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Analysis on the pattern and driving factors of industrial wastewater discharge in the Wuhan Metropolitan area

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ABSTRACT

As China's ecological civilization gains momentum and the ecological development of the 'Yangtze River Economic Belt' strategy pushes forward, the research on water environment protection and management in Wuhan Metropolitan Area (the central urban agglomeration) is of great significance. According to the data of the industrial wastewater discharge in the nine cities of the Wuhan Metropolitan Area from 2005 to 2015, the study will construct a decomposition model to analyze the pattern of the discharge with reference to the Kaya identity and the LMDI decomposition model. By doing so, the pattern and driving factors of industrial wastewater discharge can be cleared. The following conclusions on the industrial wastewater discharge of the Wuhan Metropolitan Area can be achieved. Firstly, industrial wastewater discharge in the Wuhan Metropolitan Area shows a decreasing trend year by year (684 million tons to 433 million tons) from 2005 to 2010, but rises sharply (504 million tons to 652 million tons) from 2010 to 2011, reaching a peak in 2011. After that, it witnesses a quick and stable drop. Secondly, the absolute differences in industrial wastewater discharge among cities are continuously narrowed, in which Wuhan (the highest value is 260 million tons, the lowest value is 155 million tons) and Ezhou (the highest value is 181 million tons, the lowest value is 0.25 million tons) show the most striking abnormal statistics. Thirdly, the discharge follows the trend of expansion from Wuhan as a center to its neighboring cities from 2005 to 2015. For spatial pattern, it presents a picture of decreasing from the center to the surrounding. Lastly, for all driving factors affecting the discharge, the contribution of economic growth is always positive, which can increase the discharge greatly (the average annual contribution reaches 0.64 billion m^3). The population size has little effect. The industrial structure has an uncertain influence on it since it is decided by government policies. The influence of technological improvement is negative, which can control the discharge a lot. In the last part of this essay, the research will explore the ways to promote the saving and discharge reduction of industrial wastewater for future potential metropolitan areas, thus providing a reference for macro water environment protection and governance in the Yangtze River Basin and other regional urban areas.

Key words: driving factors, industrial wastewater discharge, spatial pattern, the Wuhan Metropolitan Area, the 'Yangtze River Economic Belt' strategy

HIGHLIGHTS

- The statistical data of industrial wastewater discharge (2005–2015) are analyzed.
- The decomposition model of industrial wastewater discharge is constructed.
- Decomposing the factors into technological improvement, industrial structure, economic growth, and the population size.
- The temporal and spatial characteristics and driving factors are defined.
- Guiding the protection and control of macro viewing water environment.

1. INTRODUCTION

Over the past century, as global industrialization and urbanization accelerate, the economy is increasingly booming; however, it also brings about great resource consumption and environmental pollution, in which water resource suffers most (Hou *et al.* 2006; Zhang *et al.* 2015). At present, the global water cycle system is affected by both human activities and climate change, and the conflict between water supply and demand is becoming more and more prominent (Khan *et al.* 2020; Valipour *et al.* 2020; Maja & Ayano 2021). According to the World Water Development Report issued by the United Nations in 2021, the discharge of global wastewater has reached the summit. Actually, 80% of wastewater is discharged without any treatment. One half the water resources in the United States, 50 rivers in Europe, and most rivers in the cities in Asia are polluted. There are four billion people in the world who face the problem of lacking water at least one month in a year (Kumar *et al.* 2020; Li 2021). Since the inception of reform and opening up, China's comprehensive economic strength has grown while the overall wastewater discharge is also rising. The wastewater discharge in urban areas in China witnessed a sharp rise from 44.534 billion m^3 in 2014 to 52.112 m^3 in 2018. In this context, the issue of water reservation has become an essential issue to dictate the economic sustainable development, and it is imperative to control the industrial wastewater discharge (Jia & Zhang 2011; Choi *et al.* 2017; Zhang & Chen 2020), wastewater treatment capacity, and resource utilization need to be urgently improved (Kuriqi 2014; Kuriqi *et al.* 2016). Currently, China has published the Action Plan for Prevention and Control of Water Pollution and advocates the idea that lucid waters and lush mountains are invaluable assets, both actions aim to promote environmental safety. For the reason that the industrial wastewater discharge is large and well concentrated, the government supervises the water environment as an important target (Liu *et al.* 2014; Ali *et al.* 2020; Zhang *et al.* 2020).

The research on industrial wastewater discharge in China and the rest of the world is mainly focused on such subjects as environmental science, economics, geography, and so on. The hot issues are on the time sequence, the difference of regional distribution, and the influencing factors of it (Mei & Feng 1993; Tang *et al.* 2011; Li *et al.* 2013; Chen *et al.* 2016; An *et al.* 2019; Wang *et al.* 2019; Bu *et al.* 2021). In the early studies in the academic circles, the research perspectives are mainly from the nation, province, and river area. The following research methods such as Environment Kuznets Curve (EKC) (Wu & Tian 2012; Mao & Wang 2013), input–output model and vector autoregressive model, and so on (Su *et al.* 2010; Li *et al.* 2012; Shen & Lu 2015; Hu *et al.* 2020) are adopted to study the relationship between economic growth and industrial wastewater discharge, the direct consumption coefficient, and the regression relationship of the industrial wastewater discharge. However, as there is no study on spatial–temporal patterns, the result can only show the changes in the total discharge and regional differences. As a result, the overall spatial pattern and pollution intensity measurement cannot be cleared (He 2016). As the research is pushing forward, the scholars begin to explore spatial–temporal patterns, effective mechanisms, the prevention of industrial wastewater discharge, and so on (Chen *et al.* 2017; Yang *et al.* 2019; Ma *et al.* 2021). The discharge in other areas in China including the Yangtze River Delta Urban Agglomerations, the rapid urbanization regions of the lower Yangtze River, the region of Qingling Mountain, and Huaihe River are taken as cases (Wu *et al.* 2020; Zhang *et al.* 2021). The following methods, such as the LMDI model (Zhang & Wu 2015; Ma 2016; Zhang & Yang 2017), VAR, FDI, and STIRPAT (Wang & Ding 2020; Fang 2021), are taken of. The factors that are relevant to the discharge are also deeply analyzed, such as population, property, technology, structure, and scale (Liu *et al.* 2011).

In summary, the academic community has already researched the spatial and temporal distribution characteristics and driving factors at the regional macro level to achieve the stage results. However, industrial wastewater discharge is regulated by multiple factors such as policy and economy, showing closely related spatial and temporal pattern changes, and there are few empirical studies involving the urban circle scale, and the analytical models are insufficient to fully reflect the driving factors of industrial wastewater discharge, which limits the practical application of industrial wastewater control in environmental management and ecological protection, etc. (Hu *et al.* 2016). In the past, the aim to develop the Yangtze Economic Belt was to build it as a golden waterway and a three-dimensional traffic corridor, now the idea is changed. We have put forward the development strategy of the Yangtze River Economic Belt to strengthen environmental protection rather than seeking rapid growth at the cost of the environment, so restoring the water environment in the Yangtze River Economic Belt is given top priority (Ali *et al.* 2019; Wu & Yuan 2021). The Wuhan Metropolitan Area is a core area of Hubei province and an essential part of urban agglomerations in the middle of the Yangtze River Economic Belt. Given to it is a key part of safeguarding national environment safety to control wastewater discharge. In this essay, according to the data of industrial wastewater discharge in the nine cities of the Wuhan Metropolitan Area from 2005 to 2015, the study of industrial wastewater discharge is extended to an empirical study at the city circle scale by drawing on the Kaya identity and LMDI decomposition model to construct a decomposition model of industrial wastewater discharge factors. The decomposition model includes four factors: economic growth, population size, industrial structure, and technological improvement (Zhuang *et al.* 2018). By means of analyzing the different influences of the four factors on discharge, we can further explore the spatial–temporal pattern and driving factors of the Wuhan Metropolitan Area, which can provide strong support for environment preservation and sustainable economic development.

2. STUDY AREA, DATA, AND METHODS

2.1. Introduction to researching area

Located in China's central Hubei province, the Wuhan Metropolitan Area includes nine cities, which are Wuhan, Ezhou, Huanggang, Huangshi, Xiaogan, Xiantao, Tianmen, Xianning, and Qianjiang, which are all within the area of 100 km^2 around Wuhan. The first five cities are at the prefecture level, and the other four cities are provincially controlled. It is an integrated area with a large population and a highly booming economy with the area accounting for one-third of Hubei province, the population one-half, as well as the GDP, which has a prevailing part of more than 60%.

The Wuhan Metropolitan Area is a city cluster in the middle of the Yangtze River Economic Belt and a significant planning area for China's ecological environment protection. The area has abundant water resources. However, due to heavy water consumption by chemical industries and industrial wastewater discharge, the water in the branches of the Yangtze River and the Hanjiang River (which also flows across Hubei province) is lightly polluted. What is worse, the water in the lake is in a trend of eutrophication. Therefore, the water in the lake and reservoir cannot meet the needs of daily life and production (He *et al.* 2020). The Wuhan Metropolitan Area acts an important role. It is a lead area to boost the economy of Hubei province, a key modern three-dimensional transportation hub and the fourth economic growth pole following the Yangtze River Delta, the Zhujiang River Delta, and the Beijing–Tianjin–Hebei region (Xiao *et al.* 2021). In this connection, the harmony between economic booming and environment reservation is super significant, in which the water environment improvement is the most important (Figure 1).

2.2. Source of researching data

Now, China has entered the era of urbanization. The rate of urbanization has increased from 17.9% in 1978 to 56.15% in 2015. From 2005 to 2015, the industrial wastewater discharge in the Wuhan Metropolitan Area was large, and the industrial economy in the surrounding areas had a high level of development under the action of radiation diffusion, which in turn brought about a large amount of industrial wastewater discharge. After 2016, the proportion of industrial wastewater discharge data in the Wuhan Metropolitan Area affected by government policies has increased, and the growth rate of the total industrial increase has gradually slowed down. In view of this, the data about the industrial wastewater discharge needed by this study are mainly from the Environmental Statistics Bulletin and Environmental Statistics Yearbook which were issued by these nine cities of the Wuhan Metropolitan Area from 2005 to 2015. In this essay, the study will construct a decomposition model to analyze the influential pattern of the discharge with reference to the LMDI decomposition model. The pattern includes four factors: economic growth, population size, industrial structure, and technological development. What is more, such statistics about the city as industrial added value, GDP, per capita GDP, and the total number of

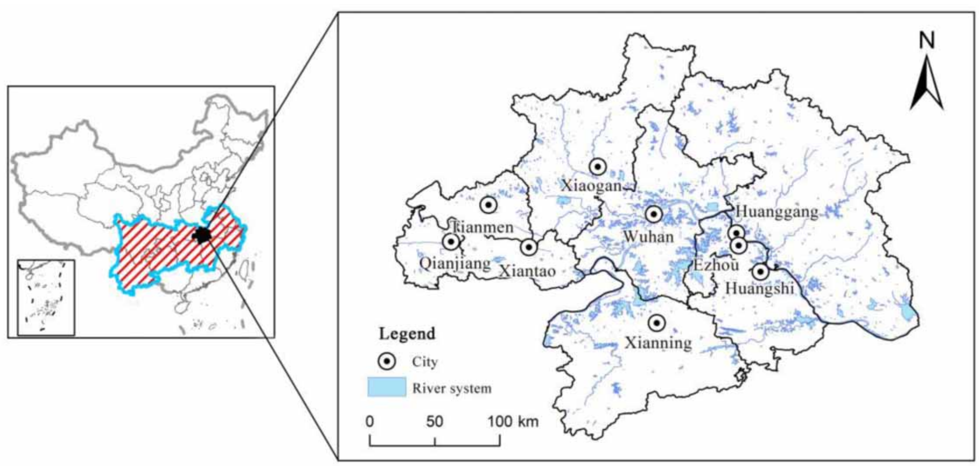

Figure 1 | Location map of the Wuhan Metropolitan Area.

populations at the end of the year are applied for the purpose of making sure the data are scientific, representative, and available. These statistics all originated from the China Statistical Yearbook, China City Statistical Yearbook, and official websites of the relative Bureau of Statistics from 2005 to 2015. As for lacking the data in a few years, the interpolation method is used to supplement and improve the statistical data of the corresponding year.

2.3. Researching methods

2.3.1. Introduction of the Kaya identity

The Kaya identity was first proposed by a Japanese scholar, Yoichi Kaya, in a seminar held by the United Nations Government Climate Change Committee (IPCC) in 1989. The equation was put forward to solve the difficulty of quantitatively studying carbon dioxide emissions. It was unanimously agreed upon by the attendees in the seminar. It is widely used in the research field of carbon dioxide and other pollutant emissions (Eskander & Nitschke 2021):

$$\mathrm{CO_2} = \frac{\mathrm{CO_2}}{\mathrm{PE}} \cdot \frac{\mathrm{PE}}{\mathrm{GDP}} \cdot \frac{\mathrm{GDP}}{\mathrm{POP}} \cdot \mathrm{POP} \tag{1}$$

For Kaya identity, CO_2 represents the amount of carbon dioxide emissions, PE is the total primary energy consumption, GDP is the gross domestic product, and POP is the total number of population.

The Kaya identity can decompose the factors that are difficult to quantify into factors related to human daily production and life, which can provide reference to explore the pattern of the industrial wastewater discharge. The study will explore the pattern of the industrial wastewater discharge under the guidance of the decomposition idea of carbon dioxide emissions contained by the Kaya identity. In the meanwhile, in the light of the conditions of the discharge, the study will decompose the factors working on it to find out the relationship between various factors and the change in the total discharge.

2.3.2. Introduction of LMDI (logarithmic mean index method)

In the 1980s, economists first proposed the decomposition method (IDA) to solve complex economic problems, and studied the overall impact of sub-items with the decomposition idea. After years of improvement and research by scholars, the Di's and La's index decomposition methods have been discovered, which are mainly used to analyze the causal relationship between energy consumption and energy intensity. Since the 21st century, based on the decomposition method (IDA), Ang and his team proposed the LMDI method (Logarithmic Mean Index Method), which solves the problems of traditional weighted average residual, 0 value, and negative value, and can explain problems such as residuals arising from decomposing objects. The model is suitable for factor decomposition and driving factor contribution exploration, such as assuming each decomposition element as a continuously differentiable function of the decomposed variable, differentiating the decomposed variable, and then using the simpler additive and multiplicative forms of decomposition formulas to derive the relationship between changes in each decomposition element and changes in the decomposed variable (Ang 2005). Meanwhile, the LMDI decomposition model is a decomposition model suitable for data with few variables and involving the nature of time series.

At present, the LMDI decomposition model is mainly adopted in the fields of energy, environment, economy, and ecology. Its unique mathematical model construction has important reference and guiding significance for the study of the driving factors for industrial wastewater discharge in the Wuhan Metropolitan Area.

2.3.3. Modeling construction

To know what the driving factors are and how they work on the discharge more clearly, this study decomposes the factors into four parts. They are technological improvement, industrial structure, economic growth, and the population size with Kaya identity and LMDI decomposition model reference. Firstly, according to the Kaya identity, the factors are decomposed as follows:

$$Q^t = \sum_i^n Q_i^t = \sum_i^n \left[\frac{Q_i^t}{Z_i^t} \cdot \frac{Z_i^t}{G_i^t} \cdot \frac{G_i^t}{P_i^t} \cdot P_i^t \right] = \sum_i^n (Q_{tec,i} \cdot Q_{str,i} \cdot Q_{eco.i} \cdot Q_{pop,i}) \tag{2}$$

where Q^t is the total amount of the industrial wastewater discharge in the Wuhan Metropolitan Area in the year of t, Q_i^t is the amount of discharge in i city in the year of t, Z_i^t is the industrial added value in i city in the year of t, G_i^t is the GDP in i city in the year of t, P_i^t is the total number of population in i city in the year of t, n is the total number of cities; $Q_{tec,i}$ is the technological improvement effect, $Q_{str,i}$ is the industrial structure effect, $Q_{eco,i}$ is the economic growth effect, $Q_{pop,i}$ is the population scale effect. In addition, tec is an acronym for technological improvement effect, str is an acronym for industrial structure effect, eco is an acronym for economic development effect, and pop is an acronym for population scale effect.

Secondly, according to LMDI, the contribution formula of each decomposition index can be obtained, the detailed information is as follows:

$$\Delta Q_{tec,i} = \frac{Q_i^t - Q_i^0}{\ln Q_i^t - \ln Q_i^0} \cdot \ln\left(\frac{Q_{tec.i}^t}{Q_{tec.i}^0}\right) \quad (3)$$

$$\Delta Q_{str,i} = \frac{Q_i^t - Q_i^0}{\ln Q_i^t - \ln Q_i^0} \cdot \ln\left(\frac{Q_{str.i}^t}{Q_{str.i}^0}\right) \quad (4)$$

$$\Delta Q_{eco,i} = \frac{Q_i^t - Q_i^0}{\ln Q_i^t - \ln Q_i^0} \cdot \ln\left(\frac{Q_{eco.i}^t}{Q_{eco.i}^0}\right) \quad (5)$$

$$\Delta Q_{pop,i} = \frac{Q_i^t - Q_i^0}{\ln Q_i^t - \ln Q_i^0} \cdot \ln\left(\frac{Q_{pop.i}^t}{Q_{pop.i}^0}\right) \quad (6)$$

where $\Delta Q_{tec,i}$ is the contribution degree of technology improvement effect in the Wuhan Metropolitan Area; $\Delta Q_{str,i}$ is the contribution degree of industrial structure effect in the Wuhan Metropolitan Area; $\Delta Q_{eco,i}$ is the contribution degree of economic growth effect in the Wuhan Metropolitan Area; $\Delta Q_{pop,i}$ is the contribution degree of population scale effect in the Wuhan Metropolitan Area; Q_i^0 is the industrial wastewater discharge of city i in the Wuhan Metropolitan Area in the starting year. In addition, the positive means it can increase discharge while the negative means it can prevent it.

3. SPATIAL–TEMPORAL CHARACTERISTICS OF THE INDUSTRIAL WASTEWATER DISCHARGE IN THE WUHAN METROPOLITAN AREA

3.1. Time evolution characteristics of industrial wastewater discharge

3.1.1. Overall characteristics

What can be seen from the diagram for the variation trend of industrial wastewater discharge and industrial added value in the Wuhan Metropolitan Area (Figure 2) is that the discharge, in general, goes down continuously, from 684 million tons in 2005 to 433 million tons in 2015 with the economic development. Reviewing the data, we can find that the discharge can be divided into three stages: the first stage is from 2005 to 2010, the discharge shows a decreasing trend year by year, from 684 million tons in 2005 to 504 million tons in 2010, with an average reduction rate of 36%; the second stage from 2010 to 2011,

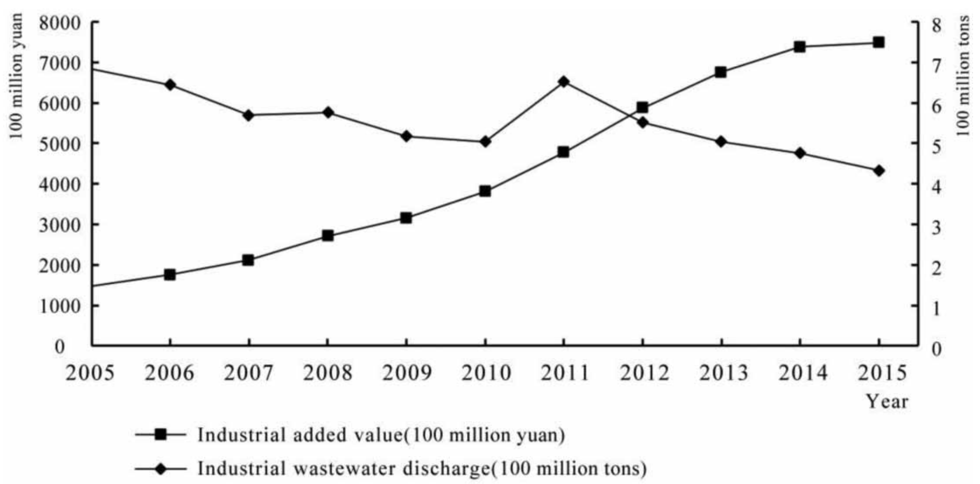

Figure 2 | Trends of industrial wastewater discharge and industrial added value in the Wuhan Metropolitan Area.

which is the only year when the total amount increases during the study period, from 504 million tons in 2010 to 652 million tons in 2011. Due to the rise in Ezhou, the total amount is increased by 148 million tons and reaches the summit only in one year (Figure 3). During the third stage from 2011 to 2015, the discharge shows a rapid and stable downward trend after a sharp rise within the second stage.

At the same time, during the research period, the industrial added value of the Wuhan metropolitan showed a rising trend, from 147.705 billion yuan in 2005 to 747.686 billion yuan in 2015. According to data, it can be divided into three stages: from 2005 to 2008, 2008 to 2014, and 2014 to 2015. During the first stage, the Wuhan metropolitan developed an export-oriented economy, and the Wuhan government invested four trillion yuan to promote economic development. From 2008 to 2014, the total industrial added value continued rising, and the economy was booming. During the third period from 2014 to 2015, the value went on increasing, but the growth rate slowed gradually due to a series of national and regional environmental protection policies.

3.1.2. Differences among cities in the Wuhan metropolitan area

In order to further analyze the differences and changes in industrial wastewater discharge among cities in the Wuhan Metropolitan Area over time, the box diagram was drawn by SPSS24.0, and the differentiation characteristics of industrial wastewater discharge among cities during the study period were analyzed (the upper and lower boundaries of each box type are the distribution area of normal values, the positions at both ends of the rectangular box correspond to the upper and lower quartiles of the data, and the middle transverse line is the median; 1 and 3 are abnormal points, which represent Wuhan and Ezhou, respectively).

Figure 4 indicates the tortuous changes for the maximum value of discharge in different cities in the Wuhan Metropolitan Area during the study period while the minimum value changes little which means the extremum was decreasing. The changing trend of the minimum value means the absolute difference of discharge between cities is narrowing down. From the figure, what can also be observed is that Wuhan displays an abnormal statistic and it is the largest contributor (No 1 represents Wuhan); the second one is Ezhou (No 2 represents Ezhou), whose discharge is higher than other cities except Wuhan, and are also abnormal in 2011 and 2012, respectively. The discharge in the Wuhan Metropolitan Area goes down year by year, and the industrial wastewater treatment has scored impressive results. Only Huangshi, Ezhou, and other individual cities in some years (such as 2008, 2011) increased.

3.2. Spatial characteristics of the industrial wastewater discharge

In order to explore the spatial variation characteristics of industrial wastewater discharge in the Wuhan Metropolitan Area and clarify the spatial pattern among cities, the study refers to the spatial distribution difference of industrial wastewater discharge in the Yangtze River Economic Belt, adopting ArcGIS10.8 software to divide the data of the nine cities from 2005 to 2015 into three grades (0.00 $\leq$low discharge zone $\leq$0.50 billion tons, 0.51 $\leq$medium discharge zone $\leq$150 million tons and 1.51 $\leq$ high discharge zone $\leq$300 million tons) on the basis of the natural breakpoint. Moreover, 2006, 2009, 2011, and 2015

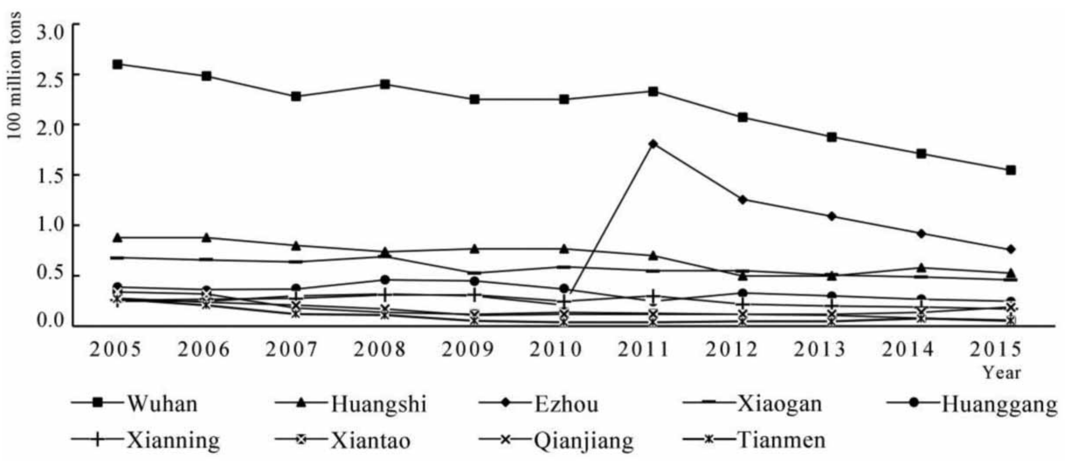

Figure 3 | Trends of industrial wastewater discharge in the Wuhan Metropolitan Area from 2005 to 2015.

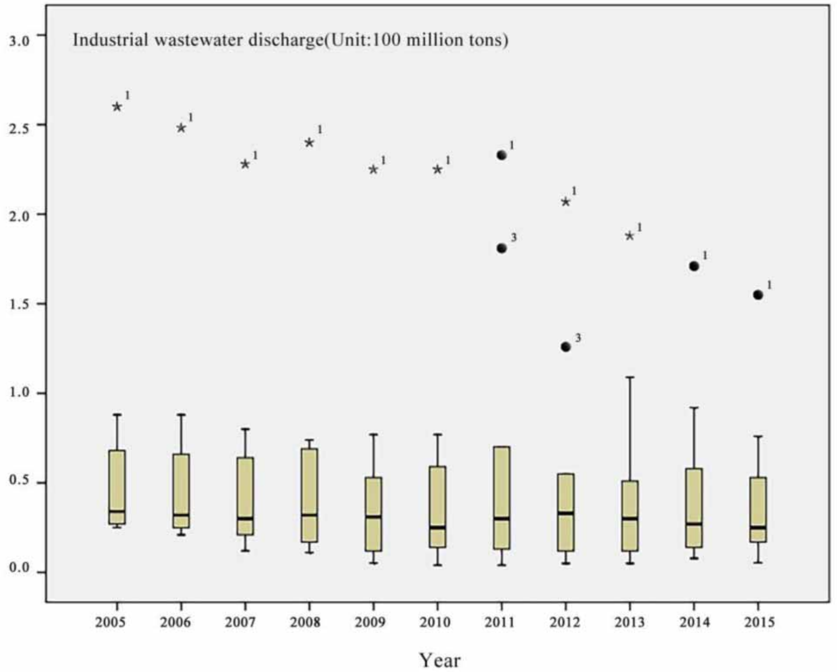

Figure 4 | Box chart of industrial wastewater discharge in the Wuhan Metropolitan Area.

are selected as four analysis sections, then the map about the overall spatial distribution of industrial wastewater discharge is drawn (Figure 5).

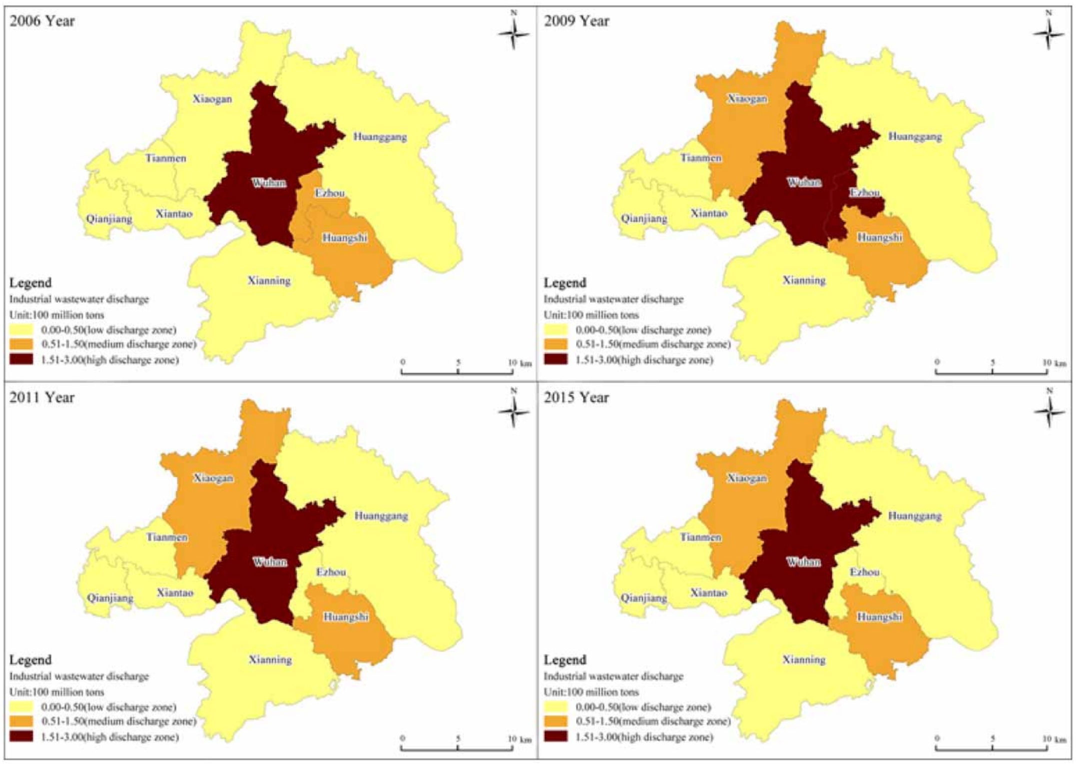

Figure 5 | Spatial distribution of industrial wastewater discharge in the Wuhan Metropolitan Area.

Overall, the industrial wastewater discharge of almost every city in the Wuhan Metropolitan Area reduces from 2005 to 2015, especially the surrounding cities with striking changes. From the perspective of the distribution pattern, the discharge indicates a decreasing pattern from the center to the surrounding. According to the chart, the hot spot, which is also called the high discharge zone of industrial wastewater discharge, has always been Wuhan, the central city of the Wuhan Metropolitan Area, while the sub-center Huangshi has always been at the level of 'medium discharge zone', and cold spot areas are mainly occupied by the periphery of the city circle. In view of changing characteristics, the industrial wastewater discharge volume of the Wuhan Metropolitan Area shows a trend of expanding from Wuhan the central city to the peripheral cities of the area, and the discharge in exterior and interior areas does not change greatly. Both Wuhan (the central city of the area) and Huangshi (the sub-central city) have been at the level of 'high discharge zone' and 'medium discharge zone'. Xiaogan, which is adjacent to Wuhan, has been transformed from a 'low discharge zone' to a 'medium discharge zone'. Ezhou is transformed from 'medium discharge zone' to 'high discharge zone', and then from 'high discharge zone' to 'low discharge zone'. The exterior areas including Huanggang and Xianning, Tianmen, Xiantao and Qianjiang have always been classified as a 'low discharge zone'.

4. ANALYSIS ON THE DRIVING FACTORS FOR THE INDUSTRIAL WASTEWATER DISCHARGE IN THE WUHAN METROPOLITAN AREA

4.1. Characteristics of the driving factors

4.1.1. Characteristics of the contribution on the added value of the industrial wastewater discharge by the decomposed driving factors

With the development of the economy and the introduction of national environmental protection policies, the total amount of industrial wastewater discharge in the Wuhan Metropolitan Area is continuously reducing, but economic development is still a high positive contributor while technological improvement can prevent the discharge greatly. The role of industrial structure and population size are not so remarkable (Figure 6).

In general, according to the analysis of all factors affecting the industrial wastewater discharge in the Wuhan Metropolitan Area, we can find that economic growth can always be considered as a positive and dominant contributor. The minimum discharge amount caused by economic development is 22 million m^3 in 2015 but reaches 100 million m^3 in 2008 with an average amount of 64 million m^3 for each year. As for technological improvement, it increases the discharge in 2010 and 2011 but prevents it greatly in other years. This means we can control the discharge remarkably by the way of improving techniques that can restore the damage from serious industrial wastewater discharge because of unhealthy economic development. The third factor, industrial structure, plays an unstable role in reducing the discharge. Most of the years it can bring the discharge down but some years it can increase. The number of the population plays a small part, only striking from 2010 to 2011.

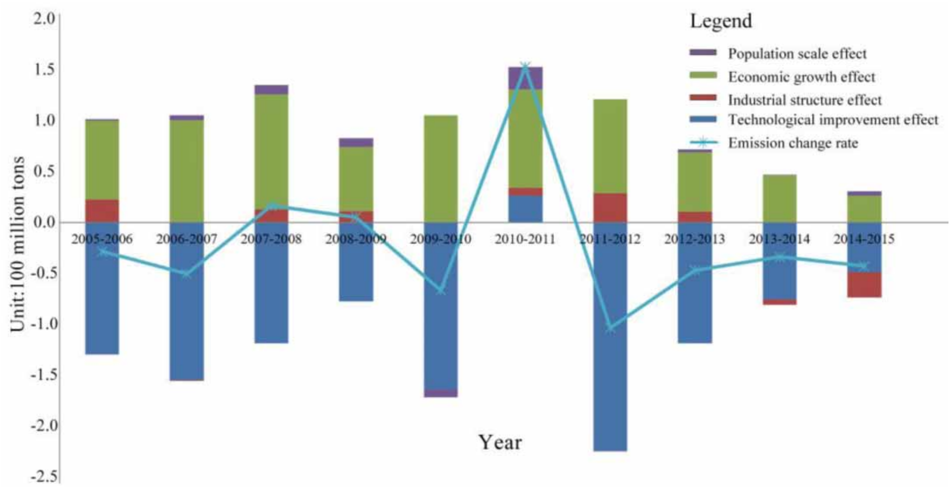

Figure 6 | Contribution distribution of each decomposition factor in the LMDI model.

4.1.2. Contribution characteristics of the decomposed driving factors on the added value in different cities

In order to further study the different driving factors for each city in the Wuhan Metropolitan Area, the LMDI analysis is adopted to obtain the contribution degree to work out the cumulative value for each city. Meanwhile, ArcGIS10.8 software is utilized to draw a layout that can show the cumulative contribution degree. Since the sub-index of each city is displayed by the histogram superimposed on the map, we can know clearly about the contribution value of the sub-index for each city (Figure 7).

Generally speaking, the spatial characteristics of the added value for industrial wastewater discharge in the Wuhan Metropolitan Area indicate as follows: the value is negative in Wuhan, Huangshi, Xiaogan, Huanggang, Tianmen, and Xiantao, while the discharge in Ezhou has the largest amount and Xianning and Qianjiang increased to a certain degree. For all cities, Wuhan is the most representative. The four factors including economic growth, technological improvement, industrial structure, and population size pose a great influence on its discharge. Technological improvement plays the most significant role in cities such as Wuhan, Huangshi and Xiaogan, etc. Economic growth is the main driving factor for cities such as Wuhan, Ezhou, Huangshi, etc. The industrial structure effect is one of the driving factors for the change in industrial wastewater discharge in cities such as Xiaogan and Huanggang, but the effect is relatively weak. The population scale effect mainly affects industrial wastewater discharge in cities such as Wuhan and Huangshi, but the proportion is relatively small.

4.2. Effect of the decomposed driving factors

4.2.1. Technological improvement

As a whole, technological progress has an inhibitory effect on industrial wastewater discharge, and the impact is profound. Especially for the Wuhan Metropolitan Area, technological progress in production and wastewater discharge treatment can greatly bring the wastewater discharge down. We can see that the added value for nine cities is negative. In addition, the highest number for reducing wastewater through techniques can reach 470 million m^3 and the lowest one is 33 million m^3. Wuhan excels in the discharge. Thanks to its prosperous economy and advanced techniques, it can reduce the number to 470 million m^3.

Talents can provide strong support for technological development. The phenomenon of talent agglomeration in the Wuhan Metropolitan Area is obvious. As the capital of Hubei province, Wuhan pools talents since it is equipped with a large number of scientific research institutes, universities, and government departments. For these reasons, the technology is full of vigor and momentum. Relatively speaking, the other eight cities are in urgent need of talent. For example, there are more than

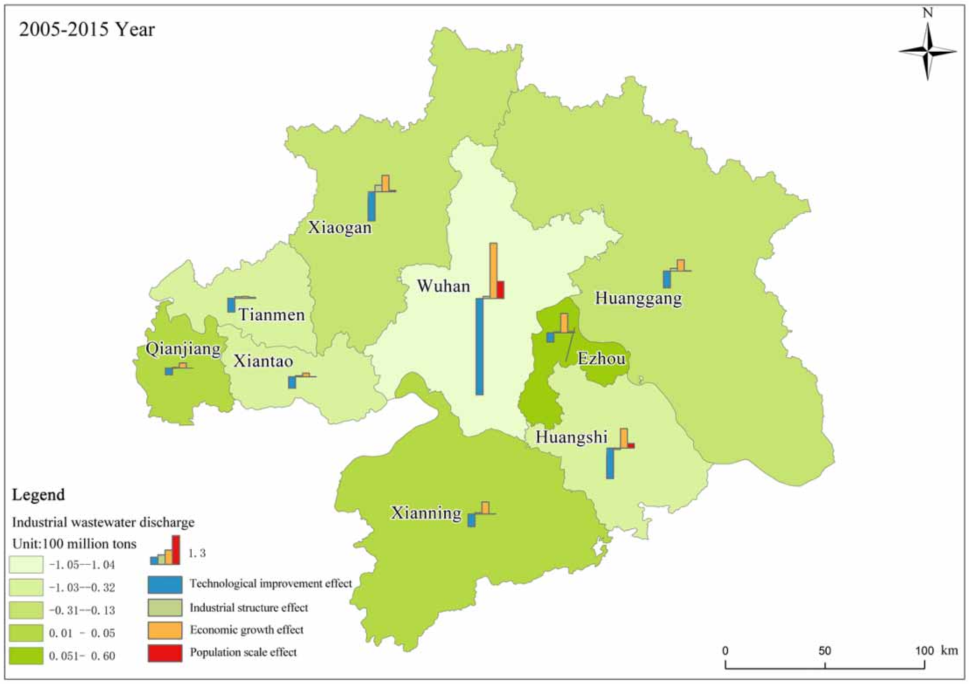

Figure 7 | Cumulative variation of wastewater and contribution of each index in the Wuhan Metropolitan Area.

50,000 professionals in Ezhou, but they are mostly employed in areas such as education, hygiene, as well as finance and accounting. The number of talents who are engaged in scientific and technological development is less than 1600, accounting for less than 5%. Currently, several other cities also suffer from a quantitative shortage and spatial imbalance of skilled personnel. These all deter the transformation of scientific and technological achievements, especially high-tech achievements in enterprises, and form a 'fence' between the two. This is also the root cause of the large difference in the reduction of wastewater discharges between Wuhan and other surrounding cities under the influence of technological progress.

4.2.2. Industry structure

The factor of industrial structure on industrial wastewater discharge in the Wuhan Metropolitan Area has become increasingly prominent, but there is still a need to increase the industrial structure adjustment. From the overall point of view of the Wuhan Metropolitan Area, the cities have suffered the rise of discharge because of the unreasonable industrial structure except for Huangshi, which benefits from the upgrading industrial structure. In these cities, compared with several other cities around Wuhan, Ezhou, Xiaogan, and Huanggang surge in the added value of discharge exceeding 100 million m^3. From the study, we know that the Wuhan Metropolitan is still in the middle phase of industrialization. As the pillar industry, the secondary industry is the main source of financial revenue. With the promotion and implementation of the national developing strategy of the central and western regions of China, the industry in the east is transferred to the central and the west, the Wuhan Metropolitan Area makes full use of the opportunity to promote the industry. However, some dirty companies bring pollution and environmental problems in which the damage on the water environment is one of the most striking. The second thing that can be observed is that the eight cities have different performances in undertaking the industrial transference from Wuhan and other regions. Firstly, Huangshi enhances its industrial competitiveness on the basis of Wuhan's major industries, especially the automobile, petrochemical, and high-tech industries. Secondly, Ezhou takes the Gedian Economic and Technological Development Zone as its priority and introduces some heavy industries such as building materials processing. There were 472 projects on the progress only in 2010, most of which posed serious damage to the environment. This is also why the wastewater surged sharply from 2010 to 2011. Thirdly, Xiaogan has docked all around with the Wuhan Metropolitan Area for the six aspects such as industrial coordination, processing and supply of agricultural and sideline products, and so on. Fourthly, Huanggang positions the chemical industrial park as a base to develop the industries of pharmaceuticals, chemicals, smelting, and coking of coal. It is the Three Ring Line to undertake the chemical industry of Wuhan. By doing so, it can upgrade the industry structure. Fifthly, Xianning boosts the docking with the Metropolitan Area to become an eco-tourism city. Sixthly, Xiantao pushes forward the industrialization of agriculture with special characteristics since it has rich resources in the Jianghan Plain and sound industry foundation. Seventhly, Qianjiang develops its industry as an important chemical raw material base. Lastly, Tianmen is a base for manufacturing, agriculture and sideline product processing and cultural tourism, and leisure.

It can be seen that the main reason for the high industrial wastewater discharge in Ezhou, Xiaogan, and Huanggang is that the companies with high emissions are transferred to them. In contrast, Huangshi, a national resource-exhausted transition pilot city, has focused on manufacturing and service industries to achieve the industrial structure adjustment in recent years. It has gained some good results by weakening the impact of heavy industry on economic growth. Therefore, it is the only city that can reduce the industrial wastewater discharge during the adjustment periods of the industrial structure.

4.2.3. Economic growth

Regional economic development is the dominant factor affecting industrial wastewater discharge, and the per capita GDP is positively correlated with it. What can be seen from Figure 6 is that all cities in the Wuhan Metropolitan Area have increased the wastewater discharge due to economic development, and the discharge in these cities is proportional to the urban economic volume. Among these cities, the discharge in Wuhan reaches 270 million m^3 because of the economic boom, far more than the other eight cities. In cities with relatively large economic volumes, emissions caused by economic development are also correspondingly large, such as Huangshi, Ezhou, and Xiaogan.

There are two reasons to explain the condition. On the one hand, Wuhan, presenting the most prosperous economy, has always been the leader in the economic development of the Wuhan Metropolitan and Hubei province. Other cities fall far behind it. This is also the direct cause of the large difference in discharge between Wuhan and its surrounding cities. On the other hand, we cannot develop the local economy at the expense of the environment. The super high discharge caused by economic development in Wuhan has seriously damaged the natural and social-ecological environment and even affected the overall pattern of ecological environment protection in China. Therefore, the discharge standards and total discharge of industrial wastewater in different cities should be reasonably set on the basis of the actual situation in different regions. The relevant controlling measures should be implemented, and the supervision and punishment should be strengthened.

4.2.4. Population size

The population size poses little influence on the industrial wastewater discharge, and it is the least significant among these decomposition factors. The effect is only impressive in Wuhan, which has the largest population. The total amount discharged is 83 million m^3, which is followed by Huangshi with the data of 23 million m^3. The total population in Xianning, Xiantao, and Qianjiang is relatively low, so the discharge is also relatively small. In conclusion, the influence is not obvious.

As the most developed city in the Wuhan Metropolitan Area, Wuhan has attracted a large number of college graduates and migrant workers, mainly young and middle-aged people. Besides, the migration rate is on the rise with a net increase almost every year. As a result, the local economy gains new impetus. However, we cannot ignore the fact that it also leads to large industrial and sanitary wastewater. In respect of Huangshi, it has been working on industrial structure upgrading, environment improvement, and talent introduction. By doing so, Huangshi attracts a large number of highly educated talents to settle down, which generates endogenous motivation for industrial innovation. Actually, in terms of the overall population size, the increase of highly educated talents will fundamentally have little impact on the changes in the industrial wastewater discharge, while it has a more direct impact on domestic sewage. In conclusion, the impact of population size is relatively weak compared with others.

5. CONCLUSIONS AND DISCUSSIONS

As China's industrialization and urbanization are pushing ahead, it is an essential part to protect the environment and reduce water pollution and emissions for the purpose of promoting ecological civilization. Within this context, the study takes the idea of factor decomposition as a reference to analyze the amount of industrial wastewater discharge of nine cities in the Wuhan Metropolitan Area from 2005 to 2015 from the perspective of spatial pattern. It also probes into the ways and countermeasures to reduce the wastewater discharge in the Wuhan Metropolitan Area through the inquires of its temporal and spatial characteristics and driving factors. These explorations are expected to provide a reference for the policy of macro water environmental protection in metropolitan areas. From the study, the following conclusions can be drawn:

Firstly, the overall condition of discharge in the Wuhan Metropolitan Area displays a continuous downward trend over time, and the changes in each city are different. Of all cities in the area, Wuhan has the highest discharge, and the number of low-emission cities is increasing. The discharge from 2005 to 2010 declines year by year but shoots up from 2010 to 2011, reaching the summit in 2011. After that, it witnesses quick and stable falls. The discharge in the Wuhan Metropolitan Area descends year by year, industrial wastewater treatment has achieved remarkable results. Only a few cities such as Huangshi and Ezhou ascend the discharge in some years (such as in 2008 and 2011).

In terms of spatial characteristics for discharge, it indicates a descending pattern from the center to the surrounding cities. Wuhan (the central city of the area) has always been at the level of 'high discharge zone' (also called hot spot) and Huangshi (the sub-central city) has been at the level of 'medium discharge zone' (also called cold spot). The 'low discharge zone' is distributed around the exterior of the Wuhan Metropolitan Area. Wuhan, the central city of the city circle, and Huangshi City, the sub-central city, have been at the level of 'high discharge zone' and 'medium discharge zone' during the study period.

Lastly, the driving factors of the industrial wastewater discharge in the Wuhan Metropolitan Area can be decomposed into four factors: economic growth, industrial structure, technological improvement, and population size. For the four driving factors, the contribution of economic growth is always positive, which can increase the discharge greatly. The population size has little effect. The industrial structure has an uncertain influence on it since it is decided by government policies (the discharge will go up if the secondary industry is encouraged. Otherwise, it will go the other way). We can control discharge greatly through technological improvements. The influence of technological improvement is negative, which can control the discharge a lot.

Now, China is implementing the strategy of building a resource saving and environment-friendly society, and the national synthetically reform testing district is speeding up. In addition to that, with the fulfillment of the 14th Five-Year national development Plan, the core and key issues for the future social development of the Wuhan Metropolitan Area and others have been changed. The past emphasis is on how to boost the economy while now it is on how to achieve the harmony between economic development and environmental protection. Although certain gains are made in the energy saving and emission reduction for the Wuhan Metropolitan Area from 2005 to 2015, the total discharge still exceeds that of most cities in China, moreover, water pollution still needs to be concerned about. The decomposition model of industrial wastewater discharge factors constructed in this study inherits the advantages of existing analytical models, introduces Kaya identity and LMDI decomposition models, draws on the idea of dimensionality reduction, decomposes the industrial wastewater discharge factors into economic growth, population size, industrial structure, and technological improvement effects, and considers the contribution degree of each element to the discharge of industrial wastewater, which can achieve a deeper study of the pattern and driving factors of industrial wastewater discharge. Meanwhile, on the basis of macro scales such as the Yangtze River Delta, the lower reaches of the Yangtze River and the river basin, this study expands the research on industrial wastewater discharge to the empirical research of the urban circle scale, explores the spatio-temporal pattern of industrial wastewater discharge in the Wuhan Metropolitan Area, analyzes its deep-seated driving factors, supplements and improves the industrial wastewater discharge control system, and provides an important premise and foundation for the practical application of industrial wastewater discharge control. Therefore, in order to move forward with the sustainable development of the Wuhan Metropolitan Area, we should view water environment restoration and treatment as a priority. Going forward, considering China's integrated ecological functional pattern, we will work on promoting green economic innovative development, industrial structural adjustment, technological revolution, and population edge to further control the industrial wastewater discharge. We should also take into full consideration local realities. That means we must make specific water environment policies and energy saving and emission reduction targets for different cities.

AUTHOR CONTRIBUTIONS

Shuai Liu and Kunlun Chen conceived and designed the experiments; Shuai Liu, Xiaoqiong Liu, and Bowen Ma performed the experiments; Shuai Liu, Zewei Ding, and Bowen Ma analyzed the results and wrote the paper.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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