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Digital Economy and Green Total Factor Productivity: Theoretical Connotation, Mechanism of Action, and Research Progress

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Abstract. In the context of the growing pressure on the climate, the growing severity of the resource and environmental limitations, green development has become a important path of high-quality economic development. The quality of the economic development is commonly measured with the help of green total factor productivity (GTFP), integrating resource consumption and pollution emissions into the conventional productivity model. At the same time, the rapid growth of digital technologies, including big data, cloud computing and artificial intelligence, has turned the digital economy into one of the main factors of industrial restructuring and transformation of production modes. In this regard, scholars have increasingly shown interest in how the digital economy affects GTFP. The paper is a systematic review of the existing research based on which the relevant literature is evaluated regarding theoretical connotation, mechanisms, and research methods. Available literature suggests that the digital economy mainly enhances GTFP by technological innovation, human capital accumulation, and industrial upgrading, and also has spatial spillover effects. Nevertheless, it is important to note that, although much has been made, future studies need to widen the scope of cross-border comparisons, micro-mechanisms, and how the digital economy interacts with environmental regulation.

Keywords: Digital economy; Green total factor productivity; Green development.

1. Introduction

Against the background of the increasing global pressure caused by the climate change and increasingly severe resource and environmental constraints, the ecological environment improvement and the preservation of economic growth have become a burning question of the countries. Although the traditional growth model has been associated with economic growth, there have also been the problems of excessive consumption of resources coupled with increased pollution of the environment. To address this paradox, green development has slowly emerged as a significant trend of economical change. Green Total Factor Productivity (GTFP) brings environmental elements, including resource consumption, pollution emissions into the traditional productivity model and is much more indicative of the level of coordination between economic efficiency increase and environmental protection. Thus, it is therefore widely used to evaluate the level of green economic development.

Meanwhile, there is a fresh wave of digital technology revolution that is radically transforming the manner in which the economy is conducted. The digital technologies, which are symbolized by big data, cloud computing, and artificial intelligence, are becoming more and more a part of production, distribution, and consumption, and the digital economy becomes an influential force that promotes economic restructuring. In addition to greatly lowering the cost of information, digitalization can also maximize the spillovers of knowledge and diffusion of technology and contributes to significant improvement in resource allocation and modernization of the industrial structure. It is against this backdrop that the possibility of the digital economy becoming a leading driver in the drive towards green development is becoming a hot topic of research in the academic world.

The available literature tends to suggest that the emergence of digital technology has offered a fresh source of drive towards the transformation of green. Nevertheless, the related literature continues to indicate the lack of consensus on certain action mechanisms, regional variations and institutional settings. Other studies have suggested that digital development can have a large effect on enhancing

green productivity through technological innovation and industrial upgrading, whereas other studies have indicated that in the short term the rising costs of technology investment and growing energy demand may inhibit green efficiency, which is why the effect of digitization is phased or even non-linear. As new areas like digital finance, digital trade and supply chain digitalization rapidly advanced, corresponding studies have gradually grown not only in the focus of the analytical approach to one technological side but also on the multi-dimensional analytical approach that incorporates the factors of the institutional environment and policy.

In this study, the systematic review of the current studies is of immense importance. This paper is written as a reflection of the theoretical connotation, mechanisms and research developments of the digital economy and green total factor productivity based on the already existing literature. It also talks about the weaknesses of the existing studies and the ways in which future studies may take.

2. Theoretical Implication of the Digital Economy and GTFP

Green total factor productivity is a product of the expansion of the traditional productivity theory in the state of environmental restrictions. It consists in the fact that it introduces resource input, anticipated output and unwanted output indicators into the production function framework to better represent the coordination of economic efficiency and environmental protection. As the concept of green development has grown more profound, GTFP has emerged as a valuable instrument in determining the quality of economic development, and it has found extensive application in the research areas of environmental regulation, industrial agglomeration and green finance.

With the further evolution of digitalization, the scholarly community has started to investigate the mechanisms of the effects of the digital economy on productivity through the prism of new growth theory and technology diffusion theory. Associated studies indicate that digital technology has the potential to enhance the efficiency of resource allocation by lowering information acquisition costs and increasing the knowledge spillovers, which may offer a novel source of productivity growth [1]. Simultaneously, an explanation of the phased features which can exist in the process of digital development has also been done with the help of new economic geography and productivity paradox theory. Zhang et al. based on empirical research at city level in China concluded that there is a distinct U-shaped relationship between the level of development of the digital economy and the green total factor productivity of the cities [2]. During the initial phases of digitalization, green efficiency can be somewhat suppressed because of the expense of the technology adoption and reallocation of the resources; the contribution to the encouragement of green productivity can be noticed only when the level of digitalization reaches a certain threshold.

There is also a macro-development view of the digital economy as a significant institutional space to facilitate the green transformation. Similar studies suggest that green transformation has the capability of establishing a synergistic relationship between economic growth and environmental protection, and that the digital economy policies may play an important moderating role in this process [3]. This observation shows that in addition to the impacts on production efficiency that are influenced by technological means, digitalization is also redefining the forces behind the green development through the institutional environment and policy factors.

In general, the interplay between the digital economy and green total factor productivity could be interpreted as the productivity transformation through digital technology under the environmental constraint. Its essence is to foster the green development model by following several avenues including technological advancement, industrial restructuring, and optimization of the institutional environment.

3. Processes by Which the Digital Economy Influences GTFP

3.1. Knowledge Diffusion Mechanism and Technological Innovation

Technological innovation is frequently considered to be a significant channel of transmission of the digital economy to influence the green total factor productivity in the current body of research. The emergence of digital technology has transformed the conventional paradigm of knowledge production and dissemination. On one side, it offers better conditions to the innovation activity of enterprises by minimizing the costs of information search and R&D, on the other side, digital platforms and network organization increase the level of knowledge spillovers, which enhances the spread of green technologies between various entities. According to related studies, the digital economy has the opportunity to facilitate the enhancement of GTFP in the form of scale effect, structural and technological effects, and technological advancement is the most important avenue of impact [1].

Regarding the empirical research at the enterprise level, digital transformation can greatly improve the green innovation of enterprises and encourage the growth of green total factor productivity by using intermediate mechanisms including technological innovation and human capital distribution [4]. Meanwhile, the emergence of fintech has offered new sources of funding to corporate innovation. Studies reveal that fintech may play an important role in enhancing corporate levels of GTFP by reducing the lack of financing and encouraging technological change [5]. At the urban scale, the growth of the digital economy has also been discovered to be a driver of low-carbon transformation, the most important process being the enhancement of technological innovation capacity and the effectiveness of distributing digital resources. In addition, the digital technologies contribute to the growth of green productivity, improving the efficiency of the use of natural resources [6].

3.2. Mechanisms of Human Capital and Organization Capability Improvement

Knowledge-intensive industries and highly skilled workforce are largely relied on in the development of the digital economy, thereby enhancing the accumulation of human capital to a great degree. It has been found that human capital is not only a significant base of the digital technologies application but a main contributor to the green productivity increase. A sample of listed companies in strategic emerging industries was used by Chen et al. and it was discovered that the digital economy has the potential to substantially enhance the level of GTFP of enterprises, and human capital accumulation can be considered an influential intermediary channel, and the effect is more evident when the size of the enterprise exceeds a certain threshold [7].

Meanwhile, digital technology is also enhancing productivity through the restructuring of corporate structure and resource allocation patterns. The literature on the topic indicates that digital transformation improves green innovation potential and facilitates green productivity through more efficient human capital allocation and greater corporate strategic flexibility [4]. Digital inclusive finance at the city level can also enhance industrial upgrading through investment in education and skills upgrades and produce a synergist impact on reducing pollution and improving efficiency [8].

3.3. Mechanism of Industrial Structure Upgrading and Resource Allocation

The other branch of the study is on the efficiency of resource allocation and industrial restructuring. New endogenous growth theory argues that industrial upgrading plays a key role in the economic growth in the long run, and the digital economy increases the quality of economic growth by maximizing the distribution of resources and industrial upgrading. Some related studies demonstrate that digital development can not only facilitate the upgrading of industrial structure, but also facilitate the high-quality and green development of urban areas through the enhancement of resource allocation efficiency.

Subsequent studies have discovered that the digital economy also helps to promote the efficiency of natural resource utilization significantly, by enabling the rationalization of industrial structure and enhancing resource utilization efficiency [6]. Following this, other scholars have extended their

research scope to digital trade and digitization of supply chain. It has been demonstrated that the digitalization of supply chains can also increase green productivity by maximizing the allocation of resources and advancing technological innovation [9]. Simultaneously, it is also believed that the digital trade development will substantially enhance the GTFP level of the city, with the extent of trade liberalization and foreign direct investment serving as a multiplier effect, in this case [10].

3.4. Mitigation Mechanism of Financial Development and Financing Constraints

Green transformation, in most cases, needs large financial input whereas the conventional financial system is usually challenged by issues like information asymmetry and problems in risk evaluation in supporting green projects. In this matter, there have been studies that have looked at it through the lens of digital finance, where it is argued that digital inclusive finance has the potential to support corporate green investment and technological innovation by reducing financing thresholds and enhancing information asymmetry [11].

Meanwhile, the synergistic effect of environmental emission reduction and the improvement of production efficiency through the development of digital finance may also be attained by encouraging the growth of human capital and the upgrading of industrial structures [8]. As the green finance system has been constantly improved, the synergistic effect of the digital economy and green finance has gradually gained attention. It has been determined that green finance policies can greatly decrease the energy usage of cities, and the evolution of the digital economy and the enhancement of GTFP are significant in this procedure [12].

3.5. Spatial Spillover and Institutional Coordination Mechanism

Digital technologies have many network externalities, and their influence usually crosses administrative borders and creates spatial spillover effects. The spatial econometric analysis indicates that the digital economy does not only contribute to the green development of local manufacturing but also has a positive spillover impact to the neighboring regions. Nevertheless, the impact fades away with the geographical distance [13].

In this process, the institutional environment is also important. According to related research, achieving high GTFP relies not on a single condition, but a synergistic effect between digital technology, innovation capabilities, and multidimensional environmental regulation, and government regulation is considered to be one of the primary drivers [14]. Moreover, there can also be fiscal policies affecting the connection between digitalization and green transformation. It has been discovered that digital-green industrial sector transformation can be used to enhance agricultural GTFP, although this impact is regulated by the level of fiscal decentralization and presents apparent nonlinear features [15].

4. Significant Improvements in Research Methodology and Empirical Inferences

4.1. Research Methods

Concerning methodology of research, the literature primarily employs Data Envelopment Analysis (DEA) and its expanded models in gauging green total factor productivity including the SBM model, the GML index and the Malmquist index. Based on these measurement methods, numerous studies go an extra step to use fixed-effects models, spatial econometric models, and instrumental variable methods to address possible endogeneity issues. To illustrate, Zhang et al. applied a spatial error model to examine the effects of the digital economy on urban GTFP, whereas Luo and Qiu applied a spatial Durbin model to determine the spatial spillover impacts of digital economic development [2, 13].

With regard to identifying the mechanism, recent research has progressively brought forth mediation effect model, threshold model, and configuration analysis techniques. It is common to apply threshold models in order to unveil the nonlinear influence of enterprise size or the degree of digitalization [7],

whereas configuration analysis highlights the combined effect of various factors in facilitating the improvement of GTFP [14]. Moreover, digitalization policies have also been evaluated using the multi-period difference-in-differences methodology in order to determine the influence of these policies on urban development and green productivity [9].

In general, the current studies are slowly developing a multi-scale analytical model based on the enterprise, city, to provincial, and is continuously evolving to sub-areas of digital finance, digital trade and supply chain digitalization.

4.2. Main Empirical Findings

Available empirical literature is largely in agreement with the idea that the digital economy has emerged as a major facilitator of green development. The main ways in which digital technologies increase the green total factor productivity include the minimization of information costs, the intensification of the effects of knowledge spillover, and the optimization of resource allocation [1, 3]. More specifically, the digital economy stimulates the green total factor productivity in terms of technological innovation, human capital accumulation, industrial upgrading, and financial development [4, 14]. Technological innovation is at the core of them since it enhances the spread of green technologies and an efficient use of resources [2].

In the meantime, spatial spillover effects also occur with regard to digital economy. Based on the data of the Chinese cities, Zhang et al. discovered that the emergence of the digital economy does not only enhance the local green productivity, but also enhances the green development productivity but [2]. Moreover, the effects of the digital economy on the green total factor productivity are also not fully linear as empirical studies indicate. The results of Chen et al. revealed that the high cost of investment in high technology and the rising need of energy in the initial phases of digital progress can depress the efficiency of green; when the extent of digitalization surpasses a specific point, the beneficial impacts of knowledge spillovers and resource optimization become predominant [7].

4.3. Research Limitations

Although the current research has achieved significant advancements, there are still a number of gaps. To start with, the vast majority of research targets China, and there is the lack of cross-national comparative studies [6]. Since the global population is full of digital technologies, their effects on green productivity may be quite different in different institutional settings and stages of development. Thus, it is possible to partially weaken the external validity of the available findings in the context of the absence of an international comparative point of view.

Second, the literature available has proposed a number of transmission channels but the micro-mechanisms that are involved are not clearly defined. Considering digital transformation, such as organizational restructuring, accumulation of digital assets, and the formation of long-term capabilities have not been analyzed systematically [4]. This weakness renders it hard to describe the impact of the digital economy on green total factor productivity at the firm level comprehensively.

Third, the dynamics of interaction between digitalization and environmental regulation do not have a dynamic analytical framework. In spite of the fact that the current research highlights the necessity of institutional synergy, the dynamic relationship between digital economy policies, industrial policies, and environmental regulations is not considered exhaustively [14]. Moreover, there is only limited evidence that the two have a possible U-shaped relationship, though there are some studies that have found it [2], its theoretical foundation and the long-term evolutionary direction remains a subject of research.

4.4. Future Research Directions

Despite these shortcomings, future studies can be extended in a number of ways. On the one hand, the enterprise, city, and international data need to be combined to undertake more multi-level, cross-national comparative research and enhance the universality of the results obtained [6]. In addition,

the next generation of studies must put more emphasis on micro-level processes, with enterprise-level data being used to investigate the overall effect of digital transformation on green productivity in a systematic way [4].

At the same time, the institutional coordination mechanisms should be considered further. It is possible to develop a dynamic analytical framework of the interaction of digital economy policies, industrial policies and environmental regulations and show the synergistic nature of various policy tools [14]. In addition, the nonlinear association between the digital economy and the green total factor productivity should be further investigated in future studies, especially how the threshold effect is formed and the long-term development path [2, 7].

5. Conclusion

This paper reviews the theoretical connotation, mechanisms, research methods, and empirical findings concerning the relationship between the digital economy and green total factor productivity. Existing research generally shows that digitalization promotes GTFP through five interconnected channels: technological innovation and knowledge diffusion; human capital and organizational capability; industrial upgrading and resource allocation; financial development and the easing of financing constraints; and spatial spillovers and institutional coordination. Technological innovation is the most consistently identified mechanism. At the same time, the effect is not uniformly linear: early adoption costs, resource reallocation, and additional energy demand may temporarily constrain green efficiency, whereas deeper digitalization strengthens knowledge spillovers and resource optimization. Network externalities further allow these effects to cross administrative boundaries, while environmental regulation and fiscal arrangements shape their magnitude.

Methodologically, research has expanded from DEA-based productivity measurement and fixed-effects models to spatial econometrics, threshold and mediation models, configurational analysis, and policy-evaluation methods, with evidence spanning firms, cities, and provinces. Nevertheless, the literature remains concentrated on China, firm-level organizational processes are not fully clarified, and dynamic interactions between digital-economy policies and environmental regulation require more attention. Future studies should strengthen cross-national and multi-level comparisons, use firm-level data to identify organizational and capability-building mechanisms, and develop dynamic frameworks for nonlinear effects and policy coordination. Overall, digitalization is best understood not as a single technological shock but as a systemic transformation in which technological, organizational, industrial, financial, spatial, and institutional factors jointly shape sustained improvements in GTFP and green development.

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