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Research article

Effects of inter-industry agglomeration on environmental pollution: Evidence from China

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Abstract: Industrial pollution comes not only from within industries, but also from between industries that are strongly linked. From the perspective of agglomeration, this study explores the mutual transmission of pollution between different manufacturing industries. We found that there is an inverted U-shape relationship between inter-industry agglomeration and environmental pollution among 20 Chinese manufacturing industries. Energy intensity, which is an important transmission path from agglomeration to pollution, is positively related to the energy consumption of industries with some degree of agglomeration. Besides, the expansion of production scale caused by inter-industry agglomeration leads to more energy consumption and pollution. Furthermore, the innovative technology resulting from inter-industry agglomeration reduces environmental pollution but does not have a significant impact on energy consumption.

Keywords: inter-industry agglomeration; environmental pollution; scale effect; energy; innovation

1. Introduction

With the acceleration of industrialization worldwide, collaboration among industries is deepening and the effects of inter-industry agglomeration between different industries are becoming increasingly complex. On the one hand, the development of industrialization promotes the penetration of technological resources and optimizes the allocation of resources. On the other hand, the division of labor and cooperation among various industries, as well as the expansion of the productive scale, increase the severity of inter-industrial pollution. Therefore, understanding the relationship between inter-industry agglomeration and environmental pollution problems is extremely important.

It is undeniable that the rapid growth of China's economy in the past has been partly driven by high energy consumption, which has resulted in high pollution [1]. According to British Petroleum's Energy Statistics Yearbook 2020, China accounts for 30.7% of global carbon emissions, making it one of the largest carbon emitters. SO_2, nitrogen oxides, dust, dust, industrial wastewater and other pollutant emissions also rank among the top in the world. In recent years, the frequent occurrence of environmental events has been pushing governments to pay much more attention to the environmental pollution problem. In 2020, the total investment in environmental pollution control nationwide is 1063.89 billion RMB, of which the total direct investment in pollution control facilities is 737.78 billion RMB, accounting for 69.3% of the total investment in environmental pollution control.

The current research mainly focuses on the agglomeration between manufacturing and services to reduce transaction costs [2,3]. For example, service industries tend to locate near manufacturing industries, thus forming an inter-industry agglomeration. Industrial agglomeration can improve the environment, strengthen environmental regulation and alleviate the "pollution paradise" problem [4]. Government-dominated industries only significantly promote local ecological environmental pollution control, while market-driven inter-industry agglomeration can also promote ecological environmental pollution control in the surrounding region through its spatial spillover effect [3]. Due to the exchange of technology and knowledge, the manufacturing sector gathers to expand the production scale, resulting in environmental pollution problems. Therefore, as compared to previous studies, we pay more attention to the cluster between different manufacturing industries, or inter-industry agglomeration.

In this study, we aimed to elucidate the relationship between inter-industry agglomeration and environmental pollution. Also, we endeavored to understand the mechanism behind pollution caused by agglomeration across industries, laying a foundation for the realization of energy conservation and emission reduction in the industrial industry. Based on the measure of inter-industry agglomeration for 20 Chinese manufacturing industries[1], we found that there is an inverted U-shaped relationship between inter-industry agglomeration and pollution. Energy intensity is an important transmission path from agglomeration to pollution, and it is positively related to industrial energy consumption and inter-industry agglomeration. The expansion of the production scale brought about by the inter-industry agglomeration leads to an increase in energy consumption and pollution. In addition, innovation caused by inter-industry agglomeration does not reduce energy consumption, but has a significant negative impact on environmental pollution.

The contributions of this paper are as follows. First, the pollution is not caused by a single manufacturing industry. Under the backdrop of the professional division of labor, the agglomeration among industries has deepened, and environmental pollution is not only caused by its own production, as it is also related to other industries with close cooperation. The energy consumption and pollution would be different due to the different agglomeration schemes among industries, which reflects the economic connection between production and operation among different industries based on agglomeration. Second, we attempted to put the manufacturing inter-industry agglomeration, energy intensity and environmental pollution in a unified research framework. This paper analyzes the effects of manufacturing inter-industry agglomeration on environmental pollution in consideration of whether inter-industry agglomeration can play a role in energy conservation and emission reduction, and whether energy intensity can serve as a bridge between saving energy and reducing pollution. Furthermore, we analyze the changes in environmental pollution caused by inter-industry

[1] According to "The Industry Classification Standards of National Economy Industry Classification and Code" (2002)

agglomeration from the perspective of energy intensity, which can reveal the mechanisms behind transmission paths from agglomeration to pollution across different industries.

The rest of paper study proceeds as follows: Section 2 provides a literature review; Section 3 introduces the theoretical analysis; Section 4 shows the empirical method and data; Section 5 presents the empirical results and potential mechanisms; Section 6 concludes the paper.

2. Literature

2.1. Industrial agglomeration and environmental pollution

The concept of inter-industry agglomeration was first proposed by Ellison and Glaeser [5], and it is mainly manifested in the correlation between different industries and the existence of overlap in their spatial layouts [6]. In essence, coagglomeration is a phenomenon resulting from inter-industry agglomeration. At present, scholars mainly focus on coagglomeration between the manufacturing industry and the producer services industry [2,3,7], frequently adopting the perspective of industrial spatial layout to measure the coagglomeration [8]. To reduce transaction costs, service industries tend to locate near manufacturing industries, thus forming an inter-industry agglomeration. Government-dominated industries only significantly promote local ecological environmental pollution control, while market-driven inter-industry agglomeration can also promote ecological environmental pollution control in the surrounding region through its spatial spillover effect [3,9]. Ellison and Glaeser [5] observed the nature of the agglomerative force, exploring it through the agglomeration of related industries and those with strong upstream and downstream linkages.

There are few studies on the impact of inter-industry agglomeration on environmental pollution, and most scholars are committed to examining the impact of industrial agglomeration on environmental pollution. On the one hand, industrial agglomeration can offer positive externalities that reduce environmental pollution. Because agglomeration is based on the specialized division of labor, specialized agglomeration promotes inter-industry technology exchange and consumes less energy; thus, it is characterized by positive externalities [10]. Industrial agglomeration reduces environmental pollution mainly by reducing resource mismatch [11], forming scale effects [12], promoting industrial structure adjustment, producing spillover effects and driving innovation [13–18]. Industrial agglomeration can improve the environment, further strengthen environmental regulation and alleviate the “pollution paradise” problem [4]. Sun et al. [19] believe that the central government should reduce market fragmentation, promote market integration, improve resource allocation efficiency and improve environmental quality [20]. Industrial agglomeration can promote economic growth, technological progress and environmental awareness [21–24], thus improving regional environmental pollution. Glaser and Kahn [25] believes that economic agglomeration effectively reduces the commuting distance and traffic pollution emissions, implying that cities are more economical and environmentally friendly than villages. Zeng and Zhao [4] included cross-sector and trans-boundary pollution in their new economic geography model, and their research shows that manufacturing agglomeration can reduce the “pollution paradise” effect to the point of non-existence given strict environmental regulations. Environment-oriented technological progress can promote the improvement of environmental quality and realize coordinated development between the economy and the environment.

On the other hand, agglomeration also represents a negative externality that affects the environment. The expansion of production caused by industrial agglomeration leads to more serious environmental pollution problem through the increase of energy consumption. Brakman [26] proposes that agglomeration has a congestion effect, and they found that it could have a negative impact, such as environmental pollution, limited resources and transportation problems. Frank [27] pointed out that agglomeration is the main factor leading to high levels of air and water pollution. Industrial agglomeration leads to shortages in land supply, aggravates the development of land resources and causes pollution that reduces water quality [28]. The concentration of environmental pollution is related to the energy rebound strength, and the energy rebound strength is closely related to the economic development stage [29]. An extensive economic development mode causes a stronger energy rebound effect to occur, and technological innovation in this mode does not reduce pollution emissions, but would produce technology in the "energy-saving, low-efficiency trap", which is not conducive to optimizing the environment. Wang et al. [30] believe that the entry of new enterprises is an important factor leading to the scale expansion of the development zone, and that environmental pollution is also due to the introduction of polluting enterprises. There is a two-way causal relationship between environmental pollution and agglomeration, i.e., agglomeration intensifies pollution emissions, while pollution limits industrial agglomeration to a certain extent. The energy rebound effect caused by technological changes reduces the cleaning effect brought about by the energy structure and aggravates haze pollution. Liu et al. [31] have shown that industrial agglomeration intensifies the level of environmental pollution, although the negative environmental effect of industrial agglomeration began showing a weakening trend after China's economy entered the new normal.

However, some scholars believe that the impact of agglomeration on the environment has a dual effect and is not simply either a one-way promotional or inhibitory effect. Erik and Peter [32] found that there is a nonlinear relationship between industrial agglomeration and pollution in China's industry. Fan and Scott [33] discuss agglomeration in the less-developed countries of East Asia and its relationship with economic development and growth. Lan, Kakinaka and Huang [34] support the research conclusion of nonlinearity at the urban level. Zhu and Xia [35] used a general equilibrium model, selected a new city as the threshold variable and verified the inverted U-shaped curve relationship between industrial agglomeration and pollution. Liu et al. [31] divided the data into two stages before and after the "new normal"; they found that the negative externalities of the agglomeration environment gradually weaken. Ye and Yu [36] studied industrial agglomeration and haze pollution across China, including the central and eastern regions, finding that they maintain a typical inverted U-shaped curve relationship.

2.2. Industrial agglomeration and pollution

Energy consumption is the most direct factor affecting environmental pollution. At present, considering the relationship between agglomeration and energy intensity, scholars prefer to improve energy efficiency through technological progress [37,38]. Increasing levels of localized knowledge spillovers and the substitution of internal inputs with external inputs may lead to fewer errors in decision-making, as well as in the execution of production tasks, causing firms to become technically more efficient relative to the production frontier. Naik and Bagodi [39] believe that the prevailing technology is efficient, and that a lack of skilled labor, a lack of accessibility to updated or modern technology and a lack of compatibility with new technology are barriers to energy efficiency improvement. Yi et al. [40] pointed out that energy-saving technology advances cannot effectively reduce smog pollution due to the energy rebound effect. Tveteras and Battese [41] found econometric support for positive agglomeration externalities for both the production frontier and technical inefficiency. Ciccone and Hall [42] studied changes in the role of agglomeration externalities in the industry life cycle. According to their research, because the competitive mode, innovation and learning opportunities of the industry change over time [43–45]. Martin et al. [46] discussed whether the agglomeration economy originates from specialization (within industries), diversity (between industries) or overall density. Research supports the idea that industrial clusters located within diverse and dense cities can enhance productivity. Only industrial agglomeration can have a positive impact on industrial energy efficiency [47]. The regional development policy implemented by the state has slowed down the pace of energy efficiency improvements in China's paper industry. The government needs to take regional characteristics into consideration and consciously guide industrial enterprises to concentrate in advantageous areas. Tahir and Ahmad [48] argue that energy intensity may decline with economic growth due to the technological changes that accompany growth. Technological innovation [49,50] is not only able to reduce regional haze pollution, but it can also indirectly reduce haze pollution in neighboring provinces through the knowledge spillover effect [51]. Provincial energy efficiency has a significant spatial spillover effect [52,53], and agglomeration has a U-shaped effect on energy efficiency. Rahman and Alam [54] explored the relationship between health status and health expenditure (public and private), energy consumption and environmental pollution in the SAARC-BIMSTEC region.

In the energy and environmental pollution research, most scholars focus on analyzing the energy consumption structure and believe that it is closely related to environmental quality. Both resource extraction and environmental pollution have significant inhibitory effects on regional long-term economic development. Environmental pollution is the main source of the resource curse. Sun et al. [55] established a new indicator system for the relationship between China’s economic and social development, natural resource consumption and environmental pollution. The combustion of coal-based fossil energy directly causes air and water pollution and aggravates environmental deterioration. Some of the results show that servitization leads to an improvement in energy consumption, which thus improves environmental performance [56]; alternatively, Faisal and Afra [57] examined the relationship between energy consumption and carbon emissions from the perspective of economic growth. With economic development, carbon emissions show a growth trend [58,59] with the relationship chain, and economic growth also increases. Li and Xu [60] pointed out that the impact of investment bias [61–63] and a factor market [64–66] should be considered when formulating energy conservation and emission reduction policies. Different industries have different emission reduction potentials [67] and energy-saving potentials. Baydoun and Aga [68] show that economic growth and energy consumption decrease environmental sustainability, while globalization improves it. There is a one-way causality from energy consumption and globalization to CO_2 emissions in Gulf Cooperation Council (GCC) countries. According to the findings, environmental pollution in GCC countries is output-driven, which means that it is determined by the amount of energy generated and consumed. This is consistent with the conclusion of Liu et al. [69]. Energy consumption is the main factor leading to ecological pollution. Some scholars estimated the energy rebound effect in China’s industrial sector [70,71]. Output growth is the main factor driving industrial energy consumption, while energy intensity reduction and structural change play leading roles in moderating industrial energy consumption. Ushifusa and Tomohara [72] pointed out that energy intensity has an inverted U-shaped impact on carbon emissions, and that it plays an intermediary role in the economic agglomeration and pollution emissions. Li [22] analyzed the impact of the energy rebound effect on carbon emissions in different urbanization stages. The impact of the short-term energy rebound effect on carbon emissions is greater than that of the long-term energy rebound effect [73], and both decrease with an increase in the urbanization rate.

Adjusting the energy consumption structure appears to be an effective way to alleviate serious pollution. Starting from the internal structure of energy consumption, Mudakkar et al. [74] divided energy into electrical energy, fossil energy and nuclear energy and explored the differences in the environmental impact of the energy consumption structures in different industries. The long-term governance of air quality depends upon the improvements to the energy consumption structure. In the short term, it is necessary to reduce the use of coal to alleviate severe ecological problems. To adjust the energy structure, the industrial structure also needs to be adjusted. The long-term strategy for achieving a green environment is to adjust the energy structure and the internal structure of the industry. Liu and Xiao [75] further verified through empirical research that the energy structure is the main factor affecting carbon emissions, emphasizing that regions with coal consumption as the main energy source should explore the use of emission reduction methods in their energy consumption structure to reduce environmental pollution. There is no environmental Kuznets curve (EKC) for CO_2 emissions from economic growth, nonrenewable energy production or foreign trade in China. However, Chen et al. [76] found that the inverted U-shaped hypothesis of the EKC is supported in the long run after the renewable energy production variable is added. Administrative power leading the allocation of resources creates obstacles in the flow of factors between regions, aggravates the market segmentation of resource-based cities and is not conducive to knowledge spillover and pollution control technology sharing [77,78].

Existing literature on the relationship between industrial agglomeration, energy intensity and environmental pollution is relatively rich, but the following points can be improved. First, all studies focus on the agglomeration of a single industry but do not pay attention to the coagglomeration among different types of industries. Through the division of labor and cooperation or the coagglomeration of upstream and downstream industries in the industrial chain, the impact of inter-industrial agglomeration on energy demand and pollution emission is also affected by the industrial type. Second, there are few studies on inter-industry agglomeration, industrial innovation and environmental pollution under the same theoretical framework. Inter-industry agglomeration brings economies of scale through centralized regulation and technology spillover effects, affects energy consumption and ultimately affects industrial pollution emissions. Internal relationships exist among the three, and putting them in the same framework allows for a more comprehensive understanding of the impact of inter-industry agglomeration on pollution, as well as provides a reasonable basis for energy conservation and emission reduction. In this study, based on the existing literature, we improve the related research on environmental pollution by addressing the above two shortcomings, thereby providing valuable results that can be used to support environmental governance.

3. Theoretical analysis

The impact of inter-industry agglomeration on environmental pollution is mainly related to the transmission of energy intensity, and there is a positive correlation between energy intensity and environmental pollution, so we should pay more attention to the impact of inter-industry agglomeration on energy intensity. With economic growth, energy consumption and industrial agglomeration have increased significantly. Industrial agglomeration and energy have a significant “inverted U-shaped” relationship [79]. In the early stage of industrial development, the scale effect [80] caused by inter-industry agglomeration would lead to the increase in energy consumption, resulting in more environmental pollution. With the development of industry, technology, labor and capital continue to interact between industries [81,82]. There is a spillover effect [53,83,84] among industries through the division of labor and cooperation between industries, as all types of public infrastructure are built and some enterprise clusters form. Inter-industry agglomeration could reduce the cost of production and transportation and increase the exchange of technology and knowledge. The manufacturing industries are gradually shifting toward low-energy consumption and low-pollution industries, reducing energy consumption and pollutant emissions [85]. Therefore, the influence of inter-industry agglomeration on energy intensity presents as an inverted U-type relationship, and it further affects environmental pollution. Hypothesis 1 is proposed.

Hypothesis **1: The impact of inter-industry agglomeration on the environment is represented by an inverted U-type relationship through the path of energy intensity.**

Inter-industry agglomeration can lead to technology improvement because technology connectivity shares public technology or overflows among industries [84]. Therefore, inter-industry agglomeration would promote the reduction of pollution emissions through technological upgrades. Manufacturing coagglomeration brings about technological upgrades and uses advanced equipment to reduce pollution emissions [86]. Because the government collects emission fees on enterprises [87,88], enterprises pay more attention to emission reduction effects rather than energy-saving effects. Furthermore, technological progress caused by inter-industry agglomeration would lead to the expansion of the production scale [89], which would increase energy demand. The new technologies adopted by enterprises are often used to reduce emissions, but they cannot effectively reduce energy demand by the scale of production [90]. The coagglomeration of manufacturing industries brings technological progress [91,92], prompting enterprises to be more motivated to expand the production scale, which leads to an increase of energy demand. Due to the continuous expansion of the industrial scale, the new technology would have difficulty offsetting the increased energy demand caused by scale expansion, resulting in more energy consumption with the new technology than that without the new technology [93]. Therefore, we propose Hypotheses 2a and 2b.

Hypothesis 2a: The technology innovation induced by inter-industry agglomeration can reduce environmental **pollution.**

Hypothesis **2b: The expansion of the production scale brought about by coagglomeration has a negative effect on environmental pollution.**

4. Research design

4.1. Model settings

Inter-industry agglomeration impacts the environmental pollution caused by other related industries in the process of production, transportation and exchange. We focus on the coagglomeration of 20 manufacturing industries (Table 1). This paper discusses the impact of coagglomeration on pollution emissions. The model is as follows:

$$M_{it} = \beta_0 + \beta_1 W_{ijt} M_{jt} + \beta_2 (W_{ijt} M_{jt})^2 + \beta_3 z_{it} + u_i + v_t + \varepsilon_{it} \tag{1}$$

$$y_{it} = \lambda_0 + \lambda_1 M_{it} + \lambda_2 z_{it} + u_i + v_t + \varepsilon_{it} \tag{2}$$

where W_{ij} indicates the coagglomeration level of industry i and industry j[2]. The coagglomeration that needs to be noted is represented by an $n \times n$ matrix, and the other indicators are given in an $n \times 1$ matrix.

[2] W_i is the agglomeration of the same type of manufacturing industry i, and W_{ij} indicates the agglomeration of different types of manufacturing industries (industry i and industry j). Therefore, $W_i \times M_{it}$ and $W_{ij} \times M_{jt}$ have different meanings. $W_i \times M_{it}$ indicates the synergy of an industry's agglomeration and the energy intensity of the industry. $W_{ij} \times M_{jt}$ indicates the synergistic effect of the agglomeration between two manufacturing industries (industry i and industry j) and the energy intensity of the manufacturing industry j.

Due to the particularity of the coagglomeration index, we cannot observe the impact of coagglomeration on environmental pollution separately. Considering that energy intensity is a mechanism between coagglomeration and the environment [94], we studied the impact of the interaction between coagglomeration and energy intensity on the environment. That is, the energy intensity of industry *i* is affected by the energy intensity of others converging with it; it is used to obtain the impact of coagglomeration on environmental pollution by analyzing the energy intensity. y_{it} is the emissions of pollutants for industry *i* during period *t*. We chose to focus on wastewater emissions, sulfur dioxide emissions, carbon dioxide emissions, smoke (dust) emissions, solid waste generation and comprehensive indicators of environmental pollution when estimating the impact of coagglomeration in the industry on different pollutants; z_{it} indicates the relevant control variables, including environmental regulation, openness, ownership and Research and development strength (R&D) intensity. M_{ij} is the energy intensity of industry *j* during period *t*, u_i represents the industry fixed effect, v_t represents the time fixed effect and ε_{it} indicates the random interference term.

Table 1. Classification of manufacturing industry.

Industry code and name	Industry code and name	Industry code and name
C13 Agricultural and sideline food processing industry	C26 Chemical raw materials and chemical products manufacturing	C35 General equipment manufacturing
C14 Food manufacturing	C27 Pharmaceutical manufacturing	C36 Special equipment manufacturing industry
C15 Wine, beverage and refined tea manufacturing	C28 Chemical fiber manufacturing industry	C37 Transportation equipment manufacturing industry
C16 Tobacco products industry	C31 Furniture manufacturing and nonmetal mineral products	C39 Electrical machinery and equipment manufacturing industry
C17 Textile industry	C32 Ferrous metal smelting and calendering industry	C40 Computer, communication and other electronic equipment manufacturing industry
C22 Paper and paper products industry	C33 Nonferrous metal smelting and calendering industry	C41 Instrumentation and cultural manufacturing
C25 Petroleum processing, coking and nuclear fuel processing industries	C34 Metal products industry	

Notes: Two-digit and 20 sub-industries were selected based on Industry Classification and Code of the National Economy. The reason for choosing these sectors is that, first, they cover various factor-intensive industries, representing the overall level of manufacturing development. Second, these industries are not heavily dependent on natural resources, which means that they can be transferred between regions and will have a strong scale effect.

Formula (1) shows that the energy intensity of industry *i* is affected by the energy intensity of industry *j* in the case of inter-industry agglomeration. $\boldsymbol{\beta_1}$ indicates that the energy intensity of industry *i* is affected by the inter-industry agglomeration of industry *i* and industry *j* and the energy intensity of industry *j*. $W_{ij}M_{jt}$ indicates the effect of the synergy between the two industries (industry *i* and industry *j*) and the energy intensity of another agglomeration industry *j*. Formula (2) reveals that the energy efficiency of the industries affects the level of energy consumption and, then, of pollution emissions. Combining Formulas (1) and (2), it can be observed that the pollution emissions of industry *i* are affected by the energy intensity of industry *j* at a certain level of inter-industry agglomeration, which indicates that the environmental pollution of industry *i* is also affected by the energy consumption of related agglomeration industries.

4.2. Index selection and data source

4.2.1. Index selection

Explained variable. The main methods for measuring environmental pollution are the factor synthesis method, principal component analysis method, entropy method and comprehensive index method, among others. In this study, the entropy method [95] was used to calculate the environmental pollution index, which includes SO_2 emissions, smoke or dust emissions, CO_2 emissions[3], wastewater emissions and solid waste production. Then, the principal component analysis method [97] was used to measure the environmental pollution index for the robustness test. CO_2 emissions were calculated by using Formula (3).

Outcome variable. We were interested in capturing the degree of energy intensity [94] and that of manufacturing coagglomeration. The detailed data sources and the process for computing the inter-industry agglomeration index are as follows:

(1) The total industrial output value for all regions and industries. The index takes 1990 as the base period for the gross industrial output value for all regions and industries and adjusts it according to the factory price index of industrial producers. The data were taken from the China Industrial Economic Statistical Yearbook from 2000 to 2016.

(2) The number of enterprises in different types of industries. Due to the lack of data on the number of enterprises in various industries in 2005, we used the averaging method to fill the data gaps. Because the micro data of the national industrial database are only available through 2013, the H index was only calculated to 2013. To ensure the integrity of the data, the H index values from 2014 to 2016 were predicted by exponential smoothing.

(3) The total output value for each region. The gross output value of each region was measured by GDP (100 million rmb), and the data were taken from the China Statistical Yearbook (2000–2016).

Control variables. Environmental regulation is also an important factor affecting environmental pollution. We referred to Lin et al. [96] to measure the comprehensive utilization rate of waste. When the environmental regulation intensity increases, enterprises are afraid to discharge too many pollutants and the comprehensive utilization rate of waste is high; otherwise, the utilization rate is low. R&D intensity is measured by internal and external R&D expenditures [98]. According to endogenous economic growth theory, the higher the R&D investment, the better the technological innovation and progress, which causes corresponding improvements in the industrial production efficiency [99] and green economic efficiency. Therefore, the greater the R&D intensity, the more likely that environmental pollution emissions would be reduced. The degree of opening up is determined by the shipping ratio [100]. Opening up is conducive to attracting foreign investment and green technology to support energy conservation and emission reduction. In addition, the following control variables were selected at the industrial level: ownership structure is represented by the proportion of state-owned enterprises [96], as ownership is found to be an important factor affecting the industrial

[3] Carbon dioxide emissions from the manufacturing production process are mainly related to the combustion of chemical fuels. For example, manufacturing industries, such as the metal smelting, oil processing, coking and nuclear fuel processing industries, produce a large amount of carbon dioxide in the production process, leading to abnormal climate, elevated sea levels, melting glaciers and reduced numbers of animals and plants, which has a negative impact on the natural environment. Therefore, we include carbon dioxide in the category of pollutants.

structure; the population of the employed labor force was selected for the scale, noting that the output levels of each industry are different because of productive scale; and the energy consumption structure is represented by the proportion of coal consumption in total energy consumption [101]. The cost structure determines the volume of pollution emissions.

4.2.2. Measures of relevant indicators

A. Carbon emissions

In the industrial production process, environmental pollution is caused by energy consumption. To objectively reflect the pollution situation of various industries, we selected the following five types of pollutants: sulfur dioxide emissions, smoke or dust emissions, carbon dioxide emissions, wastewater emissions and solid waste generation. However, although carbon dioxide emissions are the main indicators of greenhouse gases, the relevant data are not provided in the relevant yearbook. According to the research of Qu et al. [101], carbon dioxide emissions can be calculated by multiplying the energy consumption by the carbon dioxide emission coefficient of the focal industry; the formula is as follows:

$$\sum_{i=1}^{n} CO_{2i} = \sum_{i=1}^{n} E_i \times NCV_i \times CEF_i \times COF_i \times (\frac{44}{12}) \tag{3}$$

where n refers to the types of energy consumption in the industry. In this study, the following eight sources of consumed energy were selected: coke, coal, kerosene. gasoline, fuel oil, natural gas, diesel oil and crude oil. E_i is the i-th source of energy consumed, NCV_i is the average calorific value of the i-th energy source, CEF_i is the carbon content per unit calorific value of the i-th energy source and COF_i is the oxidation level of the i-th energy source. The molecular weights of CO_2 and carbon are 44 and 12, respectively. The CO_2 emissions of the n-th energy source can be calculated by using Formula 4, and the total CO_2 emissions of various industries can be obtained by summing the CO_2 emissions of all n energy sources.

B. Agglomeration between different manufacture industries

Based on the calculation method of Ellison and Glaeser [5], we considered the scale of enterprises in various industries, the market structure of industries and other factors as factors influencing inter-industry agglomeration. The calculation formula is as follows:

$$W_{ij} \equiv \frac{[G_i/ (1\text{-}\sum_i^M x_r^2)] - \sum_i^M x_i^2 H_i - \sum_i^{i=20} W_i x_i^2 (1-H_i)}{1\text{-}\sum_i^{i=20} x_i^2} \tag{4}$$

where W_{ij} represents the coagglomeration of different types of manufacturing industries and W_i represents the agglomeration within the industry and the same industry type. Therefore, Formula (5) represents intra-industry agglomeration, which is different from Formula (4). H_i said that the i-th industry H index is the enterprise summary of industry data. G_i is the spatial Gini coefficient. The specific calculation is as follows:

$$W_i \equiv \frac{G_i - (1\text{-}\sum_i^M x_r^2) H_i}{(1\text{-}\sum_i^M x_r^2)(1 - H_i)} \tag{5}$$

$$G_i = \sum_{i=1}^{M} (q_{ir} - x_r)^2 \tag{6}$$

$$\boldsymbol{H_i} = \sum_{j=1}^{N_{i\,total}} \boldsymbol{Z_p^2} \tag{7}$$

q_{ir} represents the GDP of the *i*-th industry in the *r*-th region in that year, and it is deflated by the industrial producer price index (1990 = 100); x_r represents the gross domestic product of the *r*-th region as a proportion of the national gross domestic product; Z_P represents the employment number of the *p*-th enterprise as a proportion of the total employment, which measures the relative scale of the enterprise in the industry. The data are at the enterprise level (a total of 161671 enterprises). $\boldsymbol{M}$ represents the number of provinces and cities in China.

4.2.3. Data sources

CO_2 emission can be calculated by using Formula (3). The average heat generation ($\boldsymbol{NCV_i}$) data for various energy sources were taken from the General Rules for Comprehensive Energy Consumption Calculation (GB/T 2589-2008). The carbon content per unit calorific value (CEF_i) and oxidation rate (COF_i) of various energy sources were taken from the Intergovernmental Panel on Climate Change (IPCC) national greenhouse gas inventory guidelines. The energy consumption data were taken from the China Energy Statistical Yearbook. The relevant indicators of industrial wastewater, waste gas and waste were taken from the China Environmental Database; other data were taken from the China Industrial Economic Statistics Yearbook (1999–2016).

When we calculate inter-industry agglomeration, the spatial Gini coefficient needs to be measured first (Formula (6)). The data were used to calculate the Gini coefficients from the China Industrial Economic Statistical Yearbook. We calculated the Heffendar index by using Formula (7); the data were derived from the statistical yearbook of China's industrial enterprises and the statistical yearbook of China's industrial economy. Finally, we calculated the level of intra-industry agglomeration (Formula (5)) and the level of inter-industry agglomeration (Formula (4)). Controls of the variable data source were taken from the Statistical Yearbook of China Industrial Economy (1999–2016).

4.2.4. Results of agglomeration of Chinese industries

We measured the level of coagglomeration among Chinese manufacturing industries from 2000 to 2016 based on the method proposed by Ellison and Glaeser [5]. First, we calculated the intra-industry agglomeration by using Formula (5) and divided into three stages according to Ellison and Glaeser [5]. Three industries (C28, C40 and C41) were calculated to be in the high agglomeration stage, namely, 0.1287, 0.0794 and 0.0912, respectively. The industries in the medium and low intra-industry agglomeration stages account for a large proportion, and the number of manufacturing industries in the medium and low intra-industry agglomeration stages accounts for half of each.

Second, we further calculated the inter-industry agglomeration levels among various industries according to Formula (4). It shows that the inter-industry agglomeration result is a symmetric matrix (Appendix 1, Table A3). From the perspective of the average over the years, C28 and C41 have the highest levels of inter-industry agglomeration with others, all greater than 0.1. First, it shows that the C28 chemical fiber manufacturing industry had the highest synergistic agglomeration level in the whole bisection-digit manufacturing industry, which was as high as 0.2696. In the first half of 2019, the main business revenue of the chemical fiber industry was 428.7 billion yuan, up 7.1% year on year;

the total profit was 13.3 billion yuan. Chemical fibers are made from natural polymer compounds or synthetic polymer compounds. Because of their different chemical compositions, they have different properties and wide uses. For example, adhesive fiber is used as a curtain cloth in industry applications, so it is closely related to the transportation manufacturing industry. Polyester and silicone rubber are used to produce artificial skulls, which are applications that are closer to the medical manufacturing industry; Cotton is used to make fishing nets, toothbrushes and brush-related products for the food manufacturing and textile industries. Acrylic has aging resistance and water absorption properties, which are appropriate for applications in the construction, water conservancy, medical and clothing industries. Therefore, chemical fiber and other industries have the highest levels of inter-industry agglomeration. Second, the C41 instrument, cultural office supplies machinery, other measurement instrument manufacturing industry and other industries reached the second-highest level. These include many industries and are widely used in the industrial manufacturing industry. Instruments can also have automatic control, alarm, signal transmission and data processing functions. For instance, pneumatic adjustment instruments used for the automatic control of industrial production processes, electrical adjustment instruments and distributed instrument control systems are essential in the entire industrial manufacturing process. In addition, the C40 communication equipment computer and other electronic equipment manufacturing industry ranked third in the degree of coordination, and the agglomeration level with other industries ranged between 0.08–0.22. Communication equipment and other electronic equipment serve as the hub of signal transmission in the production of other industries, cooperating with each link and each department, and the industry has a high degree of coordination with others.

5. Empirical results

5.1. Main results

Inter-industry agglomeration can affect energy intensity through economies of scale effects and technology spillover effects. It drives changes in energy efficiency and ultimately impacts environmental pollution. Therefore, this section is divided into the following two types of results: the first focuses on the impact of inter-industry agglomeration on energy intensity, and the second focuses on the effects of energy intensity on environmental pollution. To more clearly illustrate the impact of inter-industry agglomeration and energy intensity on pollution emissions, the annual mean of the above three indicators has been used.

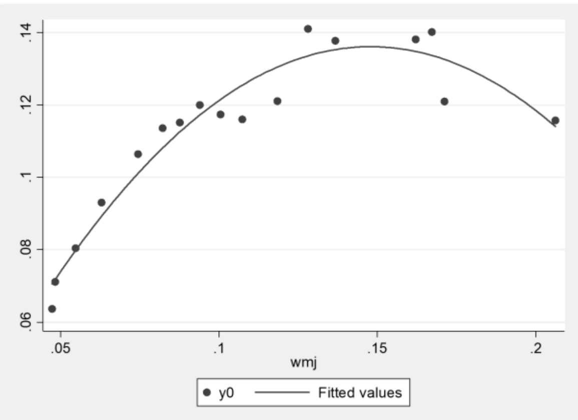

Figure 1. Average of inter-industry agglomeration and pollution emissions.

Figure 1 shows the interaction between the collaborative concentration (*i* and *j* industries) and energy intensity of other industries (*j* industries); the joint impact on environmental pollution in industry *i* shows an inverted U-shaped relationship. This indicates that pollution emissions in a certain industry are related not only to the inter-industry agglomeration, but also to the energy intensity of coagglomeration in other industries. Because energy consumption is a direct source of environmental pollution, the greater the energy intensity, the greater the pollution emissions, and the relationship between energy intensity and pollution emissions is positive. Therefore, we used the quadratic term in the model settings, arguing that the joint effect of inter-industry agglomeration and energy intensity showed a U-type relationship with environmental pollution.

Inter-industry agglomeration can lead to environmental pollution caused by production, transportation and technology exchange within and across different levels of industries. Based on the panel data of 20 manufacturing industries from 2000 to 2016, the 2SLS regression model was used. It is worth noting that, when considering the impact of manufacturing inter-industry agglomeration on energy intensity, as well as the impact of energy intensity on pollution, the corresponding explanatory variables lagging 2–3 periods were used as instrumental variables.

We take the result of 2SLS as an example in Table 2. The primary and secondary coefficients for the interaction capturing the agglomeration and the energy intensity of industry *j* were 1% and 5%, respectively, and an inverted U-shaped curve was formed. The multiplication of the coagglomeration index and the energy strength of other industries was less than 0.649. Energy intensity increases with the energy intensity in others and fails to yield the dividend effect of inter-industry agglomeration under the constraint of the coagglomeration, which is not conducive to the reduction of energy consumption [79]. In the early stage, when the inter-industry agglomeration is low, the industrial chain is not mature, the common technology or information technology is relatively low and, thus, clusters do not have a technology spillover effect. With the deepening of the inter-industry agglomeration, the professional division of labor between manufacturers deepens and the industrial chain is increasingly improving. The scale effect of the coagglomeration is prominent. Besides, coagglomeration enables manufactures with similar or common technologies to achieve technology exchange and improve energy utilization efficiency, and the energy intensity shows a downward trend.

The impact of energy intensity on environmental pollution is shown in Table 3. Energy consumption is a direct factor in environmental pollution. The consumption of fossil fuels represented by coal directly generates CO_2, SO_2 and other pollutants, which aggravates environmental pollution. The empirical regression yielded that energy intensity has a significant positive correlation with environmental pollution, which verifies that enhancing the energy intensity does indeed aggravate environmental pollution. Furthermore, considering how energy intensity influences different pollutants, the energy intensity of industry *i*, at a significance level of 10%, has a negative correlation with industrial wastewater, industrial SO_2 and soot emissions of other industries. Generally, industrial wastewater and smoke and dust emissions are mostly non-energy-dependent industries, with low energy demand. When the production of energy-dependent products is increased, it naturally occupies the production space of non-energy-dependent products and reduces the emission of pollutants such as wastewater and soot. However, energy intensity has a significant positive correlation with the total amount of industrial solid waste and carbon emissions, indicating that an increase in energy intensity can bring an increase in solid waste and carbon emissions for other industries, thus aggravating environmental pollution.

Table 2. Impact of coagglomeration on energy intensity.

Variables	Energy-2SLS (M_j)	Energy-FE (M_j)
$W_{ij}*M_j$	0.959***	1.356**
	(0.247)	(0.589)
$(W_{ij}*M_j)^2$	-0.739**	-2.270**
	(0.301)	(1.014)
Regulation	-0.01	-0.001**
	(0.015)	(0.000)
Opening	0.064***	0.170*
	(0.022)	(0.084)
R&D	-0.183**	-0.112**
	(0.092)	(0.048)
Scale	-0.045**	0.061
	(0.018)	(0.112)
Constant	0.064*	-0.019
	(0.034)	(0.048)
Year FE	Yes	Yes
Industry FE	Yes	Yes
Observations	300	340
R-squared	0.955	0.275

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels. The regression R-value generally reflects the presence of unobservable factors in the economic models and does not affect the causal identification effect. The magnitude of the R-value is not used as a criterion for the judgment of the model. For example, the value of the R-value in Column 3 of Table 2 is 0.275, which does not affect the explanations of the coefficients in the study.

Table 3. Impact of energy intensity on environmental pollution.

Variables	Comprehensive pollution	Wastewater	SO_2	Solid waste	Smoke or dust	CO_2
M_i	1.443***	-0.730***	-0.930**	2.105***	-1.332***	1.318***
	(0.362)	(0.226)	(0.426)	(0.444)	(0.422)	(0.259)
Regulation	-0.0004	-0.0001	0.0007	-0.0005	0.0002	-0.0001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Opening	-0.276***	0.046	0.250**	-0.254*	0.245**	-0.041
	(0.107)	(0.067)	(0.125)	(0.131)	(0.124)	(0.076)
Ownership	-0.251*	0.118	0.395***	-0.258	0.324**	0.044
	(0.128)	(0.080)	(0.151)	(0.157)	(0.150)	(0.092)
R&D	0.745*	-0.457*	-0.657	0.139	-0.911*	0.128
	(0.416)	(0.260)	(0.489)	(0.510)	(0.484)	(0.297)
Structure	0.290***	-0.010**	-0.227**	0.145	-0.215**	0.047
	(0.076)	(0.047)	(0.089)	(0.093)	(0.088)	(0.054)
Constant	-0.127	0.412***	0.212**	-0.132	0.258**	-0.063
	(0.091)	(0.057)	(0.107)	(0.111)	(0.106)	(0.065)
Observations	320	320	320	320	320	320
R-squared	0.349	0.961	0.866	0.590	0.710	0.914
Year FE	yes	yes	yes	yes	yes	yes
Industry FE	yes	yes	yes	yes	yes	yes

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels.

Combining Tables 2 and 3, the primary and secondary coefficients for the interaction between inter-industry agglomeration and energy intensity were calculated to be 1.3838 and −1.0664, respectively. This shows that the pollution emission level of industry *i* is closely related to the energy consumption of other industries, and that, as the degree of inter-industry agglomeration deepens, the pollution emission level first rises and then declines. When the inter-industry agglomeration reaches a certain value, the energy intensity of industry *j* affects the pollution emission of industry *i*. Therefore, to achieve the goal of reducing pollution, an industry must also consider the energy efficiency and energy consumption of other industries that are closely related to its industrial production, division of labor and exchange.

5.2. Robustness test

5.2.1. Comprehensive index of environmental pollution

We selected five types of pollutants and then used the entropy method to fit the comprehensive index of environmental pollution. To avoid biased research issues caused by different research methods, we further used principal component analysis for verification. The results are shown in Table 4. Columns (1) and (2) show the increased significance of the impact of inter-industry agglomeration on the environment, indicating that energy intensity is the intermediate mechanism between coagglomeration and environmental pollution.

Table 4. Impact of industrial agglomeration on pollution emissions.

Variables	Energy (M_i)	Main component	Drop CO_2
M_i		0.076***	0.418***
		(0.006)	(0.037)
$W_{ij}*M_j$	0.959***		
	(0.247)		
$(W_{ij}*M_j)^2$	-0.739**		
	(0.301)		
Constant	0.064*	0.002	0.001
	(0.034)	(0.003)	(0.002)
Controls	Yes	Yes	Yes
R-squared	0.955	0.943	0.928
Year FE	yes	yes	yes
Industry FE	yes	yes	yes
Observations	300	320	320

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels.

5.2.2. Removal of the greenhouse gas CO_2

There is some dispute about whether CO_2 is an environmental pollutant. In the previous section, CO_2 is included in the comprehensive index of pollutants. To consider this alternative perspective, we reconstructed the comprehensive index of environmental pollution by removing CO_2. The results are shown in Table 6. Columns (1) and (3) show the results for the comprehensive impact of the coordinated agglomeration of two different industries on environmental pollutants through the transmission of energy intensity; Column (5) is the impact of the interaction of intra-industry agglomeration and energy intensity on the environment; the results excluding CO_2 emissions as a pollutant are consistent with the calculation results, indicating that the environmental pollution of manufacturing industries is not related only to their own energy intensity. The conclusion is consistent with the previous conclusion.

5.3. Mechanisms

5.3.1. Impact of the productive scale on environmental pollution

In the relationship between coagglomeration and the environment, the amount of pollution emissions is related not only to the inter-industry agglomeration, but also to the intra-industry agglomeration and the scale [84]. We further analyzed the impact of two factors on environmental pollution (Table 5). Because the industrial scale adopts each industrial proportion in the total industrial output value, we used the panel data of 20 manufacturing industries from 2000 to 2016 for the regression.

Table 5. Impact of intra-industry agglomeration and productive scale on the environment.

Variables	Energy (M_i)	Comprehensive pollution ($y0_i$)
$W_{ij}*M_j$	9.400***	
	(2.200)	
$(W_{ij}*M_j)^2$	-9.017***	
	(1.969)	
M_i		0.100***
		(0.029)
Intra-industry agglomeration	5.593***	0.224
	(1.160)	(0.177)
Scale	3.594**	3.290**
	(1.790)	(1.549)
Constant	0.795***	-0.097
	(0.173)	(0.076)
Controls	Yes	Yes
R-squared	0.830	0.983
Year FE	yes	yes
Industry FE	yes	yes
Observations	280	280

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels.

The results show that the relationship between inter-industry agglomeration and energy intensity is affected by the intra-industry agglomeration and productive scale; the significance levels are 1% and 5%, respectively. However, the impact of energy intensity on the environment is mainly related to the scale of production, and the relationship with the intra-industry agglomeration is not statistically significant, indicating that the scale of industrial production is the main factor affecting the impact of energy consumption on pollution emissions. Intra-industry agglomeration only affects energy intensity and has no significant direct impact on the pollutant emission level.

Table 6. Effects of technological innovation on environmental pollution.

Variables	Energy (M_i)	Comprehensive pollution (y_i)
M_i		0.181***
		(0.022)
$W_{ij}*M_j$	1.882**	
	(0.810)	
$(W_{ij}*M_j)^2$	-2.207***	
	(0.720)	
patents	0.002	-0.009**
	(0.011)	(0.004)
Constant	0.422***	0.138***
	(0.103)	(0.019)
Controls	Yes	Yes
Observations	280	280
R-squared	0.932	0.964
Year FE	yes	yes
Industry FE	yes	yes

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels.

5.3.2. Impact of technological innovation on environmental pollution

We further explore whether agglomeration among industries influences the emission reduction effect of industrial technology innovation. The index of technological innovation uses the number of effective patents, which was taken from the industrial enterprise patent database. The panel data from 2000 to 2016 were used for the regression; the results are shown in Table 6. In the case of agglomeration among different industries (Table 6), there is no significant relationship between industrial innovation and energy intensity; however, industrial innovation was found to have a significant negative impact on environmental pollution, indicating that innovative technology does not reduce the energy consumption of enterprises, but that applying new technology in the process of energy consumption can play a role in reducing emissions. Among these, the regression results in Column (1) show that technological progress is not statistically significant for energy, but that it is positive according to the regression coefficient, indicating that technological progress increases energy intensity to some extent. Technological innovation does not reduce energy demand, as it increases energy demand. Here, we found that the nonlinear effect of inter-industry agglomeration on environmental pollution is clearly weakened, which may be the effects of knowledge and technology spillover.

5.4. Heterogeneity analysis

The manufacturing industry can be divided into labor-intensive, capital-intensive and technology-intensive industries. The specific classification is shown in the table below. We further analyzed whether the industry category would influence the effect of inter-industry agglomeration on pollution.

A. Technology-intensive industry

For technology-intensive industries, Panel A of Table 7 shows that the energy intensity of industry *i* is related to inter-industry agglomeration and the energy intensity of related industries, and that the impact of energy intensity varies for different pollutants. The industrial solid waste, industrial sulfur dioxide and carbon emission pollutants of technology-based industries are closely related to energy intensity and increase with increasing energy intensity. Technology-intensive industries, such as the chemical industry, mainly emit SO_2, and an increase in energy intensity is bound to drive an increase in pollutants. However, the amount of smoke or dust decreased with increasing energy intensity. Due to the inter-industry agglomeration of technology-based industries, such as transportation equipment and electrical machinery industries, the amount of smoke and dust decreased with increasing energy consumption.

Table 7. Heterogeneity analysis of the inter-industry agglomeration.

Variables	Energy (M_i)	Comprehensive pollution	Wastewater	SO_2	Solid waste	Smoke or dust	CO_2
Panel A: technology-intensive industries							
$W_{ij}*M_j$	-3.437***						
	(1.062)						
$(W_{ij}*M_j)^2$	2.570**						
	(1.238)						
M_i		0.050*	-0.016	0.128**	0.532***	-0.037***	0.309***
		(0.027)	(0.024)	(0.052)	(0.034)	(0.012)	(0.017)
Panel B: labor-intensive industries							
$W_{ij}*M_j$	-0.970**						
	(0.403)						
$(W_{ij}*M_j)^2$	2.857**						
	(1.178)						
M_i		1.091*	7.590***	2.944***	4.299***	-0.421	0.990***
		(0.624)	(1.593)	(0.608)	(0.807)	(0.296)	(0.012)
Panel C: capital-intensive industries							
$W_{ij}*M_j$	13.21**						
	(5.229)						
$(W_{ij}*M_j)^2$	-18.85**						
	(7.796)						
M_i		0.303***	-0.115***	0.765***	2.025***	-0.332*	1.437***
		(0.039)	(0.033)	(0.136)	(0.187)	(0.191)	(0.080)
Controls	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes
Industry FE	yes	yes	yes	yes	yes	yes	yes

Notes: The standard errors are in parentheses; ***, ** and * represent significance at the 1%, 5% and 10% levels.

B. Labor-intensive industry

The comprehensive effects of inter-industry agglomeration of labor-intensive industries are shown in Panel B of Table 7. The relationship between inter-industry agglomeration and energy intensity reached a significance level of 5%, and that between the comprehensive level of energy intensity and environmental pollution was found to be significantly positive at 10% level. Therefore, inter-industry agglomeration was found to have a significant impact on environmental pollution via the energy intensity for labor-intensive industries. Combining Columns (1) and (3), the agglomeration of different labor-intensive industries led to an increase in industrial wastewater discharge. The relationship between wastewater discharge and energy intensity was significantly positive at the 1% level, indicating that labor-intensive industries discharge the greatest amount of industrial wastewater, followed by industrial solid waste, which had a coefficient of 4.299 at a 1% level. In terms of different pollutants, labor-intensive industries have a greater impact on industrial wastewater and solid waste, which involve different pollutants. The production process is accompanied by a large amount of industrial wastewater because labor-intensive industries mainly include the production of textiles, clothing, food, etc. Besides, the biggest characteristic of labor-intensive industries is a large number of people, which would naturally produce household waste, resulting in serious solid waste pollution.

C. Capital-intensive industry

The energy intensity of capital-intensive industries has a significant impact on the environment (Panel C of Table 7), mainly because industrial solid waste, carbon emissions and sulfur dioxide from capital-intensive industries are more sensitive to energy consumption. The production processes of metal smelting and other manufacturing industries are bound to cause CO_2 emissions to rise, and energy consumption leads to the emission of sulfide and other pollutants, which aggravates environmental pollution. When the industrial solid waste, carbon emissions and sulfur dioxide of capital-intensive industries reach a certain critical value, pollution emissions begin decreasing with increasing energy consumption and the scale effect of inter-industry agglomeration becomes dominant. However, when inter-industry agglomeration exceeds a certain value, due to the expansion of the productive scale, production brings more energy consumption and environmental pollution.

In general, different industries have different effects on environmental pollution. Technology-intensive inter-industry agglomeration has the most significant impact on industrial SO_2; additionally, the agglomeration of different labor-intensive industries brings industrial wastewater discharge, while capital-intensive industries produce solid waste, carbon emissions and industrial SO_2. When dealing with different industries, emission reduction measures should be formulated according to the industry type and main pollutants.

6. Conclusions

Based on the panel data of 20 Chinese manufacturing industries, we mainly found that there is an inverted U-shaped relationship between inter-industry agglomeration and environmental pollution. At the initial stage, inter-industry agglomeration led to the increase of energy consumption. The deepening of inter-industry agglomeration gradually led to the reduction of energy consumption, which thus reduces environmental pollution. The impact of inter-industry agglomeration on the environment is related to intra-industry agglomeration and production scale. The expansion of the production scale caused by coagglomeration leads to more energy consumption and pollution. Innovation has a significant negative impact on environmental pollution, but not on energy intensity. The innovative technology caused by inter-industry agglomeration does not reduce energy consumption, but it helps to reduce pollution emissions.

The above conclusions provide some insight into global environmental pollution control. As a developing country, China plays an important role in global pollution control. First, we should improve the mechanism of industrial collaborative development. Industrial pollution comes not only from within industries, but also from collaboration between industries with strong industrial linkages. The results in this paper remind us to pay attention to the environmental problem caused by coagglomeration. Second, a reasonable productive scale should be determined according to the degree of coagglomeration to balance economic output and energy consumption. We found that the positive externalities of coagglomeration leads to the “spillover effect” of technology and knowledge, and that the manufacturing industry would further expand production to obtain more profits. The expansion of the productive scale is an important factor leading to rising energy demand and intensified environmental pollution. Because coagglomeration has inverted U-type characteristics for energy strength, we should determine the productive scale according to the coagglomeration to achieve the purpose of maximum economic output and minimum energy consumption. Finally, energy conservation and emission reduction policies should be linked. The existing policies focus more on emission reduction, and the premise of emission reduction is saving energy. However, energy consumption is the direct factor leading to environmental pollution [102], and China's rapid digital transformation increases industrial energy consumption [103–105]. Simply focusing on emission reduction and neglecting energy conservation can lead to energy consumption increasing, which means that the emission reduction policy would have a negative effect and even aggravate environmental pollution [106].

In this study, we mainly explored whether the agglomeration between industries can help to conserve energy, reduce pollution emission and upgrade technology. However, we did not consider the technical heterogeneity, which can be divided into different types, such as energy efficiency, alternative, transport and waste treatment. In the future, more analysis can be done to verify whether the agglomeration effect brought about by different industries in transportation can save costs or lead to the scale effect. Also, whether different types of technology can have heterogeneous effects on energy intensity and environmental pollution need to be considered in depth in the future.

Conflict of interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Apendix data for this article can be found in the supplementary.

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