulate and calculate the industrial water demand and water-saving potential in China from 2003 to 2030 under different technological scenarios, and verified the conclusion that optimizing industrial structure can promote industrial water-saving; Sun et al. (2019) [53] constructed an analysis framework based on the influencing factors of water use efficiency, and found that upgrading industrial structure can alleviate demand driven water scarcity and improve water-use efficiency to a certain extent; Zhou Guihuan et al. (2023) [54] combined the BBC model and Malmquist index to calculate the industrial water use efficiency of 21 prefecture level cities in Guangdong Province, and concluded that optimizing and upgrading the industrial structure will significantly improve industrial water-use efficiency; Li Kebai et al. (2023) [55] used one-way analysis of variance and non-parametric testing methods to calculate the water-use efficiency of 31 provinces and regions in China. Based on regional differences, they found a significant correlation between rural domestic water-use efficiency and the degree of industrial structure optimization, with a positive correlation between the two trends; Shi Tiange et al. (2022) [56] used the SBM-DEA model to calculate the comprehensive utilization efficiency of water resources in various provinces of China. The study found that increasing the proportion of the tertiary industry is the key to improving water resource utilization efficiency.

On the other hand, some scholars have deepened their research on the coordination between industrial structure and water resource utilization, clearly pointing out the existence of a two-way optimization path between industrial structure and water-use efficiency. Zhang et al. (2019) [57] found a bidirectional promoting relationship between water resource allocation and industrial structure layout, and constructed a bidirectional optimization multi-objective ITSP model to achieve regional industrial structure and water resource allocation structure; Zhou et al. (2017) [58] constructed an analytical framework for industrial structure upgrading and spatial optimization based on water environment carrying capacity, introducing economic and water environment information to achieve linkage between water resource management and industrial structure optimization; Wu Dan et al. [59] constructed a double-layer optimization configuration model and double-layer diagnostic criteria, and found that there is a bidirectional adaptation path between water resource utilization and industrial structure optimization in the Beijing-Tianjin-Hebei region; Bao Chao et al. (2006) [60] verified through empirical research that the bidirectional optimization simulation model of water use structure and industrial structure can optimize water resource allocation and promote the upgrading of industrial structure based on the actual distribution of inland river industry and water resources.

4. CURRENT STATUS OF RESEARCH ON TECHNOLOGICAL INNOVATION, INDUSTRIAL STRUCTURE OPTIMIZATION, AND WATER-USE EFFICIENCY EVALUATION METHODS

4.1 Evaluation Methods for the Coupling Relationship Between Technological Innovation and Industrial Structure Optimization

Scholars mainly use spatial econometric models to quantitatively measure the relationship between technological innovation and industrial structure optimization, such as spatial Durbin models, industrial structure decomposition models, panel threshold models, semi-parametric spatial panel vector autoregressive models, Bayesian quantile models, etc. [61-67]. Shao et al. (2021) [68] used a vector error correction model to study the relationship between China's marine scientific and technological innovation and industrial structure optimization; Li Xiang et al. (2018) [69] used the spatial panel threshold model to study and explore the relationship between technological innovation, industrial upgrading, and economic growth; Li Feng et al. (2021) [70] used a panel regression model to study and found that industrial structure optimization plays a supportive role in promoting economic development through technological innovation.

At the same time, some scholars use the coupling coordination degree model based on system optimization theory and coupling coordination theory to calculate the coordination degree between technological innovation and industrial structure optimization. Liu et al. (2023) [71] constructed a coupled coordination model and found that the degree of coupling between technological innovation and industrial structure optimization has a significant direct impact on green economic benefits and spatial spillover effects; Ye Tanglin et al. (2019) [7] used a coupling coordination model to analyze the coupling relationship between technological innovation level and industrial structure upgrading in the Beijing-Tianjin-Hebei region; Cheng Pengfei et al. (2021) [10] constructed a coupled coordination model and found significant spatiotemporal differences in the coupling degree between regional innovation level and industrial structure optimization level in Hunan Province.

4.2 Evaluation Methods for the Impact of Technological Innovation on Water-use Efficiency

Scholars mainly use input-output efficiency evaluation method and multi indicator decision analysis method to quantitatively measure the impact of technological progress on water-use efficiency. Such as traditional DEA models, improved DEA models, spatial econometric models, exponential models, etc. [44-46] [52] [72-74] Liang et al. (2021) [42] used a two-stage DEA method to verify that technological progress is a key factor affecting the efficiency of water resource utilization in 11 provinces and regions of China; Pan et al. (2020) [43] used the super efficiency DEA method to calculate that the improvement in water resource utilization efficiency in Shandong Province is mainly attributed to technological changes; Wei Jie et al. (2022) [45] combined the SBM-DEA model and spatial econometric model to study and verify the significant positive correlation between the level of scientific and technological innovation development in the middle and upper reaches of the Yellow River region and the degree of improvement in water-use efficiency; Miao Junyu et al. (2022) combined the super efficiency EBM model, ML index, and Tobit model to calculate the dynamic trend of industrial water-use efficiency in 9 provinces and regions of the Yellow River Basin. They found that in recent years, the driving force of technological efficiency on the improvement of industrial water-use efficiency has weakened.

4.3 Evaluation Methods of the Impact of Industrial Structure Optimization on Water-use Efficiency

Scholars mainly use goal programming models to analyze industrial water-use efficiency, or combine efficiency measurement models with regression models to calculate regional water-use efficiency and analyze its influencing factors. Ren et al. (2016) [75] constructed a multi-objective stochastic fractional objective programming model to study the optimal allocation of water resources among industries, and proposed that adjusting the industrial structure would optimize the effectiveness of water resource allocation; Wang et al. (2018) [73] used the DEA Tobit model to calculate the water-use efficiency of 30 provinces in China from 2008 to 2016 and analyzed its influencing factors. The study showed that the current industrial structure in China has a negative impact on water-use efficiency and urgently needs optimization; Wang Ying (2015) [72] found that the imbalance of industrial structure significantly affects the efficiency of water resource utilization based on the super efficiency DEA model and Tobit model; Zhang Liming et al. (2021) [76] used resource-based regions as an example to calculate the water-use efficiency of 10 typical resource-based provinces and cities in China using the DEA-BCC model, and used the grey correlation analysis method to explore the impact of industrial structure adjustment on regional water-use efficiency.

5. CONCLUSION: RESEARCH REVIEW

By reviewing the research context on the impact of technological innovation, industrial structure optimization, and water-use efficiency, it can be concluded that the current focus is mainly on the coordination between technological innovation, industrial structure optimization, and water-use efficiency. Few studies have conducted research on the coordination evaluation of scientific and technological innovation, industrial structure optimization, and water-use efficiency from the perspective of system dynamics. Through in-depth analysis of the coordination mechanism of scientific and technological innovation, industrial structure optimization, and water-use efficiency from the perspective of complex systems, a theoretical system of scientific and technological innovation, industrial structure optimization, and water-use efficiency coordination evaluation based on sustainable development theory has been formed. Therefore, in the future, it is urgent to introduce system dynamics into the research of scientific and technological innovation, industrial structure optimization, and water-use efficiency coordination evaluation based on resource constraint theory, and clarify the impact of different policy systems and governance mechanisms on the coordinated and symbiotic relationship between scientific and technological innovation, industrial structure optimization, and water-use efficiency; It is necessary to explore the coordination mechanism between technological innovation, industrial structure optimization, and water-use efficiency suitability based on regional differences. Based on the theory of complex systems, there is a must to decompose the multi-dimensional coordination goals layer by layer and construct a system of evaluation index for the coordination of technological innovation, industrial structure optimization, and water-use efficiency from a systemic perspective for the effective evaluation of system coordination, thus establishing a sustainable development model and proposing corresponding policy recommendations for technological innovation, industrial structure optimization, and water-use efficiency.

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