SIN-CHN SCIENTIFIC PRESS PTE.LTD.

*Molecular & Cellular Biomechanics* 2025, 22(4), 909.
https://doi.org/10.62617/mcb909

Article

# Research on the impact of industrial structure upgrading on China's carbon emissions: Mechanism and test

**Xiaoxu Jia**

Shandong University of Finance and Economics, Ji'nan 250002, Shandong, China; 13376408269@163.com

**CITATION**

Jia X. Research on the impact of industrial structure upgrading on China's carbon emissions: Mechanism and test. Molecular & Cellular Biomechanics. 2025; 22(4): 909.
https://doi.org/10.62617/mcb909

**ARTICLE INFO**

Received: 3 December 2024
Accepted: 16 December 2024
Available online: 5 March 2025



**Abstract:** Inspired by biomechanics, studying the relationship between industrial structure upgrading and carbon emissions and the specific impact paths is of great practical significance to the coordinated development of China's environment and economy. Biomechanics, with its in-depth understanding of the interaction and energy-efficiency principles in natural systems, provides a novel perspective for this study. This paper selected the panel data of 30 provincial administrative regions from 2001 to 2020. Inspired by the concepts of biophysical economics, which are closely related to the energy-matter flow principles in biomechanics, a two-way fixed-effect model of carbon emissions was employed to empirically analyze the relationship between industrial structure upgrading and carbon emissions. Just as biomechanics analyzes the most efficient movement patterns in organisms to minimize energy consumption, this model aims to find the most efficient industrial structure patterns to reduce carbon emissions. The conclusions show that: (1) Industrial structure upgrading can effectively reduce carbon emissions; (2) due to the differences in the economic development levels of different regions, the intensity of industrial structure upgrading on carbon emissions is different. Among them, the effect on the eastern region is the most obvious, followed by the central region, while the effect on the western region and the northeast region is not obvious. (3) Through the mediation effect model, it is found that technological innovation and labor quality improvement are effective ways to upgrade the industrial structure and reduce carbon emissions. Finally, this paper analyzes carbon emission treatment technologies from the direction of biodegradation, which has attracted wide attention due to its environmental friendliness. In biomechanics, natural degradation processes in organisms provide inspiration for human-made biodegradation technologies. Based on biomechanics, six major disposal technologies are compared and analyzed from three aspects: Indirect carbon emissions from operation energy consumption, direct carbon emissions from plastic decomposition and carbon compensation for resource recovery. This paper provides a reference for the selection of waste biodegradation disposal technology from the perspective of helping "double carbon" goal, by drawing on the energy-efficient and sustainable principles from biomechanics.

**Keywords:** industrial structure upgrading; technological innovation; quality of labor; carbon emissions

## 1. Foreword

In recent years, extreme climate events have occurred frequently around the globe, causing unprecedented scale impacts on the society and economy. The crude development model of high energy consumption and pollution as well as the irrational industrial structure have led to China's environmental problems becoming more and more prominent. According to the National Data Center, China's carbon dioxide emissions will be about 11.9 billion tons in 2021, ranking among the top in the world. The environmental problems caused by excessive carbon emissions have a serious impact on China's natural and human environment. In order to change the situation, China has made many efforts in recent years, with many inefficient, highly-polluting and energy-consuming enterprises gradually closing and transforming. The industrial structure has also been gradually upgraded from the original "two, one, three" structure to the current "three, two, one" structure, and as of 2023, the primary, secondary and tertiary industries will contribute 5.9%, 33.9% and 60.2% to the GDP respectively. Moreover, it requires the urgent formulation of an action plan for carbon emission peak by 2030, the promotion of coal consumption to reach the peak as early as possible. Therefore, it is important to study about the industrial structure upgrading and carbon emission in this context, and it is also an inherent requirement to realize the goal of "Double Carbon".

Biodegradable plastics (polylactic acid PLA, for example), mainly based on renewable resources (such as corn, sugar cane and other crops) as raw materials, are widely used in packaging, tableware, agricultural film and medical supplies and other industries. In 2021, the global annual apparent consumption of biodegradable plastics is about 1.2 million tons, and China has reached more than 150,000 tons, beginning to transition from demonstration production to large-scale industrialization. From the aspects of indirect carbon emissions from operation energy consumption and carbon compensation for resource recovery, this study uses emission factors and mass balance methods to compare and analyze the carbon emissions of waste biodegradable plastics under six disposal technologies, and provides references for the selection of waste biodegradable plastics disposal technologies from the perspective of helping the "double carbon" goal.

## 2. Literature review

Scholars have carried out useful discussions from different perspectives. For example, Xiang et al. [1] and Wang et al. [2] use spatial measurement to study the FDI on carbon emissions, and believe that the coordinated spatial development of FDI can effectively inhibit carbon emissions. Zhou et al. [3] argued that financial resources reduce the level of carbon emissions particularly significantly when they cooperate and synergize with the primary and secondary industries. Jiang and Sheng et al. [4] believe that the carbon emissions trading market reduces the regional carbon emissions.

In addition to the impact of the above economic factors, many scholars have studied the impact of industrial structure. For example, Yu [5], Yang [6], and Zhao [7], Sun et al. [8], Zhou et al. [9] believe that regional resource factor endowment and economic development level of differentiation, industrial structure adjustment on the role of carbon emissions have different impacts. From the perspective of the country as a whole, industrial structure upgrading helps to realize carbon emission reduction; while from the regional perspective, there is variability in the spatial and temporal patterns.

In order to reduce carbon emissions, biodegradable waste disposal has attracted attention from all walks of life. Kosheleva, Tseng and Bandini et al. [10–12] are committed to improving the disposal efficiency of industrial composting, anaerobic fermentation and other technologies by means of pretreatment. Abraham et al. [13]

analyzed that anaerobic fermentation is considered as one of the technologies for effective treatment of waste biodegradable plastics due to its low degree of environmental pollution and the ability to generate renewable energy such as methane. Maga et al. [14] evaluated the life cycle of thermal disposal technologies such as chemical recycling of waste biodegradable plastics, and believed that the recycling and utilization of polylactic acid products could improve their environmental performance during the life cycle. Batoriv et al. [15] separately assessed the carbon footprint and energy footprint of biodegradable material waste composting technology. In the current situation of global resource shortage, how to give full play to the biomass characteristics of biodegradable plastics and realize resource or energy recycling (such as chemical recycling, industrial composting and anaerobic fermentation) has attracted extensive attention from researchers around the world [16]. The "14th Five-Year Plan" circular economy Development Plan also specifically points out that it is necessary to thoroughly assess the full life cycle resource and environmental impact of various alternatives, and biodegradation, as the most potential substitute, is also of great significance to assess the environmental impact of waste resources or energy disposal.

In summary, this paper innovatively adopts technological innovation and labor quality as intermediary variables, constructs the intermediary effect model, and further explores the specific path to reduce carbon emission. This paper provides valuable references for eliminating the negative effects of carbon emissions and formulating carbon emission reduction policies in a rational and effective way. Finally, from the aspects of indirect carbon emissions from operation energy consumption and carbon compensation for resource recovery, this study uses emission factors and mass balance methods to compare and analyze the carbon emissions of waste biodegradation under several disposal technologies, and provides references for the selection of disposal technologies for waste biodegradable plastics from the perspective of helping the "double carbon" goal.

## 3. Research hypotheses

### 3.1. The direct impact of industrial structure

The current industrial layout in the region is not optimal, with a low level of advanced industrial structure. This is leading to inefficiencies in the utilisation of resources. However, there is an opportunity to address this through industrial structure upgrading, which can help to improve the efficiency of resource utilisation [17]. Industrial structure upgrading can effectively play the "industrial correlation effect", carry out a reasonable industrial layout within or between regions, deepen the depth of integration between various sectors, reduce duplication of construction, avoid unfavorable "homogenization effect", make resource allocation more reasonable, improve resource utilization efficiency, and improve resource mismatch [17].

### 3.2. Indirect influence of better industrial structure

Focusing on factor allocation, industrial structure upgrading is a dynamic evolutionary. First of all, in this process, industrial structure upgrading plays a "configuration effect". Industrial structure upgrading can influence the technological innovation of enterprises. Low efficiency and low output in the secondary industry will be gradually eliminated by the enterprises with low energy consumption, high efficiency and high output, and the enterprises will increase the investment in research and development to carry out technological innovation in order to form their own competitive advantages in the industry. And the results of technological innovation applied to enterprise production, will produce a huge change in the original enterprise production process and management mode, so that the enterprise production and operation is more reasonable and effective, improve the utilization of resources, help enterprises to decrease the excessive on traditional energy sources, resulting in the result is to reduce the pollution of the same economic returns. Secondly, the better industrial structure would also influence the quality of labor through the "agglomeration effect". When industries evolve from traditional industries, the employment situation of the labor force will also change, which requires a higher quality of labor. The improvement of labor quality can help to enhance labor productivity and improve enterprise production efficiency; optimize enterprise production mode, and then decrease the carbon emissions during the production process.

Hypothesis 2: The process of industrial structure upgrading can exert its allocation effect and agglomeration effect, and reduce carbon emissions by influencing technological innovation and labor quality.

# 4. Empirical study

## 4.1. Variable selection, data sources and model construction

### 4.1.1. Selection of variables

(1) Explained variables

Drawing on the practice of Zhao [18], the carbon emissions to GDP is used to express carbon intensity (CI). This indicator contains the dual factors of economic and pollution, and can effectively reflect the efficiency of resource use.

(2) Core Explanatory Variables

Previous studies have mostly used the secondary and tertiary industries in GDP as industrial structure upgrading. Although this index can reflect the results of the internal adjustment of the whole industry to a certain extent, it should measure the scale of development of industries rather than reflecting and optimization of the whole industrial structure itself. Therefore the article draws on Zang et al. [19] and An et al. [20].

$$IS = \sum_{i}^{n} k_i \sqrt{\frac{p_i}{l_i}} (n = 3, i = 1,2,3) \tag{1}$$

In the formula, $k_i$ represents the share of industries in GDP, $p_i$ is the output of industries, $l_i$ is the number of people employed in industries, and $p_i/l_i$ is the labor productivity industries.

(3) Mediating variables

The mediating variables are selected as technological innovation (TEC&IN) and labor quality (LQ). According to the previous analysis, it is known that industrial structure affects carbon emission intensity through technological innovation and labor quality. Previous studies used the number of R&D personnel, and R&D investment funds to measure innovation, and this paper refers to the study of Wang [21]. It also refers to the study of He [22] to use the number of employees in high-tech industries to measure labor force quality.

(4) Control variables

The control variables are selected as energy structure (ES), energy intensity (EI), income level (INCOME), environmental regulation level (ER), environmental regulation level (ER), urbanization level (URBAN). The use of clean non-fossil fuels can directly reduce the amount of carbon dioxide emitted into the atmosphere. Referring to the research of Liang [23], the article selects the logarithm of GDP per capita to measure the income level, GDP per capita can effectively reflect the level of economic development in different regions, and the income gap directly affects the consumption, which to a certain extent has an impact on the carbon emission intensity. Referring to the practice of Wang [24], the total investment in industrial pollution control in each region is selected as an indicator to measure the level of environmental regulation. The secondary industry is mainly dominated by industry, which often causes more environmental pollution than the primary and tertiary industries. Using the total investment in industrial pollution control can reflect the region's attention to pollution control and the effective regulation of polluting enterprises. Referring to the study of Liu and Gong [25], the foreign direct investment is measured by using the foreign registered capital of foreign invested enterprises. However, with the strengthening of developing countries' awareness, and the suppression of carbon emission intensity by the new technology and management mode introduced by FDI, the economic effect brought to developing countries is greater than the negative effect of environmental pollution.

#### 4.1.2. Data source

**Table 1.** Descriptive statistics for each variable.

| Variable | Mean | Std.Dev | Min | Max |
|---|---|---|---|---|
| carbon intensity (CI) | 5.923 | 5.473 | 0.79 | 63.68 |
| industrial structure (IS) | 0.451 | 0.088 | 0.29 | 0.836 |
| Energy mix (ES) | 0.909 | 0.052 | 0.66 | 1 |
| Energy intensity (EI) | 0.575 | 0.409 | 0.09 | 2.7 |
| Income level (INCOM) | 3.301 | 2.635 | 0.28 | 16.18 |
| Environmental regulation (ER) | 171,778.22 | 182,017.76 | 1006.4 | 1,416,464.3 |
| Urbanization level (URBAN) | 0.515 | 0.152 | 0.23 | 0.94 |
| Foreign Direct Investment (FDI) | 466.619 | 856.319 | 2.35 | 6353.39 |
| Technological Innovation (TEC&IN) | 28,024.165 | 56,789.804 | 70 | 527,390 |
| Labor Quality (LQ) | 87.214 | 51.219 | 10.25 | 360.27 |

The main sources of data for the indicators in the article are wind database, CEADs database, and CEADs database, etc. Meanwhile, the article supplements the missing values in the yearbook are supplemented by the difference method. All the information is showed in **Table 1**.

#### 4.1.3. Model construction

$$CI = \alpha_0 + \alpha_1 IS_{it} + \sum \alpha X_{it} + u_i + v_t + \varepsilon_{it} \tag{2}$$

where: $i$、$t$ denotes province and time respectively, $CI$ denotes carbon emission intensity, $IS$ denotes industrial structure upgrading, $X$ for energy structure, energy intensity, income level, environmental regulation, urbanization level, foreign direct investment.

### 4.2. Empirical results and analysis

#### 4.2.1. Benchmark regression

To verify the above hypotheses, a benchmark regression is first carried out to analyze. To reduce heteroskedasticity, the variables are logarithmically treated. Through the Husman test.

The benchmark regression results are shown in **Table 2**. Without adding any control variables and fixing time and province. From the economic point of view, every 1% change in industrial structure upgrading brings 1.835% inverse change in carbon emission intensity. Gradually adding control variables from column 2 to column 7, hypothesis 1 is valid. It shows that the upgrading of China’s industrial structure can effectively bring into play the “industrial association effect”, which makes the industrial layout in the region more rationalized; the effective integration of various economic sectors avoids duplicated construction, makes effective use of resources, reduces the carbon emission, and improves the level of environmental protection.

Among the control variables, for every 1% change in energy structure, energy intensity, per capita income level, carbon emission intensity changes by −2.808%, −0.522%, −0.308%, and −0.157%, respectively. As per capita income increases, people’s consumption concepts and habits will change, and environmental protection awareness increases, people will buy cleaner industrial products. The new technology and advanced management mode brought by the increase of foreign investment can generate economic effects and can effectively compensate for the negative effects of environmental pollution. However, for every 1% change, the carbon emission intensity changes by 0.137% and 0.639%. This shows that regulation does not have a positive influence in promoting technological innovation and process upgrading in enterprises. The urbanization process is also not playing a positive role, possibly because the urbanization of China is in a developmental stage, which requires the use of large amounts of non-clean energy, where the efficiency of resource use and development has not yet been demonstrated.

**Table 2.** Benchmark regression results.

| | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** |
|---|---|---|---|---|---|---|---|
| lnIS | −1.835*** (−13.65) | −1.858*** (−13.8) | −1.153*** (−12.48) | −0.735*** (−7.12) | −0.502*** (−4.19) | −0.54*** (−4.84) | −0.605*** (−5.27) |
| lnES | | 0.7832* (1.96) | −4.916*** (−14.71) | −4.32*** (−13.18) | −4.15*** (−12.67) | −3.99*** (−11.85) | −2.808*** (−8.09) |
| lnEI | | | −0.833*** (−27.82) | −0.737*** (−23.67) | −0.726*** (−23.5) | −0.717*** (−22.94) | −0.522*** (−14.03) |
| lnINCOME | | | | −0.185*** (−7.78) | −0.255*** (−8.44) | −0.311*** (−7.21) | −0.308*** (−7.55) |
| lnER | | | | | 0.065*** (3.69) | 0.069*** (3.92) | 0.137*** (7.43) |
| lnURBAN | | | | | | 0.1836* (1.81) | 0.639*** (5.85) |
| lnFDI | | | | | | | −0.157*** (−8.62) |
| _cons | −5.326*** (−47.5) | −5.268*** (−45.6) | −5.9*** (−74.08) | −5.264*** (−47.18) | −5.74*** (−33.9) | −5.62*** (−31.09) | −5.088*** (−28.04) |
| fixed time | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Fixed provinces | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| $R^2$ | 0.237 | 0.242 | 0.67 | 0.742 | 0.747 | 0.709 | 0.7416 |
| N | 600 | 600 | 600 | 600 | 600 | 600 | 600 |

Note: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

### 4.2.2. Robustness tests

(1) Endogeneity test

Since carbon emission intensity is affected by a variety of factors, fixed effects, although they can mitigate estimation bias to a certain extent, cannot fully cover the possible influencing factors.

(2) Indicator replacement

Replace the industrial structure indicators calculated by the formula in the previous section with the proportion of value added of the tertiary industry.

(3) Bilateral Tailoring Processing

**Table 3.** Robustness test.

| **variant** | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| lnIS | | | −0.994*** (−13.29) | −1.839*** (−15.73) |
| L.lnIS | −1.795*** (−14.63) | | | |
| D.lnIS | | −3.460*** (−4.16) | | |
| control variable | Yes | Yes | Yes | Yes |
| fixed effect | Yes | Yes | Yes | Yes |
| WaldF | 213.90*** | 177.26*** | | |
| $R^2$ | 0.2215 | 0.292 | 0.7683 | 0.2403 |
| N | 600 | 600 | 600 | 600 |

Note: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

**Table 3** shows that the regression coefficient values change slightly after accounting for endogeneity, but the sign does not change and the results remain significant. The Wald $F$-test statistics are all greater than the 1% critical value, rejecting the weak instrumental variable hypothesis. Column 3 shows that after indicator substitution, the sign of the model's regression coefficients did not change and the original conclusions still hold. Therefore, it can be shown that the original model regression conclusions are robust.

## 5. Further analysis

### 5.1. Analysis of regional heterogeneity

Due to the different geographical characteristics and differences, industrial upgrading in different regions has different impacts on carbon emission. The article divides the regions into four parts: Conducts regional heterogeneity analysis.

**Table 4.** Regional heterogeneity regression results.

| | **Eastern Region** | **Central Region** | **Western Region** | **Northeast Region** |
|---|---|---|---|---|
| lnIS | −1.171***<br>(−6.08) | −0.923***<br>(−5.4) | −0.493<br>(−1.12) | −0.191<br>(−1.96) |
| lnES | −1.673***<br>(−5.88) | −1.505***<br>(2.67) | −3.94***<br>(−4.35) | −1.99***<br>(−0.41) |
| lnEI | −0.404***<br>(−5.94) | −0.503***<br>(−5.61) | −0.658***<br>(−5.07) | −0.516**<br>(−11.5) |
| lnINCOME | −0.299***<br>(−6.08) | −0.221***<br>(−2.79) | −0.304***<br>(−4.28) | −0.382***<br>(−4.03) |
| lnER | 0.211**<br>(9.84) | 0.184**<br>(5.92) | 0.212***<br>(4.03) | 0.004<br>(0.24) |
| lnURBAN | 1.101***<br>(6.89) | 2.053***<br>(8.67) | 1.89***<br>(5.59) | −1.074***<br>(−2.59) |
| lnFDI | −0.286***<br>(−8.63) | −0.55***<br>(−11.98) | −0.253***<br>(−6.59) | −0.153***<br>(−5.87) |
| _cons | −4.481***<br>(−22.30) | −2.01***<br>(−4.19) | −3.704***<br>(−8.12) | −4.35***<br>(−9.07) |
| fixed time | Yes | Yes | Yes | Yes |
| Province fixed | Yes | Yes | Yes | Yes |
| $R^2$ | 0.779 | 0.894 | 0.482 | 0.911 |
| N | 200 | 120 | 220 | 60 |

Note: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

From **Table 4**, industrial structure has a incredible influence, with regression values of −1.171 and −0.923 respectively, i.e., better industrial structure will be able to be well inhibit carbon emission. The main reason is that the transformation in industry has been realized faster in the eastern and central regions, and the heavy industry has been gradually replaced by the service industry. However, in the western and northeastern regions, the inhibition effect of industrial structure upgrading on carbon emission intensity is not significant. Similarly, the northeastern region, because it is a heavy industrial base, the industrial structure is relatively single, mainly iron and steel, coal industry-based heavy industry, industrial structure upgrading is more difficult, so it is difficult to play a role in reducing carbon emissions.

## 5.2. Mechanism test

In order to further study how industrial structure specifically affects carbon emissions, the article chooses the practice of Ma [26] and constructs the following mediating effect model:

$$TEC\&IN_{it} = \beta_0 + \beta_1 IS_{it} + \sum \beta X_{it} + \tau_i \tag{3}$$

$$LQ_{it} = \gamma_0 + \gamma_1 IS_{it} + \sum \gamma X_{it} + \varsigma_i \tag{4}$$

$$CI_{it} = \theta_0 + \theta_1 IS_{it} + \theta_2 TEC\&IN_{it} + \sum \theta X_{it} + \sigma_i \tag{5}$$

$$CI_{it} = \rho_0 + \rho_1 IS_{it} + \rho_2 LQ_{it} + \sum \rho X_{it} + \mu_i \tag{6}$$

where: $i$、$t$ indicates province and time respectively, $CI$ is carbon emission intensity, $IS$ is industrial structure upgrading, $TEC\&IN$ is technological innovation, $LQ$ for quality of labor force, $X$ for energy structure, energy intensity, income level, environmental regulation, urbanization level, foreign direct investment.

The article adopts the method of stepwise regression to take the mediation effect test, and from the test in **Table 5**, the effect of industrial structure upgrading on technological innovation is significantly positive, and for every 1% change in industrial structure, technological innovation changes by 0.27%. For every 1% change in industrial structure, labor quality changes by 6.17%. However, among the control variables, except for energy intensity and urbanization level, which play a negative role in labor quality improvement, all other control variables play a positive role.

**Table 5.** Intermediation effect regression results.

| variant | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | lnTEC&IN | lnLQ | lnCI | lnCI |
| lnIS | 0.27**<br>(1.37) | 0.6174***<br>(4.55) | −0.611***<br>(−4.77) | −0.564***<br>(−4.23) |
| lnES | −1.585***<br>(−3.69) | 0.364<br>(1.28) | 0.423<br>(1.56) | −0.748***<br>(−2.27) |
| lnEI | 0.964***<br>(13.85) | −0.171***<br>(−3.72) | −0.307***<br>(−6.13) | −0.497***<br>(−11.01) |
| lnINCOME | 0.005<br>(0.46) | 0.273***<br>(5.96) | −0.321***<br>(−11.94) | −0.3410***<br>(−12.03) |
| lnER | 0.306***<br>(9.91) | 0.283***<br>(13.84) | 0.277***<br>(13.25) | 0.267***<br>(11.73) |
| lnURBAN | −1.74***<br>(−9.79) | −1.076***<br>(−9.13) | 0.968***<br>(8.07) | 1.109***<br>(9.05) |
| lnFDI | 0.66***<br>(25.55) | 0.365***<br>(21.35) | −0.201***<br>(−8.61) | −0.259***<br>(−11.78) |

**Table 5.** (*Continued*).

| variant | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | **lnTEC&IN** | **lnLQ** | **lnCI** | **lnCI** |
| lnTEC&IN | | | −0.17***<br>(−6.62) | |
| lnLQ | | | | −0.15***<br>(−3.79) |
| _cons | 0.096<br>(0.33) | −0.898***<br>(−4.61) | −4.016***<br>(−21.83) | −4.167***<br>(−21.74) |
| Fixed provinces | Yes | Yes | Yes | Yes |
| fixed time | Yes | Yes | Yes | Yes |
| $R^2$ | 0.876 | 0.677 | 0.679 | 0.663 |
| N | 600 | 600 | 600 | 600 |

Note:*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

From column 4 in **Table 5**, the signs of industrial structure upgrading and labor force quality are all negative. This result will change the production mode of high-pollution and low-efficiency enterprises in the secondary industry.

## 6. Biodegradation treatment technology

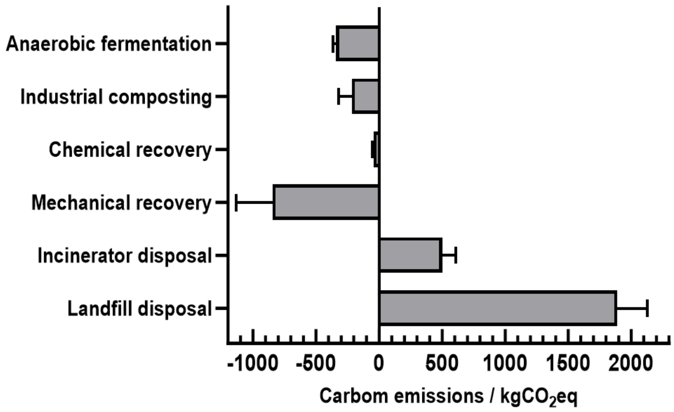


**Figure 1.** Net carbon emission during different disposal technologies.

**Figure 1** shows the net carbon emission of 1 t of waste biodegradable plastics under different technologies. The net carbon emission sequence of the six technologies was landfill disposal (1887.67 kg $CO_2$ eq) > Incinerator disposal (499.80 kg $CO_2$ eq) > chemical recovery (−44.17 kg $CO_2$ eq) > industrial composting (188.67 kg $CO_2$ EQ). −215.40 kg $CO_2$ eq) > Anaerobic fermentation (−341.55 kg $CO_2$ eq) > Mechanical recovery (−842.33 kg $CO_2$ eq). Among them, anaerobic fermentation and mechanical recycling disposal technologies show better carbon emission reduction potential. However, in terms of indirect carbon emissions from operational energy consumption, landfill disposal showed the lowest indirect carbon emissions (10.83 kg $CO_2$ eq), while mechanical recycling showed a relatively high indirect carbon emissions (248. 70 kg $CO_2$ eq). In terms of the Angle of carbon compensation from source recovery, the burning place (−1439.21 kg $CO_2$ eq) showed the highest carbon compensation effect, significantly higher than the anaerobic fermentation treatment (−845.79 kg $CO_2$ eq). This suggests that the assessment of the net carbon emissions of different technologies should take into account the source recovery, operational energy consumption and carbon offsetting potential in a comprehensive manner.

### 6.1. Comparative analysis of indirect carbon emissions from operation energy consumption

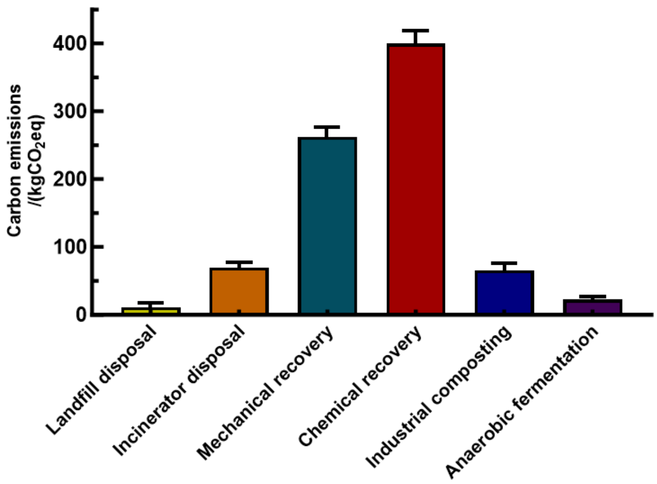


**Figure 2.** Carbon emissions from energy consumption of different disposal technologies.

The comparison of indirect carbon emissions of different waste disposal technologies is shown in **Figure 2**. The landfill disposal technology has the advantages of simple process, low equipment requirements, relatively low operating energy consumption, and indirect carbon emissions of only about 10.83 kg $CO_2$ eq. Secondly, the indirect carbon emission of 1 t waste biodegradable plastics by anaerobic fermentation is about 22.84 kg $CO_2$ eq, which is 5.72%–43.68% of the operating energy consumption of the other four waste disposal technologies, also showing relatively small indirect carbon emissions. This may be due to the fact that the operating energy consumption of the anaerobic fermentation process is mainly from the insulation and agitation of the system, which is relatively lower than the other 4 waste disposal technologies except landfill. The indirect carbon emissions of industrial composting are slightly higher than that of anaerobic fermentation, possibly due to the fact that the composting temperature required for waste biodegradable plastics is usually higher than that of anaerobic fermentation, resulting in higher energy consumption [15,16]. Mechanical and chemical recycling disposal exhibits the highest indirect carbon emissions, mainly due to the more demanding conditions of the recycling process and the greater energy consumption such as electricity and diesel [17]. Among them, the indirect carbon emissions of chemical recycling are about 60.42% higher than that of mechanical recycling, which is due to the fact that chemical recycling needs to go through more complex and energy-consuming plastic melting and repolymerization processes [14,15]. In addition, at present, most of the energy consumed in all disposal processes comes from fossil energy. In order to reduce carbon emissions and other environmental pollution in the operation process, non-fossil energy such as solar, wind and biomass energy can be actively used.

### 6.2. Comparative analysis of direct carbon emissions from plastic decomposition

The differences in carbon emissions generated by the decomposition of 1 t waste biodegradable plastics under six disposal technologies are also obvious, as shown in **Figure 3**. Among them, the direct carbon emissions from the mechanical recycling of waste biodegradable plastics mainly come from a small amount of losses in the recycling process, showing a relatively low direct carbon emission of 249.72 kg $CO_2$ eq. The direct carbon emissions of chemical recycling are about 123.40% higher than mechanical recycling, mainly due to the more complex plastic chemical recycling process and its recovery rate is relatively lower than mechanical recycling. In addition, chemical recycling may also have problems such as complex and difficult recycling technology and serious secondary pollution of chemical reagents [13]. The anaerobic fermentation disposal process has biogas energy recovery and exhibits relatively low carbon emissions of about 481.39 kg $CO_2$ eq. The direct carbon emission of industrial composting is about 970.63 kg $CO_2$ eq, which is about 101.63% higher than that of anaerobic fermentation. The reasons are as follows: Firstly, it is directly affected by its composting rate; secondly, it may be due to the fact that the C element in waste biodegradable plastics is not well fixed into the fertilizer during the composting process, and some of it still escapes into the environment in the form of $CO_2$ [11]. However, the industrial anaerobic fermentation disposal technology is not mature, and there may be problems such as long operation cycle and small disposal scale [12]. The direct carbon emission of landfill and incineration disposal was the highest, which was 1887.67 kg $CO_2$ eq. In summary, in order to reduce the carbon emissions directly generated by the decomposition of waste biodegradable plastics, we should actively promote the development of energy and resource utilization technologies, strengthen the control of pollutants, product regulation and efficiency improvement in the process, and optimize the classification management scheme of waste biodegradable plastics.

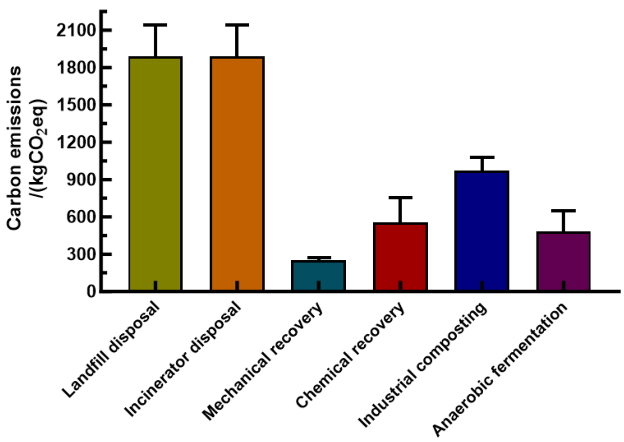


**Figure 3.** Carbon emissions from the decomposition of waste biodegradable plastics under different disposal technologies.

### 6.3. Comparative analysis of carbon compensation for resource or energy recovery

There are some differences in the carbon compensation of 1 t waste biodegradable plastics under different disposal technologies, as shown in **Figure 4**. The material flow of waste biodegradable plastics under different disposal technologies is shown with significant differences. Mechanical recycling and disposal reached a carbon compensation of −1340.75 kg CO, eq, resource recovery as high as 44.34%, CO, emission ratio is only about 6.80%. Chemical recycling disposal recycled plastic products under certain conditions [16], achieving a resource recovery rate of 35.94%, demonstrating a carbon offset of about −1001 kg $CO_2$ eq. Due to the relatively low recovery rate of plastic products in chemical recycling disposal, its carbon compensation is slightly lower than that of mechanical recycling, but the performance of its recycled plastic products is significantly better than that of mechanical recycling. The energy recovery rate of anaerobic fermentation treatment was 38.02%, while the carbon compensation was low (−845.79 kg$CO_2$ eq). The reasons are as follows: Anaerobic fermentation of waste biodegradable plastics to produce biogas is still under development. Firstly, its CH conversion rate needs to be improved. Secondly, the technology of cogeneration is not mature and the energy conversion efficiency is low [15]. Under industrial compost disposal, the resource (fertilizer) recovery rate of waste biodegradable plastics reached 24.69%, showing a certain carbon compensation (−1238.32 kg $CO_2$ eq). However, it is worth noting that the fertilizer obtained from the waste biodegradable plastic compost has a high carbon content, or needs to be mixed with nitrogen and phosphate fertilizers to achieve the use effect. The use of cogeneration for incineration disposal shows the highest carbon offset of −1439.21 kg $CO_2$ eq. However, the proportion of CO emissions from incineration disposal is the same as that from landfill disposal, up to 51.14%, which may cause serious global warming and waste of biomass resources [14]. In conclusion, resource recycling should be taken into account when assessing the carbon offsetting potential of different disposal technologies.

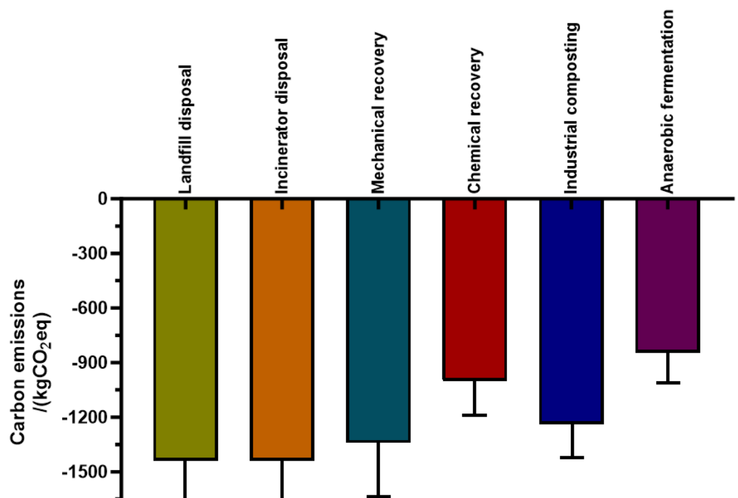


**Figure 4.** Carbon offsets from resource or energy recovery under different disposal technologies.

## 7. Conclusion and policy recommendations

The following suggestions are put forward: (1) Different regions should be based on their own development needs, and need to effectively manage the rationalization of industrial layout so that the industrial structure is in an optimal state; (2) according to the different stages of development of specific economies, a reasonable industrial structure adjustment program should be set. The role of energy structure and energy intensity should be fully considered, so as to provide a fundamental role for the industrial structure upgrading to achieve better environmental benefits, and at the same time, to make reference for the rationality of the industrial policy design. (3) Each region needs to promote the research and development of new technologies and cultivate a high-quality labor force; at the same time, enterprises need to build new, efficient and energy-saving production modes. (4) Based on regional characteristics and comparative advantages, practical environmental regulatory policies should be formulated to guide enterprises to transition to green and low-carbon development.

Finally, based on the mass balance and emission factor method, this study analyzed the differences in carbon emissions of waste biodegradable plastics under six disposal technologies from three aspects: Indirect carbon emissions from operation energy consumption, direct carbon emissions from plastic decomposition and carbon compensation from resource recovery, and comprehensively analyzed their respective net carbon emissions, drawing the following conclusions:

(1) From the analysis of carbon emission accounting results, landfill disposal has the lowest indirect carbon emission, and 1 t of waste biodegradable plastics is about 10.83 kg $CO_2$ eq; the second is anaerobic fermentation, which is only 5.72% to 43.68% of the other 4 disposal technologies. From the point of view of direct carbon emissions, landfill disposal $\geqslant$ incineration disposal > industrial composting > chemical recovery > anaerobic fermentation > mechanical recovery, mechanical recovery, anaerobic fermentation and chemical recovery showed obvious advantages.

(2) From the analysis of resource recovery rate and carbon compensation, incineration disposal showed the lowest recovery rate (about 0%) and the highest carbon compensation (about −1439.21 kg $CO_2$ eq); the anaerobic fermentation treatment showed a high recovery rate of 38.02% and a carbon offset of −845.79 kg $CO_2$ eq. The recycling of resources and the full use of their products is essential for the carbon-reducing application of waste biodegradable plastics.

(3) From the analysis of net carbon emissions, the order of carbon emissions from disposal of 1 t of waste biodegradable plastics was landfill disposal (1887.67 kg $CO_2$ eq) > incineration disposal (499.80 kg $CO_2$ eq) > chemical recovery (−44.17 kg $CO_2$ eq) > industrial composting (−215.40 kg $CO_2$ eq) > anaerobic fermentation (−341.55 kg $CO_2$ eq) > Mechanical recycling (−842.33 kg $CO_2$ eq). Among them, mechanical recycling disposal showed better carbon emission reduction potential, followed by anaerobic fermentation disposal. However, mechanical recycling still has difficulties in waste sorting, low recycling efficiency, poor performance of recycled products and other problems. Anaerobic fermentation has more development prospects from the perspective of carbon reduction potential.

**Ethical approval:** Not applicable.

**Conflict of interest:** The author declares no conflict of interest.

## References

1. Xiang Y, Dai Q. Carbon emission reduction effect and spatial spillover of two-way FDI coordinated development under the “dual carbon” target. Research in Financial Economics. 2022; 37(02): 105–121.
2. Wang Y, Liao M.Research on the emission reduction effect of the coordinated development of two-way FDI in China (Chinese). Science Research Management. 2022; 43(06): 104–112.
3. Zhou Y, Ji P. Effects of industrial upgrading and financial resource allocation efficiency on carbon emission: Based on provincial spatial panel data analysis. East China Economic Management. 2019; 33(12): 59–68.
4. Jiang H, Sun M. Carbon emission trading, Industrial structure and regional emission reduction (Chinese). Modern Economic Research. 2021; (11): 65–73.
5. Yu Z, Fan Y, Luo H. Study on the impact of industrial structure upgrading on carbon emission intensity in China (Chinese). East China Economic Management. 2019; 36(01): 78–87.
6. Yang F, Guo G, Zhang S. Technological innovation, Industrial structure adjustment and energy consumption. China Science and Technology Forum. 2020; (06): 75–84.
7. Zhao Y, Qian Z, Xu X. Study on the impact of industrial structure upgrading on carbon emissions in China under the background of carbon peaking and carbon neutrality. Exploration of Economic Issues. 2022; (03): 87–105.
8. Sun Z, Liu R, Li H. Industrial structure adjustment, technological innovation and regional carbon emission reduction: An empirical study based on regional panel data. Reform of Economic System. 2020; (03): 101–108.
9. Zhou D, Wang X. Coupling degree and coupling path between carbon emission efficiency and industrial structure upgrading in China (Chinese). Journal of Natural Resources. 2019; 34(11): 2305–2316.
10. Kosheleva A, Gadaleta G, De Gisi S, et al. Co-digestion of food waste and cellulose-based bioplastic: From batch to semi-continuous scale investigation. Waste Management. 2023; 156: 272–281. doi: 10.1016/j.wasman.2022.11.031
11. Tseng HC, Fujimoto N, Ohnishi A. Biodegradability and methane fermentability of polylactic acid by thermophilic methane fermentation. Bioresource Technology Reports. 2019; 8: 100327. doi: 10.1016/j.biteb.2019.100327
12. Bandini F, Frache A, Ferrarini A, et al. Fate of biodegradable polymers under industrial conditions for anaerobic digestion and aerobic composting of food waste. Journalof PolymersandtheEnvironment. 2020; 28(9): 2539-2550.
13. Abraham A, Park H, Choi O, Sang BI. Anaerobic co-digestion of bioplastics as a sustainable mode of waste management with improved energy production—A review. Bioresource Technology. 2012; 322: 25.
14. Maga D, Hiebel M, Thonemann N. Life cycle assessment of recycling options for polylactic acid. Resources, Conservation and Recycling. 2019; 149: 86–96. doi: 10.1016/j.resconrec.2019.05.018
15. Bátori V, Åkesson D, Zamani A, et al. Anaerobic degradation of bioplastics: A review. Waste Management. 2018; 80: 406–413. doi: 10.1016/j.wasman.2018.09.040
16. Yagi H, Ninomiya F, Funabashi M, Kunioka M. Anaerobic Biodegradation Tests of Poly(lactic acid) under Mesophilic and Thermophilic Conditions Using a New Evaluation System for Methane Fermentation in Anaerobic Sludge. International Journal of Molecular Sciences. 2009; 10(9): 3824–3835. doi: 10.3390/ijms10093824
17. Sun L, Luo Y. The spatial effect of rationalization of industrial structure on carbon emission. Chongqing Social Sciences. 2022; 335(10): 55–68.
18. Zhao L, Li Y. The impact of industrial structure on carbon emission intensity. Urban Problems. 2018; (06): 61–66.
19. Zang J, Wan L, Li Z, et al. Does emission trading scheme have spillover effect on industrial structure upgrading? Evidence from the EU based on a PSM-DID approach. Environmental Science and Pollution Research. 2020; 27(11): 12345–12357. doi: 10.1007/s11356-020-07818-0
20. An H, Xu J, Ma X. Does technological progress and industrial structure reduce electricity consumption? Evidence from spatial and heterogeneity analysis. Structural Change and Economic Dynamics. 2020; 52: 206–220. doi: 10.1016/j.strueco.2019.11.002
21. Wang B, Zhao C. Green technology innovation in China: Patent statistics and influencing factors (Chinese). Industrial Technical Economics. 2019; 38(07): 53–66.
22. He Y, Lin B. Study on the impact of heterogeneous labor force agglomeration on regional carbon emissions. Population Journal. 2002; 44(04): 39–56.

23. Liu Z, Huang H, Deng X. Population size, industrial structure and energy efficiency: An empirical study based on spatial panel econometric model. Macroeconomic Research. 2022; 285(08): 117–130.
24. Wang Y. Research on local government environmental regulation competition in China based on spatial panel model. Management Review. 2015; 27(8): 23–32.
25. Liu H, Gong M. Factor market distortion and two-way FDI scale effects on carbon emissions (Chinese). China Population, Resources and Environment. 2018; 28(10): 27–35.
26. Ma B, Wang Y, Zhang Y, et al. Research on national finance, industrial innovation and regional coordinated development: Evidence from a moderated multiple intermediary effect model. Research on Macroeconomics. 2021; 274(09): 99–110.