Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2021.26946

218 (2021) 80–86
April

Relations between upgrading of industrial structure, innovation of green technology and water environmental pollution: estimation based on dynamic simultaneous equation

Xin-yu Wang[a], Dong-sheng Zhao[b,*], Li-li Zhang[c], Han-qing Hu[d], Ya-dong Ma[a], Jiao-yue Ma[e]

[a]*School of Economics and Management, North China University of Technology, Beijing 100144, China, emails: crcet.wangxinyu@qq.com (X.-Y. Wang), mayadong@yeah.net (Y.-D. Ma)*
[b]*Department of Education, Anyang Preschool Education College, Anyang, Henan 455000, China, email: zhaodongsheng321@126.com*
[c]*Department of Life Culture, Beijing College of Social Administration, Beijing 101601, China, email: sdlxzhll@163.com*
[d]*School of Economics and Management, Beijing Information Science and Technology University, Beijing, 100192, China, email: hanqinghu@bistu.edu.cn*
[e]*National Center for Forestry Stations Management, National Forestry and Grassland Administration, Beijing 100714, China, email: 982731724@qq.com*

Received 26 May 2020; Accepted 13 December 2020

ABSTRACT

It is a crucial problem encountered by Chinese water pollution control to clarify the relations between upgrading of Chinese industrial structure, the innovation of green technology and water environmental pollution. Based on the panel data of 30 provinces and cities of China from 2004 to 2018, a dynamic simultaneous equation model is constructed to examine empirically the relations between the upgrading of industrial structure, the innovation of green technology and water environmental pollution in China. The results show: upgrading of industrial structure, the innovation of green technology and water environmental pollution of the lagged phase all show positive correlations with that of the current phase; upgrading of the industrial structure has bidirectional causality with water environmental pollution but has spiral upward relation with water environment quality; upgrading of the industrial structure shows asymmetric relation with the innovation of green technology, which has asymmetric relation with water environmental pollution; innovation of green technology promotes unidirectionally and significantly the upgrading of industrial structure, and water environmental pollution has inversed effects on innovation of green technology. Therefore, relevant governmental departments should strictly adhere to “the red line of environmental protection” and adjust the industrial structure timely and effectively when governing water environmental pollution.

Keywords: Upgrading of industrial structure; Innovation of green technology; Water environmental pollution; Simultaneous equation model

* Corresponding author.

1. Introduction

For over 40 y of carrying out the reform and opening-up policy, China has achieved remarkable achievements in economic construction by undertaking large-scale industrial transfer and improving actively its status in the international division of labor. At the same time, the Chinese industrial structure is upgrading continuously. As for the division of the three industrial structures, countries in the world are not completely consistent. China's division of the three industries is as follows: the first industry is agriculture (including planting, forestry, animal husbandry and fishery). The secondary industry is the industry and construction industry, among which industries include mining industry, manufacturing industry, production and supply of electricity, gas and water. The tertiary industry refers to all industries except the primary and secondary industries, mainly including circulation and service sectors. In 1978, the proportion between the three industrial structures was 9.8:61.8:28.4, with the contribution rate to drive the Chinese national economy of 1.1:7.2:3.3; in 2018, the proportion between the three industrial structures was 4.2:36.1:59.7, with the contribution rate to drive Chinese national economy of 0.3:2.4:3.9. However, the problems of environmental pollution brought by economic development are also prominent, among which water environmental pollution is becoming more and more serious especially, with the quantity of wastewater increasing at the annual speed of 1.8 billion m^3. Chemical oxygen demand and biochemical oxygen demand indicators exceed the standards severely, eutrophication in lakes of all provinces is prominent, and the emission facilities of highly-polluting enterprises are antiquated so that the wastewater cannot be treated timely and urban sewage cannot be dealt with efficiently. Such phenomena are becoming more and more serious in recent years, and problems, such as water degradation and soil pollution, come up one after another. Degradation of water environmental quality has affected severely the life quality of human beings and sustainable development has been threatened greatly; therefore, it has become a global consensus to improve the ecological conditions. Under the new normal economy, China's development mode at the expense of overdrawing resources and ecological environment is no longer sustainable, and the problem of water pollution requires urgent treatment. Faced with environmental threats, the world is trying to develop green technology to reduce water environmental pollution and protect the ecological environment. Obviously, it is of great academic value and practical significance to study in-depth the relations between industrial structure, green technological innovation, and water environmental pollution, which could provide data support for China's control of water environment pollution.

2. Literature review

The literature on the upgrading of industrial structure, the innovation of green technology and water environmental pollution are divided mainly into three types: first, relations between upgrading of industrial structure and innovation of green technology, second, relations between upgrading of industrial structure and water environmental pollution, and third, relations between the innovation of green technology and water environmental pollution.

2.1. Relations between upgrading of industrial structure and innovation of green technology

At present, the research on the upgrading of industrial structure and innovation of green technology mainly focuses on the upgrading of industrial structure and technology innovation. Chen et al. [1] found that upgrading and adjustment of the industrial structure showed positive correlations with technological innovation in the Beijing-Tianjin-Hebei region; Chen et al. [2] studied the influences of industrial structure changes on technological innovation by adopting the method of progressive regression, and the result showed that optimization of industrial structure could help improve the ability of technological innovation.

2.2. Relations between upgrading of industrial structure and water environmental pollution

According to Wang et al. [3], technological innovation could promote carbon productivity, and it is part of the intervening variable of environment regulation and carbon productivity. There is U-shaped relation between environmental regulation and carbon productivity. Before reaching the turning point, environmental regulation could affect carbon productivity negatively; however, after crossing the turning point, an increase in the intensity of environmental regulation could promote carbon productivity. The influences of environmental regulation on carbon productivity have significant regional heterogeneity.

Li et al. [4] found technological progress in the eastern region was more likely to promote industrial growth, while progress in the central and western regions was likely to promote increased pollutant emissions.

2.3. Relations between the innovation of green technology and water environmental pollution

Huang et al. [5] measured the influences of the upgrading of industrial structure on environmental pollution by using a bilateral stochastic frontier model, and the results showed that the interaction between factor market distortions and upgrading of industrial structure makes the distortion of factor markets weaken the function of industrial structure upgrading reducing pollution. Wang et al. [6] studied the relations between the output of various industries in the national economy and the amount of pollution emissions using Granger causality test and regression estimation, and the results found that upgrading of industrial structure is conducive to reducing the emission of environmental pollution. Chen et al. [7] thought that after the industrial structure crossed the threshold, its aggravating effects on environmental pollution would be decreased. An and Li [8] found that the proportion of the secondary industry in Tibet had significant positive effects on environmental pollution, and the relationship between the proportion of the tertiary industry and environmental pollution showed typical inverted U-shaped curve relation, which conforms to the environmental Kuznets curve hypothesis. Lu [9] believed that manufacturing industries with low technology-intensive and capital-intensive polluting industries could deteriorate water environmental pollution.

Zheng et al. [10] found industrial structure has a three-stage influential mechanism on NOx pollution and PM 2.5 pollution, and a two-stage influential mechanism on SO_2 pollution. A decrease in the proportion of the secondary industry output in the gross domestic product (GDP) can significantly reduce NOx pollution and SO_2 pollution. The industrial structure can change the effects of economic development on air pollution.

In conclusion, so far, scholars both at home and abroad have achieved abundant research results on the relations between upgrading of industrial structure and technological innovation, technological innovation and environmental pollution as well as upgrading of industrial structure and water environmental pollution, which are the bases of this study. However, there are still some problems: Most of the studies consider only the relations between two variables, without studying the interactive feedback mechanisms between these three variables under the framework of the upgrading of industrial structure, technological innovation and environmental pollution; the existing studies focus mainly on the casual relationship between the variables, without conducting further studies from the perspective of statistics.

To solve the causal relationship that may exist in the process of controlling environmental pollution, a triple simultaneous equation is established based on the panel data of 30 provinces and cities in China from 2004 to 2018, which include upgrading of industrial structure, the innovation of green technology and environmental pollution. Compared with a single equation, simultaneous equations could analyze the interactions between these three factors better, making the estimation results more robust. With the simultaneous equations, not only various effects of the upgrading of industrial structure and innovation of green technology on environmental pollution are analyzed empirically, but also the influencing factors of these effects are also demonstrated.

3. Model selection and variable description

3.1. Model selection

Considering that the relations between upgrading of industrial structure, the innovation of green technology and environmental pollution might be endogenous and complex, a single equation model cannot reveal completely the interrelations between them. However, simultaneous equations could investigate the internal relations between all the equations, so, three simultaneous equations are established for empirical test.

$$\begin{cases} \ln \text{Ind}_{i,t} = \alpha_0 + \alpha_1 \ln \text{Ind}_{i,t-1} + \alpha_2 \ln \text{Green}_{i,t} + \alpha_3 \ln \text{Pol}_{i,t} + \alpha_4 \ln \text{Hum}_{i,t} + \alpha_5 \ln \text{Gov}_{i,t} + \mu_{i,t} + \varepsilon_{i,t} & (1) \\ \ln \text{Green}_{i,t} = \beta_0 + \beta_1 \ln \text{Green}_{i,t-1} + \beta_2 \ln \text{Ind}_{i,t} + \beta_3 \ln \text{Pol}_{i,t} + \beta_4 \ln \text{Er}_{i,t} + \beta_5 \ln \text{Ier}_{i,t} + \beta_6 \ln \text{Fdi}_{i,t} + \mu_{i,t} + \varepsilon_{i,t} & (2) \\ \ln \text{Pol}_{i,t} = \gamma_0 + \gamma_1 \ln \text{Pol}_{i,t-1} + \gamma_2 \ln \text{Ind}_{i,t} + \gamma_3 \ln \text{Green}_{i,t} + \gamma_4 \ln \text{Er}_{i,t} + \gamma_5 \ln \text{Ier}_{i,t} + \gamma_6 \ln \text{Pgdp}_{i,t} + \gamma_7 \ln \text{Pop}_{i,t} + \mu_{i,t} + \varepsilon_{i,t} & (3) \end{cases}$$

where, Ind, Green, Pol stand for three endogenous variables, that is, upgrading of industrial structure, the innovation of green technology and environmental pollution; Hum is the human capital, Gov is the size of government, Er is formal environmental regulation, Ier is informal environmental regulation. Fdi is foreign direct investment, Pgdp is per capita growth domestic product, Pop is population density, μ is an individual fixed effect, *i,t* are province and time.

3.2. Variable selection and data source

Due to the different statistical caliber, Hong Kong, Macao and Taiwan are excluded. As Tibet has too many missing values, it is also excluded. Therefore, this essay adopts the panel data of 30 provinces and cities of China from 2004 to 2018 for the study. The source of the variables are as follows:

3.2.1. Endogenous variables

Upgrading of industrial structure (Ind): at present, literature mostly assess Ind with the proportion of the secondary and tertiary industries to GDP, but this method cannot reflect fully the upgrading of industrial structure. This essay adopts the method proposed by Wang and Wu [11], that is, to evaluate upgrading of industrial structure with the layer of the industrial structure of the provinces. The equation is shown as follows:

$$\text{Ind} = d_1 \times 1 + d_2 \times 2 + d_3 \times 3 \tag{4}$$

In Eq. (4), d_1, d_2 and d_3 are the proportions of the primary industry, the secondary industry and the tertiary industry to GDP of the provinces. The larger Ind value is, the higher upgrading of the industrial structure is.

Innovation of green technology (Green): this essay adopts the innovation efficiency of green technology for the assessment. To analyze the efficiency of multi-input and output, the existing literature mostly adopts a data envelopment analysis (DEA) model. Kaoru [12] put forward the non-radial, non-angular DEA model-SBM model. Taking advantage of the advantages of super-efficiency, this essay adopts Super-SBM-DEA (super-slacks-based measure-data envelopment analysis) model to measure the innovation efficiency of green technology. The following input and output indicators are selected: (1) *Capital input*: internal expense of R&D (Research and Development) research and development expenditure is selected as the input indicator of technology innovation. (2) *Labor input*: labor input is divided into technical innovation personnel and green service personnel. R&D personnel are selected to measure full-time equivalent investment of technical innovation personnel, and water conservancy, urban environment and public service personnel are used to measure green input. (3) *Resource input*: Lin and Liu [13] converted natural gas, coal, and electricity into standard coal as resource and energy input when studying the energy efficiency of Chinese industrial industry; Li and Zhao [14] selected the total energy consumption of industrial enterprises over sector industrial scale to assess the resource input. This essay selects the total regional energy consumption to assess resource input. (4) *Pollution control input*: the completed investment in controlling industrial pollution is selected to represent the input in pollution control. (5) *Economic output* is evaluated by regional gross domestic product. (6) *Scientific output*: compared with patent applications, the amount of patent grants could represent more the strength of research and development. The methods raised by Bai and Jiang [15] and Yu and Liu [16] are adopted to assess scientific and technological output. (7) *Green output*: referring to the ideas of Sun et al. [17], Langemeyer et al. [18], urban greening space and park space are included in the green output. (8) *Output of environmental pollution*: selects the output of solid wastes, soot emissions, sulfur dioxide emissions, and wastewater drainage as the indicators of the output of environmental pollution, and uses the Entropy weight-TOPSIS method to obtain the comprehensive index of environmental pollution output. Specific setting indicators are shown in Table 1.

Water environmental pollution (Pol) is assessed in this essay with the intensity of water environmental pollution (industrial wastewater/GDP).

3.2.2. Exogenous variables

As required by the analysis, the following exogenous variables are selected:

Human capital (Hum): it is assessed by the average schooling and is used to control the influences of human capital on the upgrading of industrial structure; government size (Gov) is assessed by the proportion of governmental finance expenditure to GDP and is used to control the influences of government size on the upgrading of industrial structure.

Formal environment regulation (Er): this essay adopts the method proposed by Shen and Liu [19] to measure formal environment regulation, which is used to control the influences of formal environment regulation on green technology innovation and water environment pollution. The advantage of this method is that it not only includes the actual investment in controlling industrial pollution of all provinces, but also could avoid deviation in the evaluation of environment regulation intensity caused by differences of the upgrading of regional industrial structure. The specific calculation is as shown in Eq. (3):

$$\mathrm{Er}_{i,t} = \frac{\left(P_{i,t} / Y_{i,t}\right)}{\left(Y_{i,t} / \mathrm{GDP}_{i,t}\right)} \tag{5}$$

where P is the investment in controlling industrial pollution, Y is the gross industrial output value, i,t represent i regions, t years.

Informal environment regulation (Ier): referring to the method of Pargaland and Wheeler [20], indicators of urban residents' income level, education level, GDP, age structure and population density are selected to measure the informal environmental regulations, and the comprehensive value is solved by the entropy weight-TOPSIS method to control the influences of informal environment regulations on the innovation of green technology and water environmental pollution.

Foreign direct investment (Fdi): it is expressed by the proportion of foreign direct investment of all provinces to GDP. It is used to control the influences of foreign direct investment on innovation of green technology. Per capita growth domestic product (Pgdp) is represented by per capita GDP of all provinces and cities. It is used to control the influences of economic development on water environmental pollution. Population density (Pop) is represented by the proportion of the population to the land areas of all provinces and cities. It is used to control the influences of population density on water environmental pollution.

The data adopted in this essay comes mainly from China Statistical Yearbook and China Environmental Statistics Yearbook. Some missing data is filled with the method of

Table 1
Selection of input–output index of green technology innovation efficiency

	Index	Measuring method
Input indication	Capital investment	R&D research and development expenditure
	Labor input	R&D personnel
		Water conservancy, urban environment and public service personnel
	Resource input	Converted natural gas, coal, and electricity into standard coal
	Pollution control input	Investment in controlling industrial pollution
Output indication	Economic output	GDP
	Scientific output	Amount of patent grants
	Green output	Urban greening space
		Park space
	Output of environmental pollution	Solid wastes
		Soot emissions
		Sulfur dioxide emissions
		Waste water drainage

mean value. At the same time, to eliminate the influences of heteroscedasticity, logarithmic treatment is conducted on all variables. Descriptive statistics of all variables (Table 2).

4. Empirical results and analysis

According to the necessary conditions for the identification of the simultaneous equation model, all three equations established in this essay are over-identified. In this essay, SUR estimation method is used to estimate the panel data from 2004 to 2018 and the results are shown in Table 3. It could be seen from Table 3 that R^2 in Eq. (1) is 0.942, R^2 in Eq. (2) is 0.6832, and R^2 in Eq. (3) is 0.9639, indicating that the overall fitting degree is high.

Eq. (1) shows the estimation of influences of innovation of green technology and water environmental pollution on the upgrading of industrial structure, in which upgrading of the industrial structure of the lagged stage has significant influences on the current stage, with the coefficient of 0.670. The main explanatory variables passed the significance test, among which the estimated coefficient of green technological innovation is significantly positive, and passes the test at a significant level of 1%, indicating that innovation of green technology can help upgrade the industrial structure. The estimated coefficient is 0.0120. The coefficient of water environmental pollution is significantly negative, which is –0.0116, indicating that the increase of water environmental pollution is in negative correlation with the upgrading of industrial structure. Government size also contributes to the upgrading of industrial structure. For every 1% increase in the proportion of government fiscal expenditure, upgrading of the industrial structure will increase by 0.0124 percentage points. The influences of human capital on the upgrading of industrial structure fail the significance test.

In estimation of Eq. (2), innovation of green technology of the lagged stage has significant influences on innovation of green technology of the current stage, with the coefficient of 0.449. The influence of upgrading of industrial structure on innovation of green technology is not significant. Water environmental pollution and innovation of green technology have significant positive correlations, with the estimated coefficient of 0.0226, that is, water environmental pollution could promote innovation of green technology.

In estimation of Eq. (3), the influencing coefficient of water pollution emission of the lagged stage on pollution emission of the current stage is 0.678, which passes the significance test of 1%, indicating that environmental pollution is lagging. Regional environmental pollution is a dynamic process and there is still a long way to go for environmental protection [21]. In addition, informal environment regulation, the level of economic development and population density all could inhibit the emission of water environmental pollution to varying degrees.

In general, upgrading of industrial structure and water environment pollution there has a two-way restraining

Table 3
Estimation results of simultaneous equations

	lnInd	lnGreen	lnPol
L.lnInd	0.670[c] [18.15]		
L.lnGreen		0.449[c] [10.41]	
L.lnPol			0.678[c] [19.08]
lnInd		–0.0508 [–0.21]	–2.355[c] [–5.54]
lnGreen	0.0120[a] [1.89]		0.0532 [0.69]
lnPol	–0.0116[c] [–5.21]	0.0226[a] [1.81]	
lnEr		–0.0368[c] [–5.47]	0.0274[b] [2.21]
lnIer		0.0118 [0.73]	–0.0879[c] [–2.58]
lnHum	–0.0159 [–0.70]		
lnGov	0.0124[a] [1.84]		
lnFdi		–0.0241[b] [–2.46]	
lnPgdp			–0.313[c] [–6.44]
lnPop			–0.288[c] [–2.65]
_cons	0.386[c] [5.44]	–0.318 [–1.20]	8.530[c] [7.17]
R^2	0.9421	0.6832	0.9639
RMSE	0.0130	0.0848	0.1510

Note: [a], [b], [c], respectively represent significant levels of 10%, 5%, and 1%; *t* statistics are in brackets.

Table 2
Descriptive statistics of variables

Variable	Obs.	Mean	Std. dev.	Min.	Max.	Data sources
Ind	450	2.322	0.13	2.074	2.806	China Statistical Yearbook, after processing and finishing
Pol	450	5.918	5.202	0.28	34.743	China Environmental Statistics Yearbook, after processing and finishing
Hum	450	8.738	1.014	6.378	12.555	China Statistical Yearbook, after processing and finishing
Pgdp	450	39,094.67	25,478.65	4,297.974	140,000	China Statistical Yearbook
Pop	450	440.7	645.647	7.457	3,825.692	China Statistical Yearbook, after processing and finishing
Er	450	0.002	0.002	0.0008	0.015	China Statistical Yearbook, after processing and finishing
Ier	450	0.203	0.158	0.016	0.956	China Statistical Yearbook, after processing and finishing
Fdi	450	0.024	0.019	0	0.095	China Statistical Yearbook, after processing and finishing
Gov	450	0.215	0.096	0.079	0.627	China Statistical Yearbook, after processing and finishing
Green	450	1.079	0.225	0.714	3.997	China Statistical Yearbook, China Environmental Statistics Yearbook, after processing and finishing

relationship, but the former has greater influences on the latter. Under the new normal economy, water environmental pollution is bound to affect sustainable economic development [22]. To maintain rapid and steady economic development, local governments have provided a series of guidance on adjustment of industrial structure, supporting the iron and steel, cement, paper-making and other industries to close down backward production facilities, and promoting water environmental quality and water pollutant discharge systems, which has virtually raised higher requirements for industries to increase efforts in environmental protection, improve emission standards and enhance the pressure of emission reduction on enterprises; thereby enterprise cost is increased sharply, which goes against the upgrading of industrial structure. In the process of upgrading of industrial structure, labor-intensive and energy-intensive industries are transforming towards human capital-intensive and technology-intensive industries. Industrial pollution occupies a higher proportion in water environmental pollution, while upgrading of industrial structure could improve greatly the proportion of industries in the economic structure [23]. Therefore, to improve the proportion of the tertiary industry could adjust well the relations between economic development and environmental protection, and accordingly water environmental pollution could be improved.

Upgrading of industrial structure and innovation of green technology show unidirectional relation, that is, the innovation of green technology could help to upgrade of industrial structure, but the upgrading of industrial structure cannot help in the innovation of green technology. The possible reason could be that except for the advantages of traditional technological innovation, the innovation of green technology favors more the industries of environmental protection. In a narrow sense, it is related closely to people's life, and in a broad sense, it could help the adjustment of the national industrial structure. The innovation of green technology is a leapfrog innovation that can generate new sectors and form fundamental innovation, which could promote traditional high-polluting and high-energy-consuming industries transforming towards low-carbon industries [24]. At the same time, the innovation of green technology could stimulate the public's demands and affect the residents' consumption, which could in turn promote the upgrading of industrial structure.

Innovation of green technology and water environmental pollution are in asymmetric relation. To be specific, water environmental pollution has inversed effects on innovation of green technology, while the influences of latter on the former is not so significant. The proportion of industrial pollution in water environmental pollution is relatively large, and upgrading of industrial structure can greatly improve the proportion of industry in the economic structure, therefore, to increase the proportion of tertiary industry can coordinate the relationship between economic development and environmental protection better, and accordingly water environmental pollution could be improved.

5. Main conclusion and policy implications

So far, studies on the relations between upgrading of industrial structure, the innovation of green technology and environmental pollution are mostly simple casual relationship or unidirectional relation, while neglecting the interactive feedback relations between these them. In this essay, the dynamic panel simultaneous equations model is adopted to study the interactions between upgrading of industrial structure, the innovation of green technology and water environmental pollution. By establishing a simultaneous equations model, SUR estimation is used to verify the interactions between upgrading of industrial structure, the innovation of green technology and water environmental pollution in 30 provinces and cities of China from 2004 to 2018, and the following conclusions and policy implications are obtained:

There is a bidirectional casual relationship between upgrading of industrial structure and water environmental pollution. With the improvement of the emission of water environmental pollution, the linkage effects between upgrading of industrial structure and water environmental pollution could be strengthened further. Upgrading of industrial structure could reduce the emission of water environmental pollution; and with the decrease of the emission of water environmental pollution, upgrading of industrial structure would be optimized further. Such a process is irreversible and upward spirally. At this time, the governmental departments should strengthen the construction of ecological environment protection, strictly enforce the law, and provide support for the sound interaction between upgrading of industrial structure and improvement of water environment pollution.

Upgrading of industrial structure and innovation of green technology show asymmetric relations, and innovation of green technology could help to upgrade of industrial structure. Relevant governmental departments should vigorously implement the green technology innovation-driven development strategy, create a good support environment for innovation of green technology, strengthen corporate subsidies for innovation research and development of green technology, encourage the transformation of innovation achievements of green technology, and promote the transformation of industrial structure.

The innovation of green technology and water environmental pollution show asymmetric relations, and water environmental pollution has reversed effects on innovation of green technology. Environmental protection is a thousand-year plan for China; therefore, the concept of "polluting first and then controlling" should be abandoned, the "red-line of environmental protection" should be adhered to strictly, and various administrative measures, such as fining and suspending production, should be adopted to force "large polluters" to develop green.

China and the United Nations have the same goal in sustainable development. China has made a great contribution to global ecological sustainable development. Beautiful China will eventually promote the green development of China and the world. This paper aims to provide data support for reducing environmental pollution emissions and increasing green technology innovation, and then promote it to the world.

Acknowledgments

The authors acknowledge the Project of Yuyou Group of the North China University of Technology.

References

[1] F.Z. Chen, C. Liu, J.X. Lu, The impact of technological innovation on the upgrading and adjustment of industrial structure in Beijing, Tianjin and Hebei under the background of supply side structural reform — based on the panel data of Beijing, Tianjin and Hebei from 1985 to 2016, Sci. Technol. Manage. Res., 39 (2019) 10–16.

[2] X. Chen, Z.Z. Zhang, M.L. Li, Environmental regulation, industrial structure change and technological innovation capability, Syst. Eng., 37 (2019) 59–68.

[3] L. Wang, Y. Zhang, G.L. Gao, Environmental regulation, technological innovation and carbon productivity, J. Arid Land Resour. Environ., 34 (2020) 1–6.

[4] J. Li, K.F. See, J. Chi, Water resources and water pollution emissions in China's industrial sector: a green-biased technological progress analysis, J. Cleaner Prod., 229 (2019) 1412–1426.

[5] Y.R. Huang, Z.Q. Lu, Z.B. Li, Industrial structure upgrading, factor market distortion and environmental pollution — analysis based on 283 prefecture level city panel data from 2003 to 2015, Comm. Res., 7 (2018) 113–118.

[6] Q. Wang, J.L. Zhao, Y.L. Bao, Empirical analysis of the relationship between industrial structure and environmental pollution — based on the data from 1995 to 2009, Nanjing J. Soc. Sci., 3 (2012) 14–19.

[7] Y. Chen, J. Sun, J. Lu, The impact of urban sprawl and industrial structure on environmental pollution, Urban Probl., 4 (2018) 18–25.

[8] Y.Q. An, W.Q. Li, An empirical study on the impact of industrial structure change on environmental pollution in Tibet, J. Tibet Univ., 34 (2019) 175–182.

[9] Y. Lu, Study on regional industrial structure policy and spatial effect of river basin water environment — taking Hebei Province as an example, J. Yanshan Univ., 21 (2020) 78–86.

[10] Y. Zheng, J. Peng, J. Xiao, P. Su, S. Li, Industrial structure transformation and provincial heterogeneity characteristics evolution of air pollution: evidence of a threshold effect from China, Atmos. Pollut. Res., 11 (2020) 598–609.

[11] X.Z. Wang, L. Wu, Land finance, house price rise and industrial structure upgrading: analysis based on the simultaneous equation model of panel data, Inq. Econ. Issues, 3 (2019) 32–39.

[12] T. Kaoru, A slacks-based measure of super-efficiency in data envelopment analysis, European J. Oper. Res., 143 (2002) 32–41.

[13] B.Q. Lin, H.X. Liu, Is foreign trade conducive to improving energy and environmental efficiency? Taking China's industrial industry as an example, Econ. Res. J., 50 (2015) 127–141.

[14] B. Li, X.H. Zhao, Economic structure, technological progress and environmental pollution: an analysis based on China's industrial data, J. Finance Econ., 37 (2011) 112–122.

[15] J.H. Bai, F.X. Jiang, Study on regional innovation efficiency considering environmental factors based on three-stage DEA method, Finance Trade Econ., 10 (2011) 104–112 + 136.

[16] Y.Z. Yu, D.Y. Liu, Spatial spillover effect and value chain spillover effect of regional innovation efficiency in China: a multidimensional spatial panel model from the perspective of innovation value chain, Manage. World, 7 (2013) 6–20,70,187.

[17] Y. Sun, K.Y. Wang, X.D. Yao, Study on environmental benefits of urban public infrastructure, Resour. Environ., 25 (2015) 92–100.

[18] J. Langemeyer, F. Baró, P. Roebeling, E. Gomez-Baggethun, Contrasting values of cultural ecosystem services in urban areas: the case of park Montjuïc in Barcelona, Ecosyst. Serv., 12 (2015) 178–186.

[19] N. Shen, F.C. Liu, Can high-intensity environmental regulation really promote technological innovation? — retest based on Porter hypothesis, China Soft Sci.,4 (2012) 49–59.

[20] S. Pargaland, D. Wheeler, Informal regulation of industrial pollution in developing countries: evidence from Indonesia, J. Polit. Econ., 104 (2003) 1314–1327.

[21] J.H. Bai, J.Y. Lu, S. Lu, Research on the impact of capital market distortion on environmental pollution — based on the analysis of provincial spatial dynamic panel data, J. Nanjing Audit Univ., 16 (2019) 37–47.

[22] S.C. Khoo, X.Y. Phang, C.M. Ng, K.L. Lim, S.S. Lam, N.L. Ma, Recent technologies for treatment and recycling of used disposable baby diapers, Process Saf. Environ. Prot., 123 (2019) 116–129.

[23] H. Wang, X. An, Effect of advanced treatment on ammonia nitrogen contained in secondary effluent from wastewater treatment plant, Fresenius Environ. Bull., 27 (2018) 2043–2050.

[24] P. Wang, J.B. Li, F.W. Bai, D.Y. Liu, C. Xu, L. Zhao, Z.F. Wang, Experimental and theoretical evaluation on the thermal performance of a windowed volumetric solar receiver, Energy, 119 (2017) 652–661.