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# Korean Paradox of Public Support for the Research and Development Investment in the Sustainable Performance of the Regional Economy

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**Abstract:** The Swedish Paradox is a well-known phenomenon related to high research and development (R&D) investment with supposedly low aggregate economic performance owing to economic saturation. The Korean economy has not yet become an advanced economy; however, its R&D performance is negligible. Recently, also the R&D share of the GNP has become much higher, and its contribution to the economic growth rate is rapidly decreasing, implying a negative relationship between R&D activities and economic performance. This study uses slacks-based data envelopment analysis to investigate investment performance at the local government level in Korea. Our findings reveal that the average score for R&D investment performance in Korea is 64%, indicating huge potential for an efficiency enhancement of 36%. Notably, among the 16 local governments examined, Seoul and its surrounding metropolitan areas showed the lowest R&D efficiency, while Gangwon and Gwangju exhibited superior performance. Since these two regions have promoted specific missions, such as the medical hub in Gangwon and the optical fiber strategic platform in Gwangju, precise and accurate differentiation appears necessary to avoid a lack of governance. To determine the workable mechanism of R&D support policies, we further divided R&D productivity into three categories by incorporating the Malmquist Index (MI). The paper productivity of R&D shows an increasing trend over the experimental period from 2016 to 2021. However, overall, the MI shows slightly deteriorating productivity with 0.978, owing to the aggravating effect of patents and commercialization of R&D. The success in the paper comes from the harmonized partnership between the strong push factor of the government and voluntary pull factor of the R&D support receiving universities. Thus, we suggest that the Korean government should not depend on the superficial effectiveness of R&D in the term but on public–private partnerships with stronger performance-oriented responsibility.

**Keywords:** SBM-DEA; R&D investment; Malmquist index; governance; Korean paradox

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**Citation:** Choi, Y.; Li, S.; Lee, H. Korean Paradox of Public Support for the Research and Development Investment in the Sustainable Performance of the Regional Economy. *Land* **2024**, *13*, 759. https://doi.org/10.3390/land13060759

Academic Editor: Hossein Azadi

Received: 24 April 2024
Revised: 22 May 2024
Accepted: 26 May 2024
Published: 28 May 2024



## 1. Introduction

Owing to the rapidly changing economic environment, most developing countries strongly support universities and businesses in their research and development (R&D) efforts to meet these new challenges. South Korea is not an exceptional case in terms of this public support; thus, it receives substantial focus on its economic performance and the cultural impact of the K-wave in the global market. Several developing countries, such as Vietnam and Uzbekistan, recognize Korea as their developing model. Nevertheless, Korea has experienced a rapidly decreasing trend in its economic growth potential. Even if the Korean economy has not yet become advanced, its slow-steady economic growth rate has shown a high possibility of a middle-income trap. To overcome a steadily growing gross domestic product (GDP), the Korean government has poured significant R&D support into private companies as a matching fund partnership to revive the economic engine. As shown in Figure 1, South Korea's R&D expenditure, valued at USD 89,282 billion in 2021, has emerged as the fifth highest globally, underscoring the nation's robust commitment to innovation. Furthermore, the percentage of R&D expenditure in GDP exhibited a noteworthy increase, reaching 4.93%, to secure Korea's position as the second-highest R&D expenditure worldwide. However, whether greater investment in R&D inevitably translates into superior outcomes is a complex matter that requires a comprehensive examination.

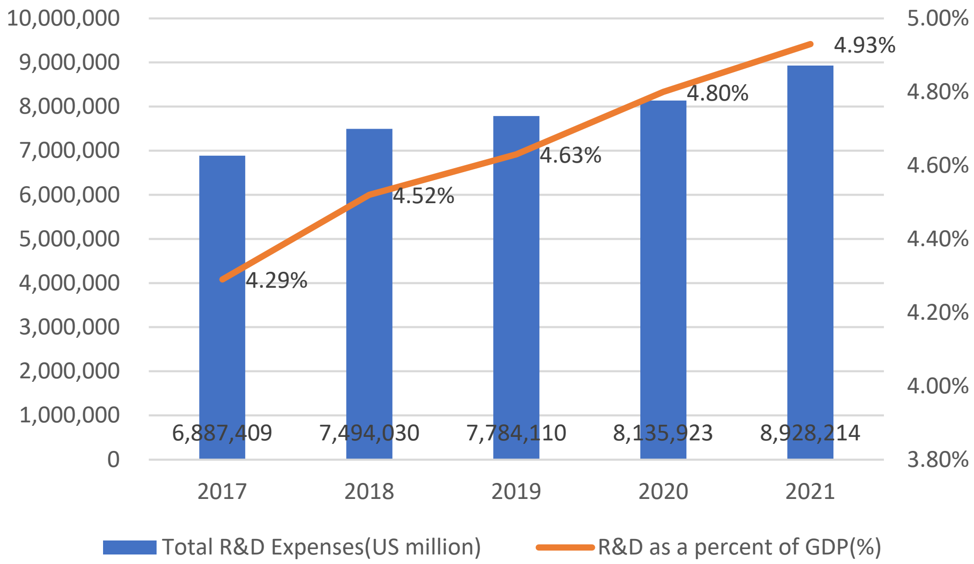


**Figure 1.** Trends in South Korea's total R&D expenses and R&D as a percentage of GDP [1].

Unfortunately, the Korean economy did not show a strong promotion effect of R&D on economic growth, similar to the Swedish Paradox. The Swedish Paradox characterizes a scenario in which substantial R&D investments do not yield corresponding improvements in corporate performance or economic growth, resulting in the pitfall of the standstill phenomenon of an advanced economy. During the 1990s, Sweden held the distinctive position as the world's foremost investor in R&D. However, the subsequent realization of economic underperformance prompted a sobering assessment. An obvious contributor to this paradox is the absence of a comprehensive R&D commercialization strategy. Sweden's emphasis on fundamental scientific research, which often remains distant from industrial applications, yielded suboptimal results. Moreover, most advanced countries, including Sweden, cannot have an outperforming economic engine for economic growth owing to saturated economic growth potential.

However, Korea has not yet become an advanced economy; thus, the Korean economy should not experience any version of the Swedish Paradox caused by the impact of R&D saturation on economic growth. Nevertheless, the Korean government recognized the Swedish Paradox during the early 2010s, which subsequently became a focal point in various forums and discussions on R&D innovation. Within the realms of science and technology, a prevailing sentiment of self-critique emerged, encapsulated by the assertion that "the paradox baton has shifted from Sweden to Korea." This articulates the concern that Korea is presently entangled with what is colloquially referred to as the "Korea Paradox." In this situation, the current Korean President, Yoon, declared a huge cut-off of public R&D support starting in 2024, which became very controversial in Korea.

However, before discussing the Korean Paradox, it is better to examine whether the full potential of R&D is realized. If not, the impediments to the lack of governance should be identified. Detractors argue that the lofty proclamations, such as being "at the top in R&D investment as a percentage of GDP globally" or "the best in patent applications as a percentage of the population", amount to little more than a "debt-driven facade".

As shown in Figure 2, as the R&D portion of GDP grows in Korea, its economic performance, represented by the economic growth rate, decreases. This shows a clear negative relationship between R&D and economic performance, implying a lack of governance for R&D policies and business strategies. Why did this type of paradox occur?

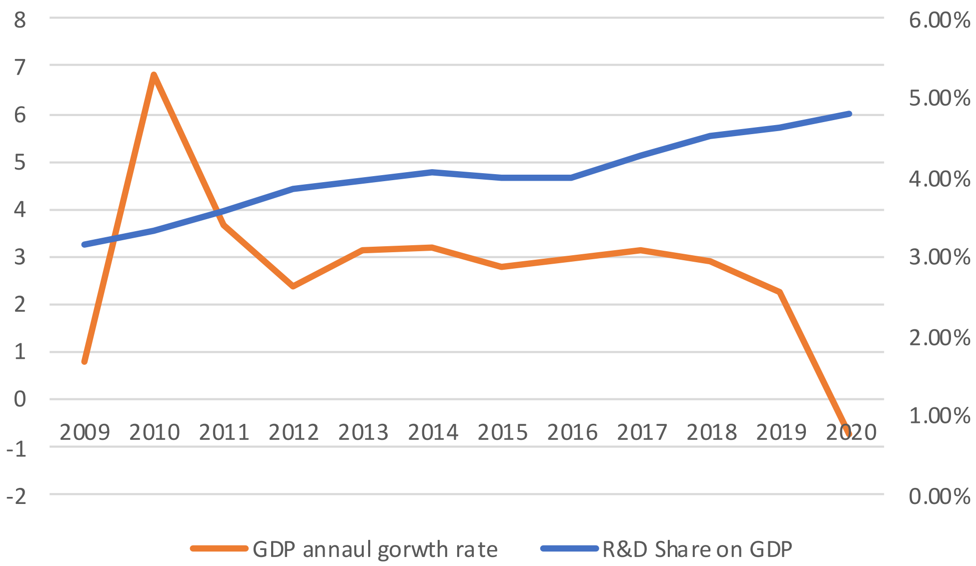


**Figure 2.** Trends in R&D share on GDP [2] and GDP annual growth rate [3].

South Korea's economic model, characterized by high-tech exports and advanced technological infrastructure, has historically relied on robust R&D to drive economic growth. However, as global economic conditions shift toward digitization and innovation, the anticipated benefits of these investments have not materialized to their full potential. This situation is particularly relevant today as countries navigate the complexities of technological disruption, international competition, and the need for sustainable development.

The relevance of the "Korean Paradox" extends beyond national borders, reflecting a broader global challenge in which high R&D spending does not always translate into economic prosperity. This is a critical issue for economies at all stages of economic development, particularly for those looking at R&D as a lever for economic transformation and competitiveness.

Understanding the "Korean Paradox" is imperative for policymakers not only in Korea but worldwide, as it provides predictable insights into the dynamics between R&D investments and economic outcomes. This paradox also highlights the urgent need for a strategic alignment between R&D activities and broader economic policies to ensure that investments in innovation lead to tangible economic benefits.

The discouraging evaluation of R&D becomes apparent when scrutinizing the performance of government-funded research institutes, which constitute the cornerstone of public R&D initiatives. Recent data published by the Korea Advanced Institute of Science and Technology Research reveal that all 25 such institutions collectively garnered USD 98.3 million in technology fees through technology transfer, licensing, and investment in the preceding year. However, despite the substantial annual tax investment of nearly USD 437 billion, the income derived from technology fees represents only 2% of the allocated budget. This underwhelming performance can be attributed to the lack of governance on patents amenable to the commercialization of R&D by the private sector. Governance is defined as the workable mechanism for sustainable performance. Some financial support for R&D seems to be a type of blind money with a lack of sustainable performance. Among the collective patent portfolio of 44,922 held by these entities, only 16,410 (36.1%) were effectively leveraged for technological implementation. The remaining patents either continue to languish as untapped assets (4655; 10.2%) or face a bleak outlook for utilization (24,574; 53.7%). This signifies that over 60% of patents are either obsolete or inactive, implying significant challenges encountered in R&D commercialization and/or technology transfer. To fill this gap in R&D governance, R&D investment efficiency should pertain to the effectiveness of converting R&D inputs into sustainable performance. Enhancing R&D efficiency involves augmenting R&D outputs while maintaining constant R&D inputs or conserving the resources allocated to technological innovation without compromising R&D outputs.

While diagnoses may vary from different perspectives, a consensus remains regarding the remedy for better governance. Although the Korean economy has not yet entered the saturating mature stage of economic development, why should the Korean economy suffer a phenomenon similar to the Swedish Paradox? Thus, the Korean economic conditions can sometimes be referred to as the Korean Paradox of R&D. The economic structure and surrounding conditions of the Korean economy are quite different from those of advanced economies such as Sweden. Many developing countries still want to learn more from the dynamically changing Korean economy; thus, the Korean government should show substantially more caution regarding optimal path control toward an advanced economy. Given this complicated situation, our research question was whether the Korean Paradox could be resolved.

To answer this research question, the Korean economy must undergo an effective and efficient transition in its R&D system from a fast follower to a global leader, accentuating the superficial shift from research-emphasizing approaches to performance-oriented strategies. This transformation is pivotal for addressing the challenges posed by the Korean type of developing countries' efforts to boost their economies. Because the R&D performance process is complicated and complex, this study focuses on the role of modulating R&D performance, such as patents, papers, and successful commercialization. These three modulating performance variables are popular in that most of the literature argues that R&D is scientific performance, while patents are technical performance. Successful commercialization is unique as applied in this study because it has not been used in previous research due to the scarcity of relevant data and its intimate and insightful signal as the sustainable performance of R&D. The purpose of this study was to assess how well 16 Korean municipal governments have invested in R&D. To evaluate this relative efficiency among local governments. First, a slacks-based data envelopment analysis model (SBM-DEA) was used. To track dynamic changes, we used the Malmquist Index.

The remainder of this paper is organized as follows. Section 2 introduces the background of the SBM-DEA and R&D investment efficiency. Section 3 presents the methodological framework of the SBM and Malmquist Index, and Section 4 analyzes the empirical results of this research model for 16 Korean local governments. Finally, Section 5 concludes the paper with diverse implications and strategic suggestions.

## 2. Literature Review

### *2.1. SBM-DEA*

To evaluate the complex causal relationships between multiple inputs and outputs, DEA was originally developed as a tool for the quantification of technical efficiency. Its evolution has led to its application across various fields, including environmental economics. The foundational stages of DEA's development can be traced back to 1957 when Farrell. Ref. [4] introduced the notion of productive efficiency, a precursor to the concept of technical efficiency. A significant breakthrough occurred in 1978 when Charnes et al. [5] introduced the DEA method, which was used as the CCR model. Traditional DEA employs a radial approach that may overlook slack variables, potentially leading to an overestimation of potential efficiency and consequently yielding weak discriminatory power. To overcome these limitations, our study adopts Tone's (2001) non-radial method, along with SBM-DEA. Tone [6] introduced the SBM within the DEA framework as a non-radial efficiency metric. SBM offers a distinctive advantage by directly quantifying efficiency through the additional assessment of excess inputs, shortfalls in outputs, and the gap between inputs and outputs concerning the production frontier, termed "slack". Furthermore, SBM permits the direct definition of efficiency values for each factor by utilizing the slack associated with individual variables, thereby enhancing granularity and specificity in efficiency assessment. The incorporation of SBM-DEA is considered to increase reliability, given its capacity to mitigate the risk of subjective efficiency evaluations arising from the arbitrary selection of weight vectors by researchers. Scholars are progressively predisposed toward integrating SBM-DEA into their studies because of its efficacy in furnishing a methodology that circumvents subjective assessments, thereby ensuring objectivity and reliability in evaluations.

The SBM-DEA method has been applied in diverse research domains, including an innovation efficiency evaluation of China's banks [7], water use efficiency measurements [8], and $CO_2$ emission evaluations [9]. This study used SBM-DEA to examine R&D investment efficiency.

### *2.2. R&D Investment Efficiency*

Traditional DEA employs a radial approach that may overlook slack variables, potentially leading to an overestimation of potential efficiency. Although alternative methods are available that can overcome this overestimation problem, such as the non-radial directional distance function (DDF) introduced by Zhou et al. (2007) [10], notably, the DDF may also introduce subjective issues related to the weighting of variables. Several studies have adopted this methodology (Lee & Choi, 2018 [11]; Zhang et al., 2019 [12]; Choi et al., 2020 [13]); however, the DDF may cause subjective issues regarding the weight of the variables, resulting in another problem in the subjective selection of weights. To avoid these subjective issues, our study adopted the SBM-DEA, which does not require subjective weight assignment and provides a better estimation in a flexible yet complicated evaluation process. The SBM-DEA has been widely used as an alternative to traditional DEA because of its ability to consider slack variables and its robustness in providing accurate efficiency estimates. Therefore, in our study, we believe that SBM-DEA is a suitable approach to address the potential limitations of traditional DEA and DDF.

Based on a comprehensive exploration of the literature surrounding the SBM-DEA method, the distinct advantages of the SBM-DEA over conventional methods have become evident. This methodology successfully addresses the limitations observed in previous studies, enhancing the precision and discriminatory capacity of efficiency assessments. With a solid foundation established in the methodological domain, we focus on evaluating the substantive aspect of the empirical test in the R&D domain.

The government has substantially facilitated public support in the form of matching R&D investment types. This strategic allocation of resources toward R&D not only signifies a commitment to fostering innovation but also serves as a pivotal driver for enterprises to excel in their technology, management, and market dynamics. Consequently, this concerted effort contributes to a notable enhancement in the overall competitiveness of economic growth potential. Given the insistent nature of international market competition, in which enterprises are compelled to be increasingly innovative and adaptable to newly emerging innovations, the government's judicious investment in R&D appears to be a critical catalyst, propelling much-needed industrial upgrading. The current literature validates the proactive role of government investment in R&D in economic development. Zhu and Zhang [14] employed a fixed-effects model to show that approximately 80% of the variance in regional economic development can be statistically explained by disparities in technological innovation capacity. Furthermore, regional disparities in technological innovation capacity correlate with variations in regional economic development levels. Zhao, Yu, and Jiang [15] provided substantial evidence that technological innovation capacity significantly and sustainably contributes to long-term economic growth. Huang and Shi [16] highlighted regional disparities in the influence of various R&D sources and composition on regional environmental productivity. Nevertheless, some scholars have posited that excessive government R&D investment may conversely impose inhibitory effects on enterprise development. Lin et al. [17] proposed an inverted U-shaped relationship between government support and enterprise R&D investment and advocated for a judicious approach that prioritizes enhancing the efficiency of government R&D investment while concurrently cautioning against enterprises over-relying on governmental support. These studies collectively emphasize the complex relationship between R&D, innovation, economic growth, environmental efficiency, and regional disparities. Policymakers are eager to promote economic development through various means against the backdrop of sustainable development strategies being pursued globally. However, when fostering economic growth, the living environment is crucial to be considered. Land-use change (LUCC) is a key indicator of regional economic development and ecological quality, serving as the link between human socioeconomic activities and natural ecological processes (Lu et al., 2016) [18]. R&D investments can drive economic development and urbanization fueled by rapid economic growth, which has led to significant LUCC, posing substantial risks to urban ecological security (Wang et al., 2023) [19]. Therefore, R&D investment indirectly influences LUCC. As energy conservation and emissions reduction have become common global goals, balancing economic development with LUCC considerations is essential.

Unfortunately, as shown in Figure 2, government support for R&D did not strongly promote economic growth in Korea, implying the existence of a Korean Paradox. Because the purpose of this research was to discern potential intricacies and dispel misconceptions within the Korean government's approach, we needed to focus on the governance of the complex role of R&D in regional economic development or LUCC. Thus, the overarching aim of this study was to encapsulate policy implementation shortcomings, with a primary focus on unraveling the reasons behind the failure of heightened R&D investment to catalyze commensurate economic growth.

To delve deeper into our model, specifically focusing on the selection of input–output variables, several researchers have pointed out labor and capital, similar to traditional production technology modeling [20–22]. Thus, our model uses labor and capital as R&D inputs. Compared with the traditional selection of inputs, the output variables exhibit more variation. That is, R&D performance can be assessed based on financial performance, as reflected by the GDP of the region or country, company revenue, and/or academic performance, as measured by the number of patents or published papers. The former focuses on the outcomes of R&D, whereas the latter emphasizes the long-term modulating role of R&D in sustainable performance. As an exemplary empirical test, Wang (2007) examined the R&D efficiency of 30 countries between 1997 and 2002, with academic papers and patents as the outputs and the stock of capital and labor force as the inputs. Based on this argument regarding financial performance, our model is based on the relative level of R&D efficiency for sustainable performance with three common variables of R&D outputs: patents, published papers, and successful commercialization (Table 1).

**Table 1.** Literature review on R&D efficiency based on the DEA approach.

| Researcher | Research Target | Period | Input Variables | Output Variables | Methodology |
|---|---|---|---|---|---|
| Rosseau S. & Rosseau R (1998) [23] | 14 European countries | 1993 | (1) R&D expenditure<br>(2) GDP<br>(3) Active population | (1) Patents<br>(2) Papers | DEA |
| Li H. & Park Y. (2005) [24] | 27 countries | 1994–1999 | (1) R&D expenditure<br>(2) Researchers | (1) Patents<br>(2) Papers<br>(3) Balance of receipts for technology | DEA |
| Eric C. et al. (2007) [20] | 30 countries | 1997–2002 | (1) R&D capital stocks<br>(2) Manpower | (1) Patents<br>(2) Papers | DEA |

**Table 1.** *Cont.*

| Researcher | Research Target | Period | Input Variables | Output Variables | Methodology |
|---|---|---|---|---|---|
| Hashimoto A. & Haneda S. (2008) [25] | 10 pharmaceutical firms in Japan | 1982–2001 | (1) R&D expenditure | (1) Patents<br>(2) Pharmaceutical sales<br>(3) Operating profits | DEA |
| Chan C. et al. (2011) [26] | 24 countries | 1998–2005 | (1) R&D personnel<br>(2) R&D expenditure stocks | (1) Patents<br>(2) Papers<br>(3) Royalty and licensing fees | DEA |
| Zhong W. et al. (2011) [27] | 30 provinces in China | 2004 | (1) R&D expenditure<br>(2) R&D personnel | (1) Patents<br>(2) Sales revenue of new products<br>(3) Profits of primary business | DEA |
| Chen K. et al. (2018) [28] | 29 provinces in China | 2006–2010 | (1) R&D expenditure<br>(2) R&D personnel<br>(3) R&D capital stock | (1) SCI papers<br>(2) Domestic granted patents | Dynamic DEA |
| Karadayi M. & Ekinci Y. (2018) [22] | EU countries | 2011–2013 | (1) Researchers<br>(2) Postgraduates<br>(3) Employment | (1) Patents<br>(2) Papers<br>(3) Publications | DEA |
| Xiong X. et al. (2018) [29] | 17 research institutes in the Chinese Academy of Sciences | 2012–2015 | (1) R&D personnel<br>(2) R&D intramural expenditure<br>(3) Patent<br>(4) Paper | (1) Income created by licenses | Two-stage dynamic DEA model |
| Liu H. et al. (2020) [30] | 30 provinces in China | 2009–2014 | (1) R&D cost<br>(2) R&D personnel<br>(3) Number of patent applications<br>(4) Number of patents in force | (1) Prime operating revenue<br>(2) Sales revenue of new products | Two-stage DEA |

The unique contribution of this study is the incorporation of successful commercialization as an output variable, represented by the proxy variable of the successful inauguration of a venture business. Therefore, in this empirical study, we employed two input variables, capital and labor, and three output variables, patents, papers, and successful commercialization. This unique addition of the commercialization variable serves at the governance level to enhance the reliability of the evaluation framework. As summarized in Table 1, by utilizing these variables based on the SBM-DEA approach for production technology, we investigated the efficiency of R&D investments across 16 local governments in South Korea.

## 3. Methodology

### *3.1. Slacks-Based Model Data Envelopment Analysis*

Based on the common factors in the literature review shown in Table 1 and our unique selection of the commercialization output variable, we utilized the SBM framework to assess R&D efficiency.

To address the primary objective of our study on the effectiveness of the R&D expenditures by Korean local governments, we focused on the non-radial method of SBM-DEA. SBM-DEA directly addresses the issues of input excess and output deficiency (Tone, 2001), thereby comprehensively capturing inefficiencies and demonstrating their significant advantages. The distinctive features of this method have the potential to overcome the limitations associated with radial methods. Within SBM-DEA, a specific decision-making unit (DMU) is considered efficient if it lies on the production possibility set (PPS) of a technological frontier without input or output slack. These efficient DMUs are assigned a uniform efficiency value. The equation assuming constant returns to scale is as follows:

$$\theta^{k^*}_{SBM} = \min_{\lambda, s^+, s^-} \frac{1 - \frac{1}{M}\sum_{i=1}^{m}\left(\frac{s_m^-}{x_m^k}\right)}{1 + \frac{1}{N}\sum_{n=1}^{N}\left(\frac{s_n^+}{y_n^k}\right)} \tag{1}$$

S.T,

$$x_m^k = \sum_{j=1}^{J} x_m^j \lambda^j + s_m^- (m = 1,\ 2,\ \ldots,\ M);$$

$$y_n^k = \sum_{j=1}^{J} y_n^j \lambda^j - s_n^+ (n = 1,\ 2,\ \ldots,\ N);$$

$$\lambda_k, s_i^-, s_r^+ \geq 0,$$

**m** = 1, 2,. . ., **M**, where m is the index representing the inputs, and **M** is the total number of inputs.
**n** = 1, 2,. . ., **N**, where n is the index representing the outputs, and **N** is the total number of outputs.
$\mathbf{s_m^-}$ are slack variables representing a potential reduction in inputs.
$\mathbf{s_n^+}$ are slack variables representing potential enhancement in outputs.
$\boldsymbol{\lambda}$ is a non-negative vector of multipliers used for constructing the PPS through linear programming.

Equation (1) defines the non-radial, non-oriented measurement of the SBM model. When $\theta^{k^*}_{\mathbf{SBM}}$ = 1, all slack variables are **0** ($\mathbf{s_i^-} = 0, \mathbf{s_r^+} = 0$), which means that the R&D activities of these specific local governments as DMUs are being conducted with the best degree of operational efficiency. Simultaneously, as highlighted above, R&D investment holds a pivotal role in the trajectory of economic development and is anticipated to foster regional economic growth.

SBM-DEA is a methodology that efficiently handles situations in which inputs do not translate proportionally into outputs, which is a common scenario in R&D environments. This methodology surpasses the limitations of traditional DEA models by directly measuring input excesses and output shortfalls, thereby precisely identifying inefficiencies in the R&D process. In particular, when assessing R&D efficiency across various regions in Korea, considering these slack variables is crucial for understanding the subtle disparities between regional economic activities and R&D outcomes. SBM-DEA quantifies the inefficiencies that traditional DEA methods may overlook by evaluating the gaps between inputs and outputs, offering a more detailed basis for policy improvement and strategic decision-making.

### *3.2. Malmquist Index*

The Malmquist Productivity Index is used to analyze productivity changes over multiple periods, measuring both technological efficiency and technological change dynamics simultaneously and providing a comprehensive evaluation of overall productivity evolution. This index is essential in environments such as Korea, where rapid technological and economic shifts occur, making it crucial to analyze the dynamic effectiveness of R&D investments. The Malmquist Index helps provide a better understanding of the temporal dynamics of R&D by assessing how advancements in technology and their economic effects evolve. Moreover, it identifies areas of efficiency decline or technological regression, providing policymakers with valuable insights into adjusting economic development strategies and optimizing R&D investment directions. This strategic use of the Malmquist Index can lead to a more targeted and outcome-oriented recalibration of Korea's R&D policies, laying a foundation for more strategic and effective public support for innovation.

To analyze the dynamics of efficiency over time, Färe [31] developed the Malmquist Index (MI). Because MI is based on the transformation effect of production technology, it evaluates the production growth potential of all DMUs over time. Suppose that $(x_{ij}^t, y_{ij}^t)$ and $(x_{ij}^{t+1}, y_{ij}^{t+1})$ are the input and output values, respectively, for a specific DMU in periods t and t + 1, respectively. To calculate the MI, four efficiency scores must be obtained: the single-period efficiency measures for each DMU in periods t (shown by $\theta^t(x0^t, y0^t)$) and t + 1 (shown by $\theta^{t+1}(\mathbf{x0}^{t+1}, \mathbf{y0}^{t+1})$), and the mixed-period efficiency scores for each DMU are shown by $\theta^t(\mathbf{x0}^{t+1}, \mathbf{y0}^{t+1})$ and $\theta^{t+1}(\mathbf{x0}^t, \mathbf{y0}^t)$. $\theta^t(\mathbf{x0}^{t+1}, \mathbf{y0}^{t+1})$ is the efficiency score of $\mathbf{DMU_0}$ when the inputs/outputs values for this DMU are $(\mathbf{x0}^{t+1}, \mathbf{y0}^{t+1})$, while for others, DMUs are $(\mathbf{x}_j^t, \mathbf{y}_j^t)$, j ∈ {1,... n} {o}. A similar definition is provided for $\theta^{t+1}(\mathbf{x0}^t, \mathbf{y0}^t)$. The MI can be evaluated by the geometrically enhanced efficiency between these two periods as follows:

$$M_0 = \sqrt{\frac{\theta^t\left(x_0^{t+1}, y_0^{t+1}\right)}{\theta^t\left(x_0^t, y_0^t\right)} \times \frac{\theta^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)}{\theta^{t+1}\left(x_0^t, y_0^t\right)}}$$

$$\frac{\theta^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)}{\theta^t\left(x_0^t, y_0^t\right)} \sqrt{\frac{\theta^t\left(x_0^{t+1}, y_0^{t+1}\right)}{\theta^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)} \times \frac{\theta^t\left(x_0^t, y_0^t\right)}{\theta^{t+1}\left(x_0^t, y_0^t\right)}} = \ldots\ldots \quad (2)$$

In this formulation, $\mathbf{M_0}$ shows the technological change in the performance of $\mathbf{DMU_0}$. $\mathbf{M_0} \geq 1$ shows efficiency growth for $\mathbf{DMU_0}$, where $\mathbf{M_0} \leq 1$ indicates efficiency loss. $M_0 = 1$ indicates no change in the efficiency of $DMU_0$ during period t to **t** + 1. $\frac{\theta^{t+1}(x_0^{t+1}, y_0^{t+1})}{\theta^t(x_0^t, y_0^t)}$ shows the changes in the relative efficiency score or technical efficiency changes during period t to **t** + 1 and indicates technological changes from period t to period **t** + 1.

Based on this production technology and its dynamic changes over time, we can evaluate the performance of R&D activities based on the causal relationship between inputs and outputs.

## 4. Empirical Evaluation and Its Implications

### *4.1. Data Selection and Descriptive Statistics*

This study analyzed the efficiency of R&D investments across 16 local governments, as shown in Figure 3. The literature was the basis for the selection of all input and output variables [20–23,25,26,32–37]. Therefore, we configured two inputs and three outputs, as shown in Table 2. All the variables were obtained from the National Research and Development Research and Analysis Report of the Korea Institute of Science and Technology Evaluation and Planning.

**Table 2.** Descriptive data.

| Variable | Type | Unit | Min | Max | Mean | Std. Dev. |
|---|---|---|---|---|---|---|
| R&D cost | Input | USD Million | 115 | 41,125 | 3888.95 | 7792.19 |
| Researchers | Input | Person | 2039 | 250,652 | 38,434.59 | 56,983.67 |
| Papers | Output | EA | 68 | 18,119 | 2360.096 | 3516.39 |
| Patents | Output | EA | 36 | 8064 | 1747.14 | 2150.729 |
| Successful commercialization | Output | EA | 30 | 7415 | 1516.61 | 1399.595 |

Source: Korea Statistical Information Service (http://kosis.kr/, accessed on 30 October 2023).

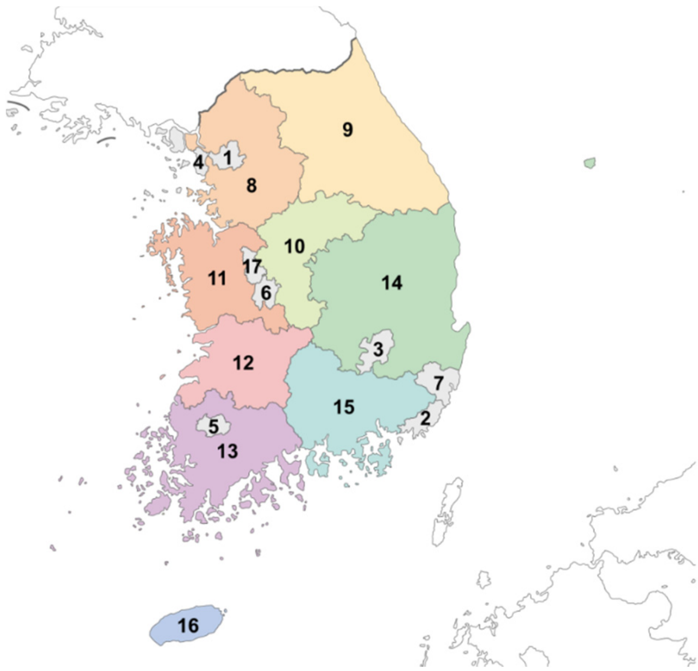


**Figure 3.** Map of 17 local governments in South Korea. (17 Sejong was excluded from empirical study because of not enough samples).

In the context of the input variables, our selection of R&D costs stems from their pivotal role in fostering the creation of novel technologies or products and the advancement of new knowledge. In this study, R&D costs specifically encompass inputs from the public sector. Regarding human resources dedicated to R&D, researchers play a fundamental role in generating, accumulating, and revitalizing knowledge, leveraging their intellectual capacity, experience, and interpersonal interactions [38]. Therefore, we designated R&D researchers as representative labor inputs, denoting the number of personnel engaged in R&D projects.

From the perspective of output variables, our research focused on a reliable number of articles published in SCI and SCIE journals worldwide. We confined our analysis to these two categories because they align with global standards for objectively evaluating non-financial but valuable performance. As an additional output, financial performance is closely associated with patents and innovation [39]. Thus, we exclusively considered the number of patents registered with the Korean Intellectual Property Office (KIPO). Given the numerous instances of unsuccessful patent applications, we used the realized number of patents as a surrogate output variable representing financial performance, thus mitigating the potential for an undue emphasis on sustained performance. The final chosen output variable in this study was successful commercialization, represented by the proxy variable of the successful launch of venture businesses. As mentioned above, because of the unique nature of R&D investments, we set the timeframe for the gap between inputs and outputs as one year to ensure the successful operation of businesses as the commercialization of R&D. The descriptive characteristics are presented in Table 2.

To examine their potential as models, we analyzed the interrelationships between these variables. The results of the Pearson's correlation coefficient analysis are presented in Table 3. The positive correlation between R&D investment and the number of researchers with output suggests a proportional relationship. As inputs, such as R&D investment and the number of researchers, increase, outputs also tend to increase proportionally. Hence, the variables selected for this study appear to be appropriately aligned with the research objectives based on their 99% statistical significance.

**Table 3.** Correlation matrix.

| Variable | R&D Cost | Researchers | Successful Commercialization | Papers | Patents |
|---|---|---|---|---|---|
| R&D cost | 1.000 | 0.929 *** | 0.851 *** | 0.434 *** | 0.647 *** |
| Researchers | 0.929 *** | 1.000 | 0.890 *** | 0.720 *** | 0.823 *** |
| Successful commercialization | 0.851 *** | 0.890 *** | 1.000 | 0.610 *** | 0.759 *** |
| Papers | 0.434 *** | 0.720 *** | 0.610 *** | 1.000 | 0.902 *** |
| Patents | 0.647 *** | 0.823 *** | 0.759 *** | 0.902 *** | 1.000 |

*** $p < 0.001$.

## 4.2. R&D Investment Efficiency

### 4.2.1. Total R&D Efficiency Scores

As the first stage in measuring R&D performance, we examined the total efficiency of Korean local governments' R&D investments for six consecutive years (2016–2021) based on Equation (1). The results are presented in Table 4 and Figure 4 (see the black graph). The R&D efficiency scores ranged from 0.274 to 1, with an average of approximately 64.0%, implying that 36.0% efficiency can be potentially improved when R&D investment is on the frontier with the best performance. A relatively large amount can be assumed to be "blind money" or non-sustainable R&D activities. If the efficiency potential is greater than 25%, this implies that there is a lack of governance, especially in financial support from the public sector.

**Table 4.** R&D investment efficiency (Total).

| Cities | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Ave |
|---|---|---|---|---|---|---|---|
| Gangwon | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Gyeonggi | 0.232 | 0.208 | 0.208 | 0.163 | 0.156 | 0.143 | 0.185 |
| Gyeongnam | 0.416 | 0.471 | 0.488 | 0.397 | 0.366 | 0.358 | 0.416 |
| Gyeongbuk | 0.533 | 0.531 | 0.454 | 0.490 | 0.530 | 0.641 | 0.530 |
| Gwangju | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Daegu | 0.822 | 0.797 | 0.874 | 0.757 | 0.783 | 0.796 | 0.805 |
| Daejeon | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Busan | 0.666 | 0.800 | 0.779 | 0.803 | 0.750 | 0.706 | 0.751 |
| Seoul | 0.784 | 0.737 | 0.770 | 0.664 | 0.710 | 0.633 | 0.717 |
| Ulsan | 0.691 | 0.660 | 0.820 | 0.519 | 1.000 | 0.697 | 0.731 |
| Incheon | 0.343 | 0.306 | 0.310 | 0.282 | 0.260 | 0.301 | 0.300 |
| Jeonnam | 0.474 | 0.485 | 0.469 | 0.382 | 0.328 | 0.412 | 0.425 |
| Jeonbuk | 0.712 | 0.726 | 0.776 | 0.722 | 0.688 | 0.712 | 0.723 |
| Jeju | 1.000 | 0.708 | 1.000 | 1.000 | 1.000 | 0.652 | 0.893 |
| Chungnam | 0.385 | 0.313 | 0.359 | 0.360 | 0.310 | 0.295 | 0.337 |
| Chungbuk | 0.509 | 0.401 | 0.365 | 0.424 | 0.456 | 0.455 | 0.435 |
| **Ave** | 0.660 | 0.634 | 0.667 | 0.623 | 0.646 | 0.613 | 0.640 |

In particular, Table 4 shows divides in R&D among high-performing and lagging regions. Regarding individual regions, Gangwon, Gwangju, and Daejeon have the best performance, implying that R&D investments in the three cities are efficient from an overall perspective. It is noteworthy that Seoul, the capital city of Korea, did not perform well, implying that more is not always the best. Gyeonggi and Incheon, two neighboring areas of Seoul, exhibited the worst performance. This result is surprising in that the Metropolitan Seoul area undertakes most R&D activities with the majority of financial and non-financial support from the public; however, this resulted in very poor performance. Thus, quantitative support did not result in qualitative performance. This indicates a serious lack of R&D governance in these economically dynamic areas.

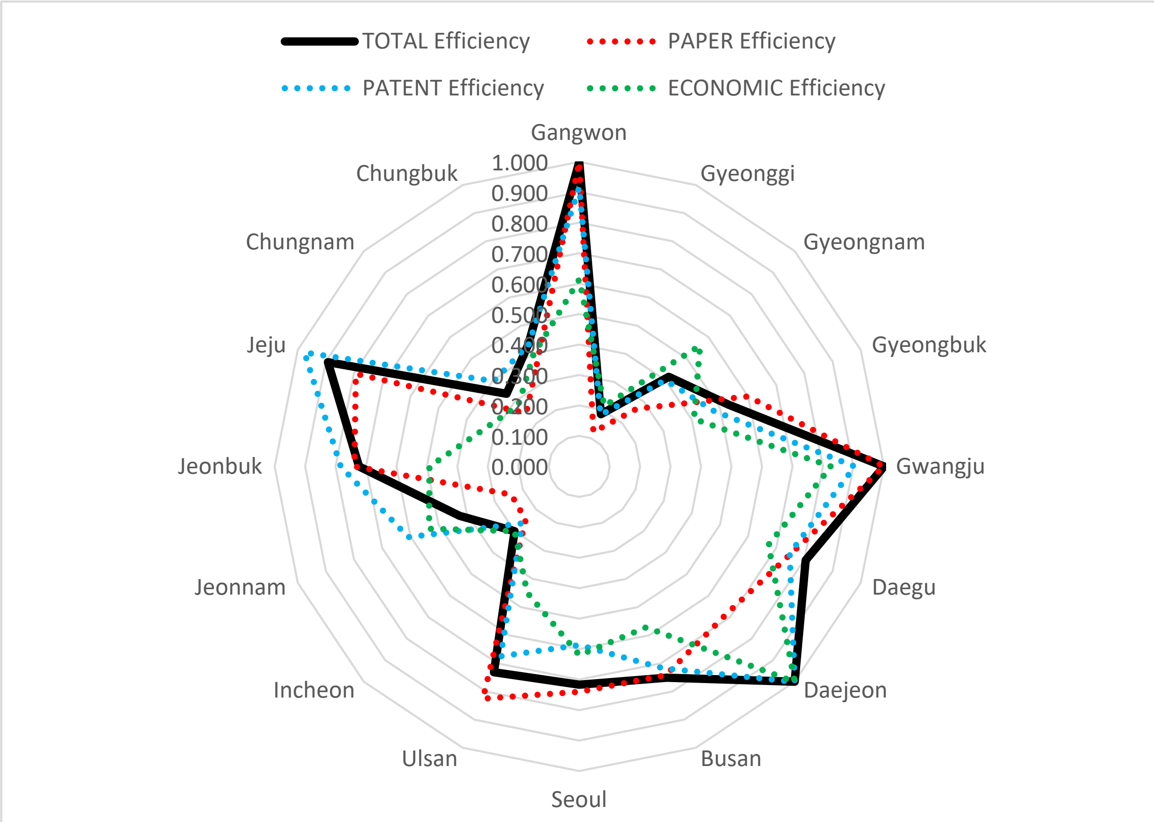


**Figure 4.** R&D investment efficiencies of each city.

Gangwon, Gwangju, and Daejeon show much higher R&D efficiency than the Metropolitan Seoul region. One reason for this may be that these areas are supported with much scrutinized favorable government policy support for specific areas, such as medical R&D in Gangwon and optical physics in Gwangju, which promotes the flourishing of customized or differentiated R&D investment. Thus, these cities may receive strong participation from specialized and concentrated companies in these particular fields. These cities are equipped with specialized R&D organizations, universities, and research teams dedicated to specific technologies or industries, resulting in efficient R&D inputs and outputs. These cities have abundant human resources, including researchers, engineers, and professionals with high levels of technology and innovation, which provide strong support for the city's research efforts. This empirical result shows the very important political insight that more specific and proactive participation of the public sector can result in better R&D performance.

The potential reasons for the low-efficiency values of the low-scoring regions are summarized as follows. First, a lack of effective government support may reduce the focal point of R&D performance. In regions with low-efficiency scores, government support may be insufficient or misallocated owing to the general and obscure direction of policies. The government may grant R&D funds based on the belief that something is better than nothing, resulting in superficial performance. Although these regions may have received substantial financial and non-financial support, this may not have translated into high-quality R&D activities. Second, poorly managed R&D activities may result in poor short-term performance. These regions may face serious problems with the management of R&D activities, leading to wasted resources and inefficiencies. The potential recipient of R&D funds may submit outstanding proposals; however, incentives for such proposals to be completed are insufficient, owing to the lack of a supervisory role from local governments that results in a lack of transparency, irrational decision-making processes, or a lack of effective monitoring and evaluation mechanisms. Third, the lack of effective field-oriented policies may result in resource wastage. Many local governments are supported by the central government in meeting innovation challenges, such as electrical batteries and AI-related projects, with only promising environmental conditions surrounding these local economies. If there are not many R&D-specific resources, sustainable performance may fail. This may be due to brain drain and a lack of policies to attract and retain talent, among other factors.

Revisiting the results based on the broader LUCC theory provides a deeper understanding of spatial variations in R&D efficiency across different cities in South Korea. LUCC serves as a key indicator of regional economic development and ecological quality, linking human socioeconomic activities with natural ecological processes. R&D investments drive economic development by promoting technological advancement and increasing productivity, which in turn significantly impacts land use and cover change (LUCC). Our study found that cities such as Gangwon, Gwangju, and Daejeon exhibit high R&D efficiency. This can be attributed to effective land-use planning and sustainable development strategies that optimize the use of available resources while minimizing the environmental impact. These cities are likely to balance economic growth with ecological preservation, thereby achieving higher R&D efficiency. However, Seoul's poor R&D performance may be partially explained by the challenges associated with rapid urbanization and intensive land use changes. Seoul's high population density and extensive urban development could lead to the inefficient use of R&D investments, as resources may be strained, and environmental degradation may offset the potential benefits of technological advancements. Therefore, it is essential to consider the LUCC when formulating R&D policies to ensure that economic development is achieved without compromising ecological sustainability. Policymakers should aim to create a harmonious balance between promoting innovation and maintaining ecological integrity to foster sustainable urban growth.

#### 4.2.2. Three Types of R&D Efficiency Scores

To examine the governance or sustainability mechanism of R&D activities, total factor efficiency was decomposed into three R&D efficiencies by sorting the three output variables. Because the three types of output variables represent economy, innovation, and academic achievement, respectively, these results will help provide more detailed implications for improving the governance of R&D promotion policies. Overall, with an average value of six years, each efficiency shows huge potential for enhancement: patent efficiency (0.629), paper efficiency (0.585), and economic efficiency (0.517). (Three types in order of each year in Table 5). This implies that patent performance is better than the other two outputs, implying that a patent is at least an easily adaptable signal of R&D performance. However, as shown in Figure 4, each region exhibits a different pattern. For instance, Daejeon showed the best performance in terms of patents and economic efficiency, while the paper did not show good performance. In contrast, Ulsan exhibited the best paper performance compared with the other two. This implies that the performance of R&D activities can be captured differently depending on the surrounding economic structure and political conditions; thus, local governments should emphasize a relatively lower field of R&D activities. For example, even if Ulsan hosts one of the most capital-intensive industries compared with other cities, such as Hyundai Heavy Industry and many oil and chemical companies, the role of R&D in patents and commercialization did not seem to work well. Thus, incentives for these relatively low-performance areas can improve the sustainable efficiency of R&D.

Thus far, we have explored R&D performance in terms of efficiency. This approach is useful for comparing relative performances; however, it is limited when it comes to exploring dynamic changes. Therefore, to analyze the changes over time, we used the Malmquist Index, which will be discussed in the next section. In most regions, the patent efficiency of R&D is higher than that of the others. This may imply that this patent, as an R&D performance index, is easily capturable; thus, most R&D recipient institutions prefer this patent. However, this could be superficial unless these patents are utilized in publications in global journals or venture types for commercialization. Therefore, local governments should emphasize sustainable R&D mechanisms to ensure beneficial circulation over time. To evaluate these efficiency dynamics over time, the MI is empirically tested in the following section.

**Table 5.** R&D investment efficiency (three types).

| Cities | 2016 | | | 2017 | | | 2018 | | | 2019 | | | 2020 | | | 2021 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gangwon | 1.000 | 1.000 | 0.606 | 1.000 | 1.000 | 0.492 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.430 | 1.000 | 0.669 | 0.460 | 1.000 | 0.828 | 0.695 |
| Gyeonggi | 0.155 | 0.188 | 0.370 | 0.150 | 0.198 | 0.208 | 0.131 | 0.200 | 0.219 | 0.106 | 0.189 | 0.144 | 0.099 | 0.165 | 0.189 | 0.099 | 0.157 | 0.158 |
| Gyeongnam | 0.288 | 0.359 | 0.628 | 0.290 | 0.406 | 0.678 | 0.272 | 0.438 | 0.765 | 0.253 | 0.447 | 0.387 | 0.243 | 0.355 | 0.504 | 0.243 | 0.396 | 0.404 |
| Gyeongbuk | 0.612 | 0.408 | 0.489 | 0.619 | 0.516 | 0.349 | 0.535 | 0.474 | 0.287 | 0.566 | 0.466 | 0.333 | 0.595 | 0.406 | 0.448 | 0.595 | 0.594 | 0.538 |
| Gwangju | 1.000 | 0.852 | 1.000 | 1.000 | 0.879 | 0.701 | 1.000 | 1.000 | 0.610 | 1.000 | 0.909 | 0.648 | 1.000 | 0.784 | 1.000 | 1.000 | 1.000 | 1.000 |
| Daegu | 0.779 | 0.691 | 0.844 | 0.796 | 0.690 | 0.562 | 0.784 | 0.783 | 0.661 | 0.704 | 0.780 | 0.471 | 0.748 | 0.683 | 0.741 | 0.748 | 0.860 | 0.754 |
| Daejeon | 1.000 | 1.000 | 1.000 | 0.675 | 1.000 | 1.000 | 0.618 | 1.000 | 1.000 | 0.619 | 1.000 | 1.000 | 0.599 | 1.000 | 1.000 | 0.599 | 1.000 | 1.000 |
| Busan | 0.656 | 0.632 | 0.612 | 0.771 | 0.791 | 0.525 | 0.799 | 0.758 | 0.481 | 0.768 | 0.734 | 0.534 | 0.747 | 0.673 | 0.666 | 0.747 | 0.716 | 0.615 |
| Seoul | 0.866 | 0.588 | 0.749 | 0.814 | 0.633 | 0.486 | 0.687 | 0.584 | 0.730 | 0.719 | 0.570 | 0.435 | 0.696 | 0.513 | 0.784 | 0.696 | 0.633 | 0.534 |
| Ulsan | 0.774 | 0.497 | 0.655 | 0.814 | 0.723 | 0.348 | 0.808 | 0.752 | 0.551 | 0.754 | 0.691 | 0.239 | 1.000 | 0.616 | 0.407 | 1.000 | 0.768 | 0.487 |
| Incheon | 0.253 | 0.267 | 0.454 | 0.251 | 0.287 | 0.258 | 0.222 | 0.305 | 0.300 | 0.246 | 0.249 | 0.228 | 0.247 | 0.189 | 0.281 | 0.247 | 0.291 | 0.281 |
| Jeonnam | 0.315 | 0.556 | 0.534 | 0.234 | 0.692 | 0.724 | 0.236 | 0.659 | 0.660 | 0.204 | 0.582 | 0.446 | 0.228 | 0.497 | 0.301 | 0.228 | 0.657 | 0.539 |
| Jeonbuk | 0.753 | 0.671 | 0.619 | 0.759 | 0.867 | 0.383 | 0.741 | 0.821 | 0.476 | 0.721 | 0.823 | 0.400 | 0.758 | 0.745 | 0.479 | 0.758 | 0.770 | 0.593 |
| Jeju | 0.909 | 1.000 | 0.472 | 0.607 | 0.892 | 0.385 | 0.667 | 1.000 | 0.337 | 0.873 | 1.000 | 0.216 | 0.863 | 1.000 | 0.181 | 0.863 | 0.968 | 0.398 |
| Chungnam | 0.262 | 0.401 | 0.431 | 0.227 | 0.335 | 0.270 | 0.251 | 0.417 | 0.274 | 0.261 | 0.486 | 0.245 | 0.237 | 0.373 | 0.258 | 0.237 | 0.364 | 0.221 |
| Chungbuk | 0.396 | 0.444 | 0.579 | 0.324 | 0.381 | 0.350 | 0.308 | 0.426 | 0.252 | 0.376 | 0.492 | 0.265 | 0.414 | 0.399 | 0.434 | 0.414 | 0.460 | 0.490 |
| Average | 0.626 | 0.597 | 0.628 | 0.583 | 0.643 | 0.482 | 0.566 | 0.664 | 0.538 | 0.573 | 0.651 | 0.401 | 0.592 | 0.567 | 0.508 | 0.592 | 0.654 | 0.544 |

Three types: paper efficiency, patent efficiency, and economic efficiency in order of each year.

### *4.3. R&D Malmquist Index*

#### 4.3.1. Total R&D Malmquist Index

The most important role of R&D can be found in the innovation effect over time; thus, R&D can move the PPS much higher over time. Therefore, to evaluate the realized R&D effect more precisely, it is better to examine the transformation performance of these technologies on the productivity of each region. Based on Equation (2) above, therefore, we evaluated the productivity change over time based on these innovation effects on the PPS. To examine this change precisely, our basic line was based on the geometric average to determine the growing projection trend of the PPS.

As shown in Figure 4, the average or overall Malmquist Index value (black line in the figure) fluctuates over time, with a value of 0.978 (Table 6), implying that even if there was no strong trend, there was still 0.22 unit of deterioration in productivity. This result suggests that R&D investment did not show any particular trends in its performance, although the government's R&D budget increased continuously during the same period. This implies that financial support by the government did not perform well in promoting R&D activities, resulting in a lack of governance. Interestingly, it shows an "M-shape" during the empirical years, which means fluctuations occur in performance during the empirical years. In particular, the reason for another peak in 2020 comes from the fact that the COVID-19 pandemic resulted in a deep recession, but to overcome this global infection crisis, the Korean government put a lot of financial support into developing immunotherapy, resulting in some outstanding innovations during the COVID-19 era, such as online education and virtual meeting systems and diverse anti-virus or immune medicine.

**Table 6.** Malmquist Index (TOTAL).

| CITIES | 2016/17 | 2017/18 | 2018/19 | 2019/20 | 2020/21 | Ave |
|---|---|---|---|---|---|---|
| Gangwon | 1.037 | 1.042 | 0.938 | 0.980 | 1.004 | 1.000 |
| Gyeonggi | 0.916 | 0.962 | 0.786 | 0.936 | 0.889 | 0.898 |
| Gyeongnam | 1.123 | 1.051 | 0.808 | 0.966 | 0.933 | 0.976 |
| Gyeongbuk | 1.033 | 0.830 | 1.096 | 1.020 | 1.141 | 1.024 |
| Gwangju | 0.975 | 1.028 | 0.991 | 1.040 | 0.965 | 1.000 |
| Daegu | 0.943 | 1.102 | 0.872 | 1.096 | 0.954 | 0.993 |
| Daejeon | 1.026 | 0.986 | 1.000 | 0.894 | 0.980 | 0.977 |
| Busan | 1.140 | 0.987 | 1.038 | 0.990 | 0.881 | 1.007 |
| Seoul | 0.917 | 1.042 | 0.859 | 1.114 | 0.837 | 0.954 |
| Ulsan | 0.957 | 1.244 | 0.647 | 1.935 | 0.682 | 1.093 |
| Incheon | 0.909 | 1.010 | 0.902 | 0.929 | 1.098 | 0.970 |
| Jeonnam | 1.007 | 0.987 | 0.810 | 0.912 | 1.197 | 0.983 |
| Jeonbuk | 0.961 | 1.085 | 0.946 | 0.987 | 0.830 | 0.962 |
| Jeju | 0.688 | 1.280 | 0.769 | 1.110 | 0.590 | 0.887 |
| Chungnam | 0.826 | 1.111 | 1.023 | 0.850 | 0.908 | 0.944 |
| Chungbuk | 0.796 | 0.879 | 1.190 | 1.104 | 0.945 | 0.983 |
| **Ave** | 0.953 | 1.039 | 0.917 | 1.054 | 0.927 | 0.978 |

If we consider this an instantaneous surge but not a sustainable effort by the government, the long-term trend of R&D efficiency may become a serious downturn, implying a serious bottleneck in R&D or a lack of governance in government promotion policies. Owing to this lack of governance, the Korean government proclaimed a very sharp reduction in its R&D promotion budget in 2024. Unfortunately, the government did not differentiate R&D performance from more precise and appropriate perspectives for each area of R&D, resulting in an increasing concern for the loss of growth potential. Greater financial support for R&D does not guarantee better performance. However, less R&D support improves the role of government support in R&D. To determine the detailed mechanism of the R&D efficiency trends, we decomposed total productivity into three types.

#### 4.3.2. Three Types of R&D Malmquist Index

As shown in Figure 5, we found different trends in the three types of productivity. From the figure, we can guess that the "M-shape" of average productivity value is influenced by economic conditions, especially the unexpected outbreak of COVID-19 in 2019–2020. Fluctuations in economic productivity owing to R&D are often indicators of macroeconomic change. According to the economic cycle theory, economies undergo cyclical fluctuations characterized by booms and recessions. During booms, investment and employment increase, productive activities flourish, and productivity levels rise. Conversely, recessionary periods are characterized by reduced investment, layoffs, and constraints on productive activities, leading to a possible decline in productivity. Thus, changes in economic productivity are closely related to macroeconomic changes. The sudden outbreak of COVID-19 resulted in a large recession, but proactive public support by the Korean government to overcome this global crisis with technological innovation became the main catalyst for economic recovery in 2020. However, these recessions and recoveries were not sustainable because of the lack of governance. As the COVID-19 pandemic eased over time, the economic recovery strongly supported the role of R&D; thus, the Korean government wanted to hold any crowding-out effect by overemphasizing financial and non-financial support for R&D, resulting in lower performance again.

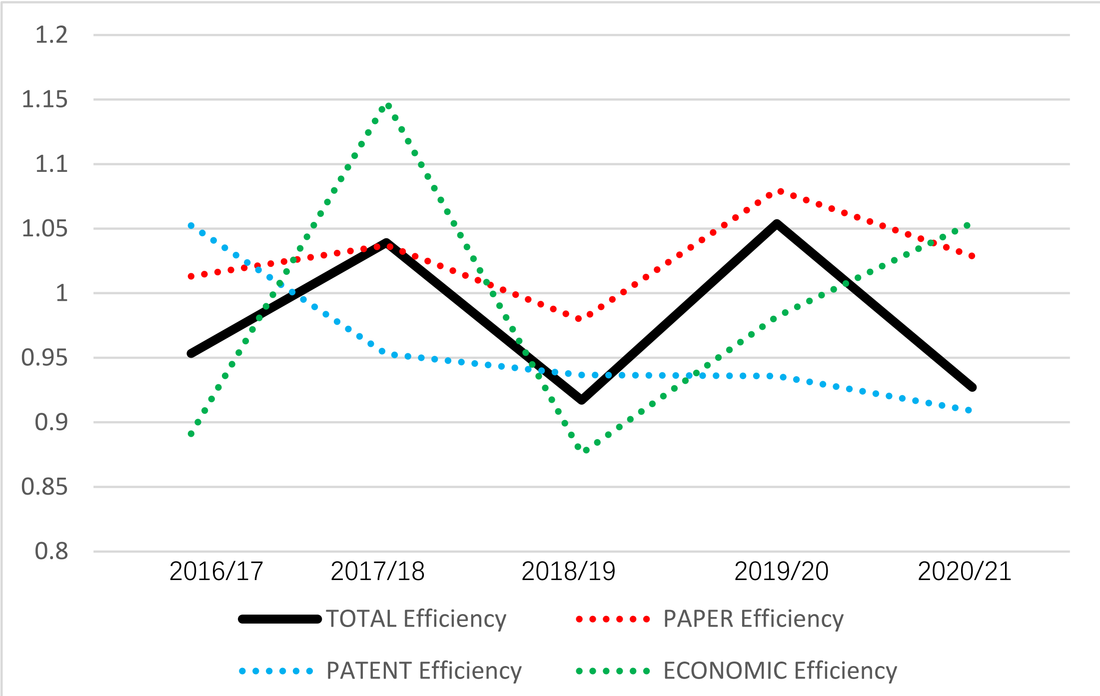


**Figure 5.** R Malmquist Index trends in R&D investment.

Nonetheless, in contrast to the comparatively lower overall productivity, paper productivity increased, with an average growth rate of 1.028. High-quality academic papers typically require substantial R&D investment. The Korean government has taken proactive steps to encourage increased academic paper activities, as exemplified by increased financial allocations to research institutes and universities. The government evaluated the ranks of all academic institutions in terms of papers published in objectively high-level journals, such as the Scientific Citation Index (SCI) or the Social Science Citation Index (SSCI). Moreover, highly ranked universities with published papers may recruit more students. Therefore, the growing emphasis on academic papers by both academic and government bodies has bolstered the support and promotion of such endeavors through R&D investments, especially for paper publications. Elevated academic prowess serves as a magnet for increased resource allocation and investment, thereby facilitating the economic translation of paper outcomes. Academic paper outcomes often boast advanced technical sophistication and innovation with significant potential for commercialization and economic exploitation. As academic standards increase, paper findings become more appealing to industrial sectors and market domains, thereby yielding economic dividends and fostering the advancement of the Korean economy. This dynamic interplay not only enhances Korea's technological innovation capacity and industrial competitiveness but also injects fresh momentum into economic growth. In essence, the economic transformation of high-caliber academic paper outcomes catalyzes the development of the Korean economy, while robust economic backing furnishes academia with the requisite resources and environment to further elevate academic standards. This symbiotic relationship engenders a virtuous cycle propelling the concurrent advancement of the Korean economy and academia.

Compared with the relatively workable role of R&D on paper, patent productivity shows a continuous downward trend that is lower than unity. Challenges in patent productivity may indicate hurdles in R&D for technological transformations. Despite robust support from the Korean government for R&D, obstacles persist in translating research outcomes into commercially viable patented products or technologies. These challenges may stem from deficient technology-transfer mechanisms, limited industry acceptance of new technologies, and insufficient market demand. Moreover, shortcomings in the Korean government's R&D policy may exacerbate the situation by inadequately directing R&D investments toward innovation and commercialization. A policy orientation overly fixed on academic paper output and neglecting patent output exacerbates the mismatch between R&D inputs and patent outputs, thereby impeding R&D input performance. The most important problem with this patent may arise from mismatches or missing links between the demand and supply. Many universities enroll an enormous number of patents every year, but most of them are not utilized or transformed into appropriate companies owing to asymmetrical information. Many industries complain that precise matching technologies are not available for business purposes. Thus, in 2009, the Korean government initiated the Korea Institute for Advancement of Technology (KIAT) to match the asymmetrical demand and supply of new technology. Nonetheless, it has not worked well because KIAT is just a simple helper as a matchmaker and not a proactive partner in recruiting and arranging all these unmatching partners.

Therefore, R&D commercialization has resulted in an ever-decreasing trend, as shown in Figure 5. Even with ever-increasing efforts in R&D, our empirical results clearly show a lack of governance with many missing links from R&D to commercialization. The paper publication showed the highest productivity trend due to the proactive support of the government, as well as the partnership from universities, while patent and economic commercialization did show a fluctuating downward trend in productivity, implying that most public support resulted in superficial, short-term performance without any significant promotion of the regional economy. The lowest efficiency in the Metro Seoul area indicates a superficial effect of policy support. This is the fundamental challenge of the Korean Paradox.

## 5. Conclusions

The global economy has been experiencing rapid changes with the emergence of new norms, such as the artificial intelligence revolution and the climate crisis. Owing to this new phenomenon, most governments have begun to emphasize green technology and sustainable innovation. To promote this transformation of the economic structure, many countries, such as Korea and China, have made great efforts to improve R&D performance. Nonetheless, we should consider R&D as a tool rather than as an objective itself. More R&D activity may not result in better performance or higher economic growth potential. In this study, we show the Korean Paradox, which implies that more R&D effort may not be statistically significant, even with a negatively aggravating effect on economic growth.

This study explored the phenomenon known as the "Korean Paradox", where significant R&D investments do not seem to correlate with proportional economic growth and productivity. Our results show that public support for R&D may result in the short-term, superficial performance of paper publications. However, patents and their commercialization did not seem to be successful in our empirical test, implying a lack of governance with much higher efficiency improvement potential. Our investigation, using a Slack-Based Measure Data Envelopment Analysis (SBM-DEA) and the Malmquist Productivity Index, provides nuanced insights into the efficiency of R&D investments across different regional governments in Korea. The analysis revealed an average efficiency score of 64% for R&D investments in Korean local governments, indicating substantial potential for efficiency improvement of up to 36%. Gangwon and Gwangju demonstrated superior R&D efficiency, which can be attributed to their specialized focus on sectors such as medical technology and optical fibers. The temporal dynamics captured by the Malmquist Index showed a slight overall deterioration in productivity despite some regions exhibiting growth due to specific policy support and sectoral focus.

To identify the missing links in this paradox, we examined the R&D efficiency and productivity of 16 local governments in Korea from 2016 to 2021. The main findings and policy suggestions are summarized as follows: The average total R&D efficiency score was 64.0% during the experimental period. This means that there is potential for a 36.0% improvement if each local government achieves its optimal R&D investment.

Otherwise, there is a huge lack of governance for this unrealized efficiency. We employed the Malmquist Index to explore the dynamics of R&D performance. The results revealed a promising upward trend in the future, albeit only when the output consisted of published papers. This trend is likely attributable to the positive impact of factors such as the Korean government's robust support for academic research and the proactive participation of universities in receiving R&D-related financial support. These factors may have contributed to the rapidly increasing number of papers, consequently increasing the overall efficiency of the research inputs.

However, this performance in paper publications seems superficial because it does not promote the next stage of the patent and its commercialization. The Korean government emphasizes only better proposals for R&D and not realized performance. Thus, most universities are not concerned about the quality of their patents. Too much focus on quantitative achievement in patents, therefore, does not result in their utilization and commercialization. A very small proportion of patents may generate profits for industries. Given this negligible income, most universities do not make serious efforts to promote their patents and their utilization. Worse than this, there are too many missing links between demand by the industrial sector and the supply of patents or new technology coming from R&D.

Based on these findings, we propose the following policy recommendations to optimize the efficiency of local governments' R&D inputs in Korea. First, the government must intensify its focus on technology transfer and the establishment of innovative ecosystems within research investment frameworks. This entails bolstering technology-transfer mechanisms, fostering greater industry acceptance of new technologies, and stimulating market demand. For example, the Fifth Science and Technology Basic Plan (2023–2027) sets out a clear mission to focus on 12 strategic technology areas and invest in targeted R&D tasks by pooling the strengths of various parties, including local governments and enterprises. In response to the technological characteristics and development stages of different areas, the central government differentiated R&D objectives and specific technology roadmaps and integrated key resources and forces of various parties in science, technology, and innovation. This task-oriented R&D system may accelerate the development and application of new technologies and, in turn, contribute to the industry's acceptance of new technologies. Nonetheless, the missions for each local government were not field- or performance-oriented. Therefore, the central government should implement more systematic value-sharing networks to facilitate the utilization of local conditions and resources.

Second, we underscore the importance of reinforcing the collaboration between academia and industry to facilitate the seamless translation and commercialization of research outcomes. For example, the Korean government has launched the National Strategic Technology Incubation Program, which has established "joint research institutes for enterprises" within public research institutes and universities to strengthen collaborative measures in areas such as core materials, parts and components, and original technologies. This initiative promotes close partnerships between enterprises and universities and effectively improves R&D efficiency. Only through the proactive guidance of government policies and concerted efforts across all stakeholders can Korea's R&D investment efficiency be heightened, thereby yielding substantial advancements in science and technology innovation and economic development.

The role of government governance in shaping R&D investment efficiency should not be overstated. Delving deeper into the dynamics of R&D performance and policy recommendations, it becomes evident that effective government intervention is pivotal for fostering innovation and driving economic growth. Therefore, to avoid the Korean Paradox, the most important challenge is a sustainable partnership between the public and private sectors. Since the sustainable performance of R&D is a complex process in the business network, all related parties should not be simple helpers but rather partners.

All parties in this R&D network should participate in value creation and share the created values. Otherwise, short-term superficial performance may occur.

Although this study makes significant contributions from several perspectives, it has some limitations. First, the scope of the data and regional focus may limit the generalizability of the findings across all types of economies. Second, the study's dependency on secondary data sources and the methods employed (SBM-DEA and Malmquist Index) may not capture all the nuances of R&D efficiency and economic impact. Future studies could expand the geographical scope and incorporate primary data collection to enhance the understanding of R&D efficiency dynamics. Investigating the impact of different types of R&D activities (basic versus applied) on regional economic performance can provide deeper insights. Longitudinal studies involving more frequent data collection intervals may reveal trends and changes in efficiency more accurately. By addressing these areas, future research can clarify the complex relationship between R&D investment and economic performance, ultimately aiding policymakers in crafting strategies to better leverage R&D for economic growth. This study's findings contribute to the ongoing dialogue on optimizing R&D expenditure to avoid the pitfalls of the "Korean Paradox" and encourage a more strategic approach to fostering innovation-driven economic development.

**Author Contributions:** Conceptualization, S.L. and Y.C.; methodology, H.L.; validation, S.L., Y.C. and H.L.; formal analysis, S.L.; investigation, S.L.; resources, H.L.; data curation, H.L.; writing—original draft preparation, S.L.; writing—review and editing, S.L.; visualization, S.L.; supervision, Y.C.; project administration, Y.C.; funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** This study was supported by an Inha University Research Grant.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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