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Spatio-temporal evolution characteristics and mitigation path of carbon dioxide emission from China's wood and bamboo processing industry

Wan-Li Lao, Liang Chang and Xin-Fang Duan*

Abstract

Quantifying carbon dioxide (CO_2) emissions from China's wood and bamboo processing industry is associated with China's emissions reduction targets, as well as mitigating global climate change. This study employed the Intergovernmental Panel on Climate Change Tier-2 methodology to investigate spatio-temporal evolution characteristics of carbon dioxide emission from the wood and bamboo processing industry in China from 2000 to 2019. The results showed that energy consumption reached a maximum value of 312,900.35 TJ in 2012. Energy consumption has been gradually transformed from raw coal to electricity and other clean energy. Energy intensity dropped from 1.39 TJ per million yuan of corrected production value in 2000 to 0.15 TJ per million yuan of corrected production value in 2019. Accordingly, CO_2 emissions reached their peak value of 31,148.1 thousand tons of CO_2 in 2012. Raw coal and electricity had profound impacts on CO_2 emissions. The CO_2 emission intensity declined from 140.04 tons CO_2 per million yuan of corrected production value in 2000 to 19.62 tons CO_2 per million yuan of corrected production value in 2019. We conclude that China's wood and bamboo processing sector is a green, low-carbon industry. The spatial distribution pattern of CO_2 emissions is highly consistent with the industrial spatial layout. Furthermore, several mitigation paths were put forward.

Keywords CO_2 emissions, Wood, Bamboo, Energy consumption, Emission–reduction, Spatial distribution

Introduction

Concerns about climate change have motivated decision-makers to reduce carbon dioxide (CO_2) emissions [1, 2]. Many countries have proposed CO_2 emissions reduction goals to fulfill international obligations. As one of the largest CO_2 emitters, China has committed that CO_2 emissions will peak by 2030 with plans to realize carbon neutralization by 2060 [3]. Because of the global requirement for reduced CO_2 emissions, various industrial sectors must explore ways to reduce CO_2 emissions. Therefore, quantifying the CO_2 emissions of different industries is important not only for emissions reduction targets, but also to mitigate global climate change.

Wood and bamboo processing industry is a sector in which wood, bamboo and other wooden materials are used as raw materials to produce products using mechanical and chemical methods [4]. China's wood and bamboo processing industry is divided into wood processing, wood-based panels manufacturing, wood products manufacturing, bamboo and rattan products manufacturing. Wood and bamboo processing industry produces a variety of panels, roundwood, sawn wood, and bamboo, etc. [5, 6]. These products are widely used in the furniture, construction, transportation, and

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packaging industries [7, 8]. China is one of the largest producers and consumers of wood and bamboo products in the world. The production of wood-based panels in China was 160.668 million m^3 in 2020, which was composed of 42.6% plywood, 36.6% fiberboard, 18.3% particleboard (PB), and 2.4% oriented strand board [9]. The quantities of roundwood and sawn wood produced in China were 341.67 and 84.04 million m^3 for 2020, respectively [9]. In 2019, 3.16 billion bamboo culms were harvested in China [10]. The total production value of the wood and bamboo processing industry attained 1339.89 billion yuan, accounting for 1.4% of China's gross domestic product and 17.7% of the production value of China's forestry industry, respectively [10]. Considering the importance of China's wood and bamboo processing industry, it is important to assess industrial CO_2 emissions and mitigation paths.

Many CO_2 emission case studies have been conducted on the production of wood and bamboo products, such as sawn wood, wood-based panels, wood chips, wood pellets in Ireland [11], medium-density fiberboard (MDF), PB, insulated fiberboard, hard fiberboard (HB) in Japan [12], and bamboo bicycle frames made in Ghana [13]. Plywood produced in China [14] and the USA [15, 16], MDF from Brazil [17], Spain, and Chile [18], Iran [19]; PB in Pakistan [20], the USA [21], Brazil, Spain [22], Iran [23] and oriented structural board (OSB) in Luxembourg [24], Brazil [25], and the USA [26] have also been studied. Furthermore, Diederichs [27] analyzed the environmental impact of 17 German wood-based panel mills. Bergman et al. [28] surveyed eight OSB plants, 17 softwood plywood plants, eight cellulosic fiberboard plants, and four HB plants, representing 21%, 32%, 89%, and 57% of total North American production. Similarly, Chang et al. [29] comparatively analyzed the environmental impact of plybamboo and other materials in Taiwan. Restrepo et al. [30] focused on a carbon footprint analysis in the manufacturing of bamboo boards in Colombia.

Most studies have focused on CO_2 emissions in the wood and bamboo products production process at the micro level. These previous microcosmic view studies provide useful data on wood and bamboo products. However, there is a need to quantify the CO_2 emissions of the entire wood and bamboo processing industry at the macro level. Thus, in the present study, the CO_2 emissions of China's wood and bamboo processing industry were comprehensively assessed at the macro level, and a mitigation path was proposed. The objectives were to improve the environmental performance of the wood and bamboo processing industry in China and to provide a reference for in-depth studies in other countries.

Methodology and data

Calculation method

The CO_2 emissions of China's wood and bamboo processing industry mainly originate from the consumption of energy during production. The CO_2 emissions from energy consumption can be divided into direct emissions and indirect emissions. Direct emissions are caused by primary energy combustion, including coal, crude, petrol, coke, kerosene, diesel, and fuel oil, whereas indirect emissions consist of electricity and heat. Therefore, the Intergovernmental Panel on Climate Change (IPCC) Tier-2 methodology [31] was adopted to calculate CO_2 emissions using the following equations:

$$\mathrm{CDE} = \sum_{i=1}^{n} (\mathrm{AD}_i \times \mathrm{EF}_i) \tag{1}$$

where CDE is CO_2 emissions. AD_i and EF_i are the activity data and emission factor of type i energy, respectively:

$$\mathrm{AD}_i = \mathrm{NCV}_i \times \mathrm{FC}_i \tag{2}$$

where NCV_i and FC_i represent the net calorific value and consumption of type i energy, respectively:

$$\mathrm{EF}_i = \mathrm{CC}_i \times \mathrm{OF}_i \times \frac{44}{12} \tag{3}$$

where CC_i is carbon content per unit calorific value of type i energy. OF_i stands for the carbon oxidation rate of type i energy. $\frac{44}{12}$ is the ratio between the relative molecular mass of CO_2 and carbon.

The CO_2 emissions from chemical reaction in production process was not considered in this study, because these emissions are very small compared to that from energy.

This study analyzed annual CO_2 emissions and CO_2 emissions intensity. Consequently, CO_2 emissions intensity was used to judge the relationship between the development of the industry and carbon emissions [32]. To eliminate the effects of price changes, CO_2 emissions intensity must to be corrected by prices. Therefore, producer price index was used in this study, and the base year is 2000. The formula is

$$\mathrm{CEI} = \frac{\mathrm{CE}}{\mathrm{PV}} \times \mathrm{PPI} \tag{4}$$

where CEI is CO_2 emission intensity. CE and PV represent the CO_2 emissions and production value, respectively. PPI is producer price index of China's wood and bamboo processing industry [33].

Energy intensity is the ratio of energy consumption to the production value, which is an indicator of energy efficiency and the development quality of the industry [34]. It is also corrected by PPI, and the base year is 2000. The formula is

$$EI = \frac{EC}{PV} \times PPI \tag{5}$$

where EI and EC represent energy intensity and energy consumption, respectively.

This study systematically analyzed the contribution rates of the different kinds of energy to further understand the sources of CO_2 emissions. The formula was

$$CRE_i = \frac{CDE_i}{\sum_{i=1}^{n} CDE_i} \times 100 \tag{6}$$

where CRE_i and CDE_i represent the contribution rate and CO_2 emissions of type i energy, respectively.

The data analysis and calculations were performed using Microsoft® Excel 2016.

Data collection

We compiled data from (1) the official reports published by China's authorities, (2) the China National Standard, and (3) international reports released by the IPCC to ensure the reliability of the data. The energy consumption data of China's wood and bamboo processing industry were collected from the China Energy Statistical Yearbook [35]. Table 1 provides the reference data for the different kinds of energy. The net calorific values of energy were obtained from China Energy Statistical Yearbook [35] and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [31] and China National Standard GB/T 2589–2020 General rules for the calculation of the comprehensive energy consumption [36]. The carbon content per unit calorific value and carbon oxidation rate of energy was based on the Guidelines for Provincial Greenhouse Gas Inventories published by National Development and Reform Commission People's Republic of China [37]. The electricity and heat emission factors were taken from Average CO_2 Emission Factor for Chinese Regional Power Grid in 2012 [38] and the China National Standard GB/T 32,151.5–2015 Requirements of greenhouse gas emission accounting and reporting—Part 5: iron and steel production enterprise [39], respectively. It is necessary to illustrate that China government, respectively, released CO_2 emission factor for Chinese regional power grid in 2010, 2011 and 2012 during 2000–2019. Therefore, we selected the relatively latest grid emission factor (2012) to facilitate CO_2 emission data comparison. In fact, the differences between grid emission factors for 2010, 2011 and 2012 is less than 3.1%. The production values of the wood and bamboo processing industry were obtained from the China Forestry Statistical Yearbook [10].

Table 1 Reference data for the different kinds of energy

Energy	NCV (GJ/t or GJ/10^4 Nm^3) [30, 33, 34]	CC (t C/TJ) [35]	OF [35]	EF (t CO_2/GJ)
Raw coal	20.908	26.37	0.94	0.0908886
Cleaned coal	26.334	25.41	0.90	0.083853
Other washed coal	12.545	25.41	0.90	0.083853
Coke	28.435	29.50	0.93	0.100595
Coke oven gas	179.810	13.58	0.99	0.0492954
Other gas	52.270	12.20	0.99	0.044286
Crude oil	41.816	20.10	0.98	0.072226
Gasoline	43.070	18.90	0.98	0.067914
Kerosene	43.070	19.60	0.98	0.070429333
Diesel oil	42.652	20.20	0.98	0.072585333
Fuel oil	41.816	21.10	0.98	0.075819333
Lubricating oil	41.398	20.00	0.98	0.071866667
Liquefied petroleum gas	50.179	17.20	0.98	0.061805333
Other petroleum products	40.200	20.00	0.98	0.071866667
Natural gas	389.310	15.30	0.99	0.055539
Liquefied natural gas	51.489	17.20	0.98	0.061805333
Electricity (kg CO_2/kW·h) [36]				0.6808
Heat (t CO_2/GJ) [37]				0.11

Results and discussion

Energy consumption

Figure 1 presents the energy consumption data of China's wood and bamboo processing industry from 2000 to 2019. The energy usage of the industry increased first and then decreased. It is well-known that the development of an industry is strongly dependent on energy consumption. Thus, with the rapid development of the wood and bamboo processing industry, energy usage also increased rapidly from 2000 to 2012, with an average annual growth rate of 11.8%. In contrast, energy usage exhibited a rapid downward trend from 2012 to 2019, decreasing by 8.86% per year. This was mainly due to technological progress, improved energy management and efficiency [40], as well as increasingly stringent energy policies and standards [41]. Energy consumption reached a maximum value of 312,900.35 TJ in 2012.

We listed the energy consumption structure only for 2000, 2004, 2009, 2014, and 2019 (see Fig. 2). In 2000, raw coal had the largest share (67.56%), followed by electricity (14.14%), heat (10.53%), diesel oil (3.62%), and gasoline (1.93%). In 2004, the percentage of raw coal increased to 73.83%, followed by electricity, heat, diesel oil, and other energy with percentages of 13.57%, 4.52%, 2.50%, and 2.48%, respectively. In 2009, raw coal still had the leading share (51.29%), followed by electricity (24.50%), other energy (15.33%), diesel oil (2.31%), and heat (1.85%). Although the contribution of raw coal was the highest, the contribution decreased to 36.72% in 2014. The contributions of electricity, other energy, diesel oil, heat, and gasoline were 35.52%, 22.00%, 1.94%, 1.33%, and 1.10%, respectively. Electricity became the most important energy type, and the proportion increased to 61.45% in 2019, followed by other energy (18.78%), raw coal (6.63%), natural gas (6.01%), and heat (4.10%). The energy consumption structure of China's wood and bamboo processing industry has been gradually transformed from raw coal to electricity and other clean energy in the past two decades. This trend agrees with the adjustment in China's energy consumption structure [42].

The energy intensity of China's wood and bamboo processing industry during 2000–2019 is described in Fig. 3. It was clear that energy intensity tended to decrease during 2000–2019, dropping from 1.39 TJ per million yuan of corrected production value in 2000 to 0.15 TJ per million yuan of corrected production value in 2019. Based on the data from China Energy Statistics Yearbook [35] and China Statistical Yearbook [33], we calculated that China's industrial average energy consumption intensity is 2.11 TJ per million yuan of corrected production value in 2019. By comparison, the energy consumption intensity of China's wood and bamboo processing industry is far lower than the average level of the national industry. This result confirms that the efficiency of energy use has improved greatly over the past two decades. In conclusion, China's wood and bamboo processing sector is a low energy-intensive industry.

CO_2 emissions

The CO_2 emissions from China's wood and bamboo processing industry from 2000 to 2019 are shown in

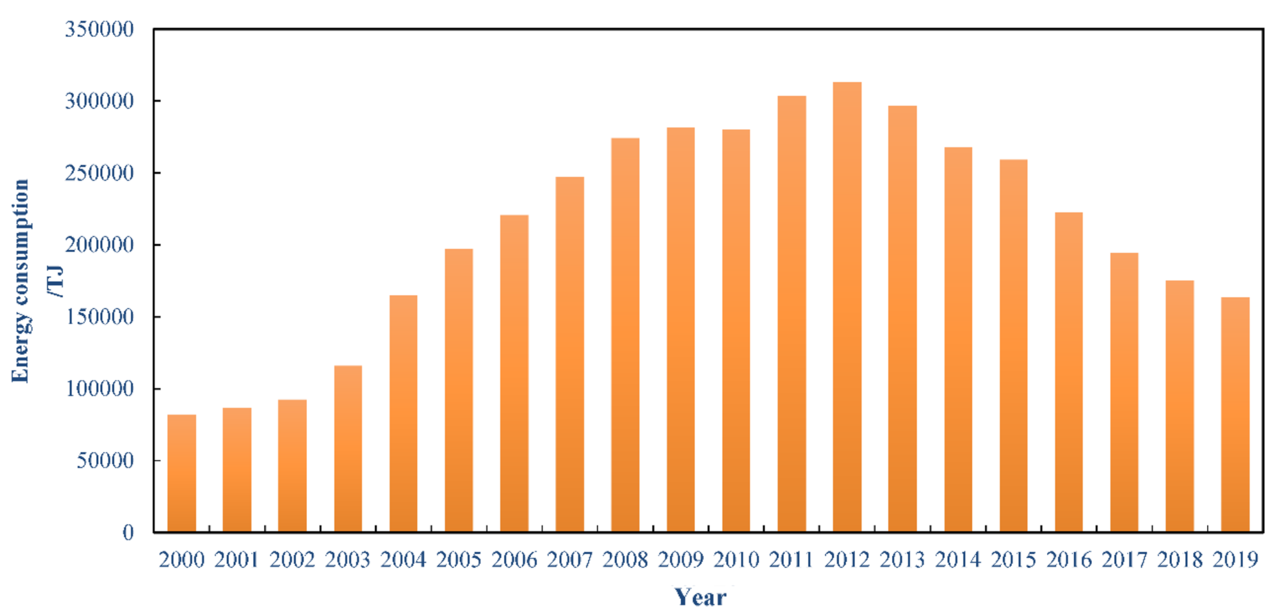

Fig. 1 Energy consumption of the wood and bamboo processing industry in China from 2000 to 2019

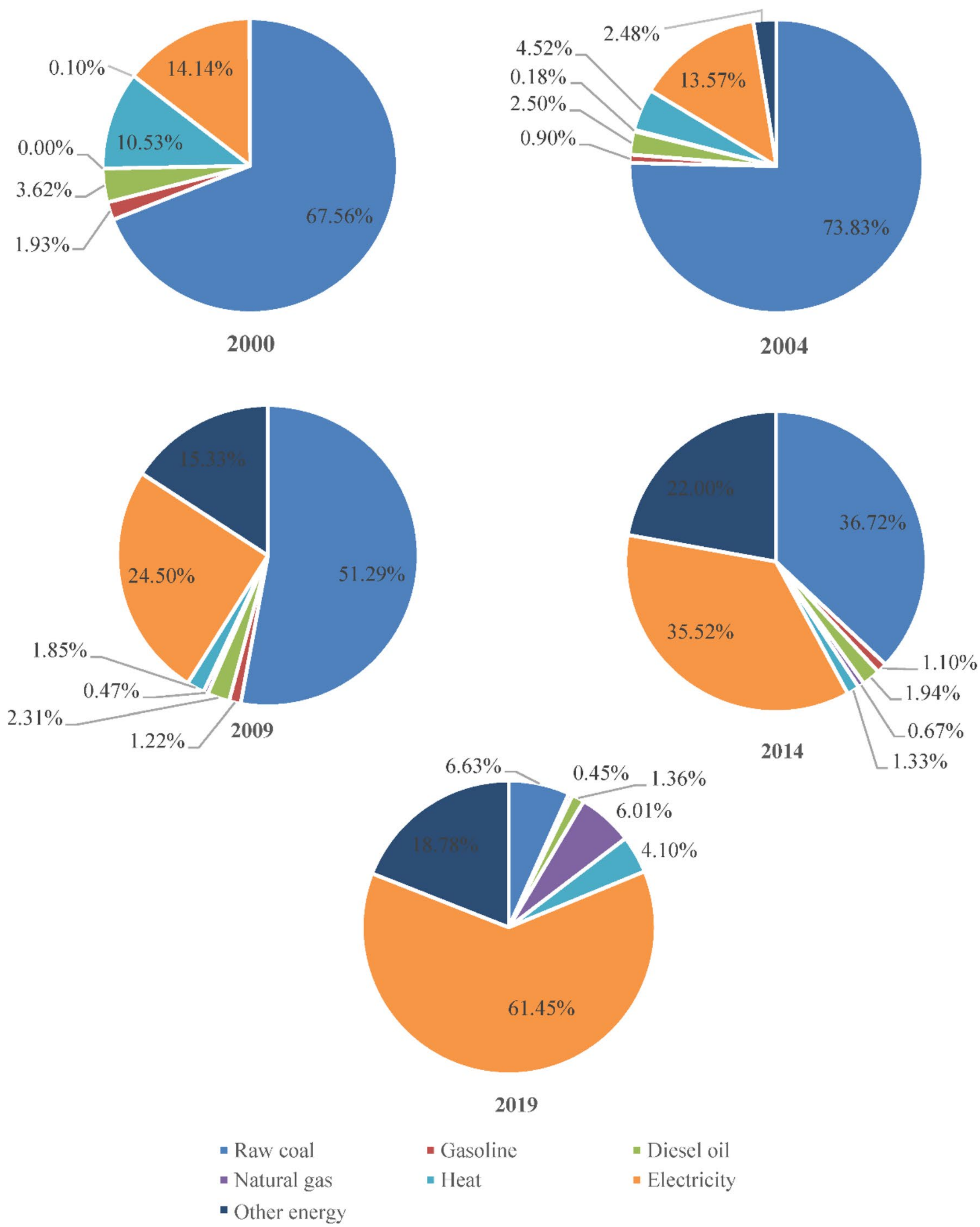

Fig. 2 Energy consumption structure of the wood and bamboo processing industry in China

Fig. 4. In summary, the CO_2 emissions of the wood and bamboo processing industry increased first and then decreased. More specifically, CO_2 emissions rapidly increased by 11.67% per year between 2000 and 2012. However, from 2013 to 2019, CO_2 emissions decreased gradually by 5.14% per year. As mentioned above, the main drivers were the change in energy consumption and energy structure, the industrial structure adjustment, and technological upgrades. These results are consistent with the results of a previous study [43], which reported that

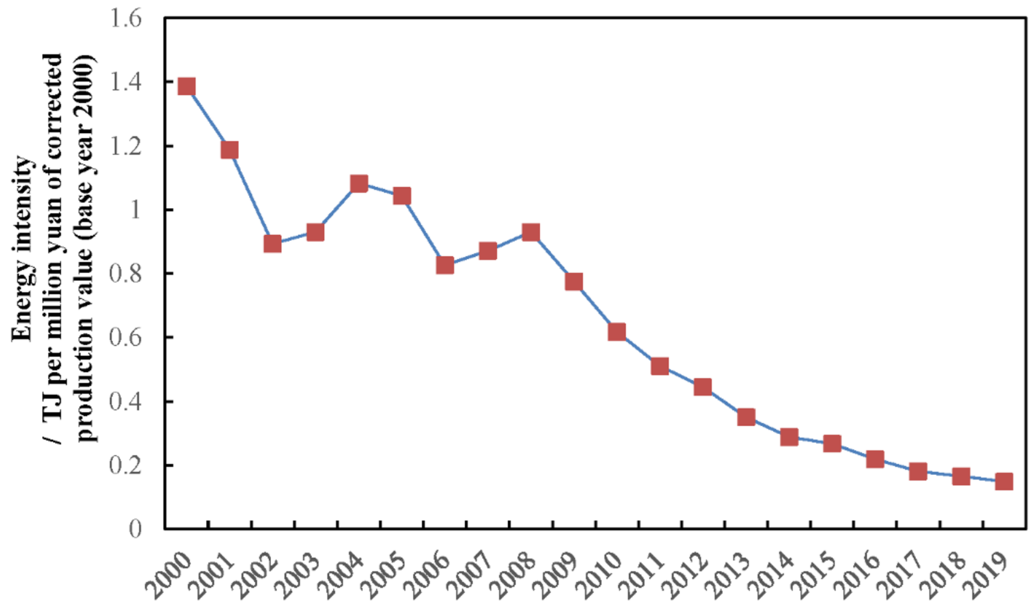

Fig. 3 Energy intensity of the wood and bamboo processing industry in China from 2000 to 2019

energy consumption has a strong impact on CO_2 emissions. Our analysis shows that the CO_2 emissions of China's wood and bamboo processing industry reached a peak of 31,148.1 thousand tons of CO_2 in 2012. This finding has not been reported previously. According to IEA data, in 2019, China's carbon emissions reached 10.2 billion tons of CO_2, accounting for 27.9% of the world [44]. The CO_2 emissions of China's wood and bamboo processing industry decreased to 21,525.2 thousand tons of CO_2 in 2019, accounting for 0.21% of China's carbon emissions.

The contribution rates of CO_2 emissions from different energy sources during 2000–2019 are listed in Table 2.

As shown in Table 2, the CO_2 emissions from raw coal were the highest from 2000 to 2007, and then declined from 56.92 to 48.34%. At the same time, the contribution rates of CO_2 emissions from electricity increased rapidly from 26.50 to 44.81%. The CO_2 emissions from electricity were the largest contributor in 2008. The contribution rates of CO_2 emissions from electricity increased continuously to 88.34% beginning in 2008. Conversely, the contribution rates of CO_2 emissions from raw coal decreased to 4.22%. As described before, CO_2 emissions are mainly caused by energy consumption. Correspondingly, these results fully reflect the adjustment in the energy consumption structure and improvements in the energy efficiency of China's wood and bamboo processing industry.

According to Fig. 4 and Table 2, we conclude that raw coal and electricity were the dominant contributors to CO_2 emissions of China's wood and bamboo processing industry, followed by heat, diesel oil, gasoline, and natural gas.

Figure 5 depicts the CO_2 emissions intensity of China's wood and bamboo processing industry from 2000 to 2019. CO_2 emissions maintained a downward trend during this period, similar to energy intensity. The CO_2 emissions intensity decreased about 7.14 times during this time, from 140.04 tons CO_2 per million yuan of corrected production value in 2000 to 19.62 tons CO_2 per million yuan of corrected production value in 2019. CO_2 emissions intensity is an indicator of development [45]. According to the existing data, we estimated that China's carbon emission intensity is about 102.94 tons CO_2 per million yuan of corrected production value in 2019. The carbon emission intensity of China's wood and bamboo processing industry is far below the national average, which accounts for 15.6% of the national average carbon emission intensity. Compared with high carbon emission industries in China, such as cement industry, iron and steel industry, papermaking industry, petroleum and petrochemical industry, wood and bamboo processing industry show remarkable advantage in terms of carbon emission intensity. The carbon emission intensity of China's wood and bamboo processing industry is only about 1.32%, 4.39%, 14.31%, 12.91% of cement industry, iron and steel industry, papermaking industry, petroleum and petrochemical industry, respectively [46–49]. The results suggest that China's wood and bamboo processing industry tended toward low carbon. These results cannot be compared to those of previous studies, which focused on CO_2

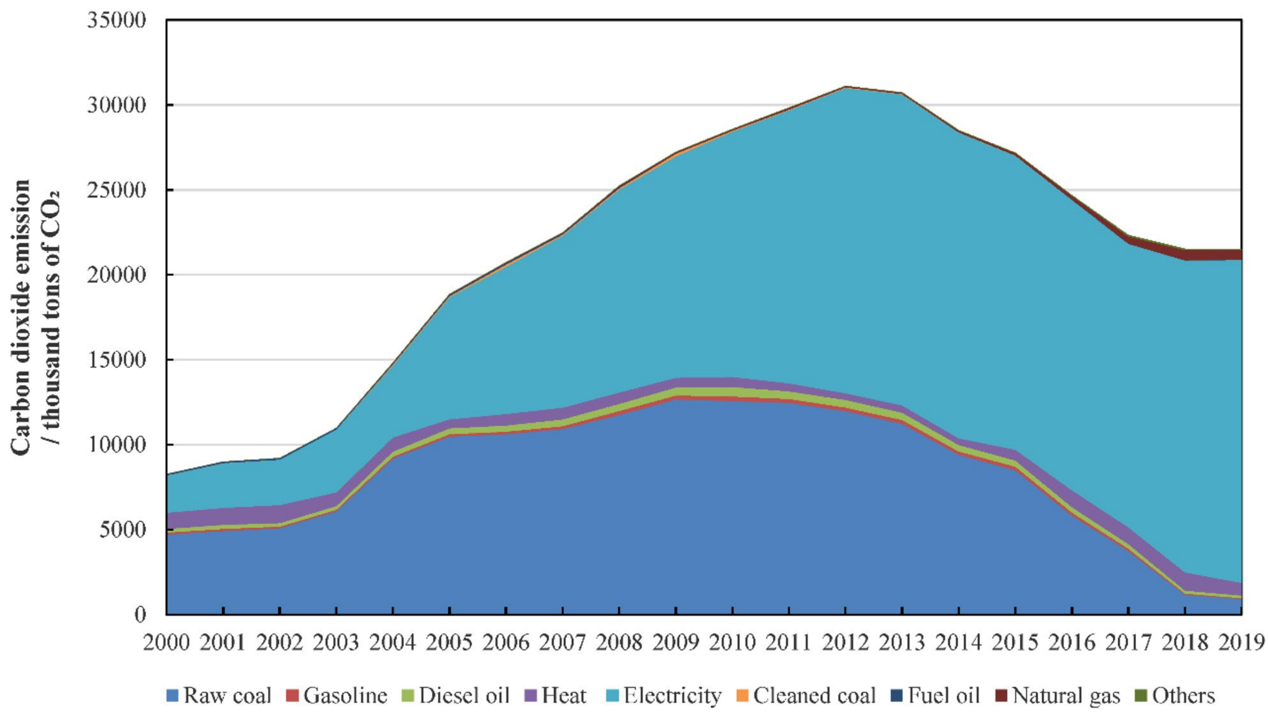

Fig. 4 CO_2 emissions of the wood and bamboo processing industry in China from 2000 to 2019

Table 2 Contribution rates of CO_2 emissions of different kinds of energy from 2000 to 2019

Years	Percentage/ %					
	Raw coal	Electricity	Heat	Diesel oil	Gasoline	Natural gas
2000	56.92	26.50	11.50	2.60	1.30	0.00
2001	54.48	29.16	11.07	2.61	1.48	0.00
2002	55.10	28.97	11.42	2.24	1.08	0.00
2003	55.20	33.68	7.21	2.08	0.82	0.00
2004	61.73	28.46	5.52	2.01	0.67	0.12
2005	55.39	37.98	2.77	1.82	0.73	0.13
2006	50.93	41.60	3.27	1.72	0.74	0.13
2007	48.34	44.81	3.03	1.79	0.72	0.14
2008	46.35	47.09	2.66	1.64	0.91	0.30
2009	46.33	47.70	2.10	1.72	0.85	0.27
2010	43.90	50.47	2.04	1.95	0.95	0.23
2011	41.70	53.82	1.59	1.50	0.78	0.30
2012	38.44	57.72	1.26	1.42	0.70	0.24
2013	36.49	59.51	1.41	1.39	0.73	0.26
2014	32.94	63.06	1.38	1.32	0.70	0.36
2015	31.09	63.36	2.31	1.34	0.76	0.51
2016	23.60	69.19	4.04	1.28	0.70	0.91
2017	16.73	74.69	4.38	1.21	0.62	1.85
2018	5.42	85.28	4.97	0.82	0.29	2.73
2019	4.22	88.34	3.43	0.75	0.23	2.64

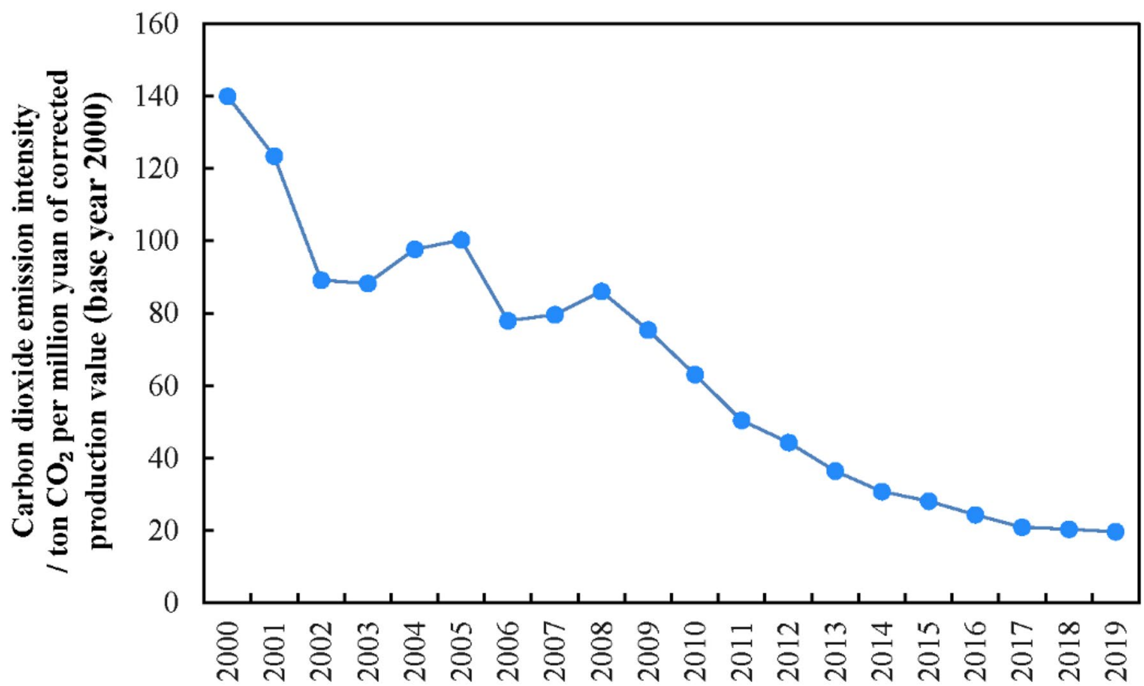

Fig. 5 CO_2 emissions intensity of the wood and bamboo processing industry in China from 2000 to 2019

emissions from the wood and bamboo products production. Because this macro-level research quantified the CO_2 emissions of the entire wood and bamboo processing industry in China while existing micro-level studies examined the CO_2 emissions of wood and bamboo products during their life cycle.

Spatial distribution pattern of CO_2 emissions

Figure 6 shows the spatial distribution pattern of CO_2 emissions of China's wood and bamboo processing industry in 2019. Highest CO_2 emissions occur in Shandong province; lowest CO_2 emissions occur in Qinghai province. We categorized provinces and regions into five subgroups by their CO_2 emissions as follows (Table 3):

- High emission areas: provinces and regions with CO_2 emissions 140.01–480.00 × 10,000 tons of CO_2
- Medium–high emission areas: provinces and regions with COv emissions 80.01–140.00 × 10,000 tons of CO_2
- Medium emission areas: provinces and regions with CO_2 emissions 40.01–80.00 × 10,000 tons of CO_2
- Medium–low emission areas: provinces and regions with CO_2 emissions 10.01–40.00 × 10,000 tons of CO_2
- Low emission areas: provinces and regions with CO_2 emissions 0–10.00 × 10,000 tons of CO_2.

High emission areas have five provinces and regions including Shandong, Jiangsu, Guanxi, Guangdong and Zhejiang, which accounts for 56.92% of the national total CO_2 emissions. Medium–high emission areas have five provinces and regions including Hunan, Xinjiang, Fujian, Henan and Hebei, which accounts for 20.44% of the national total CO_2 emissions. Medium emission areas have five provinces and regions including Sichuan, Anhui, Hubei, Jiangxi and Liaoning, which accounts for 14.46% of the national total CO_2 emissions. Medium–low emission areas has six provinces and regions including Jilin, Heilongjiang, Shanghai, Yunnan, Inner Mongolia and Chongqing, which accounts for 6.51% of the national total CO_2 emissions. Low emission areas have nine provinces and regions including Shaanxi, Guizhou, Hainan, Tianjin, Ningxia, Shanxi, Gansu, Beijing and Qinghai, which accounts for 1.67% of the national total CO_2 emissions. It should be noted that this paper did not calculate the CO_2 emissions of the wood bamboo processing industry in Taiwan, Hong Kong, Xizang and Macao due to the lack of relevant data. As shown in Fig. 6 and Table 3, the distribution of CO_2 emissions of China's wood and bamboo

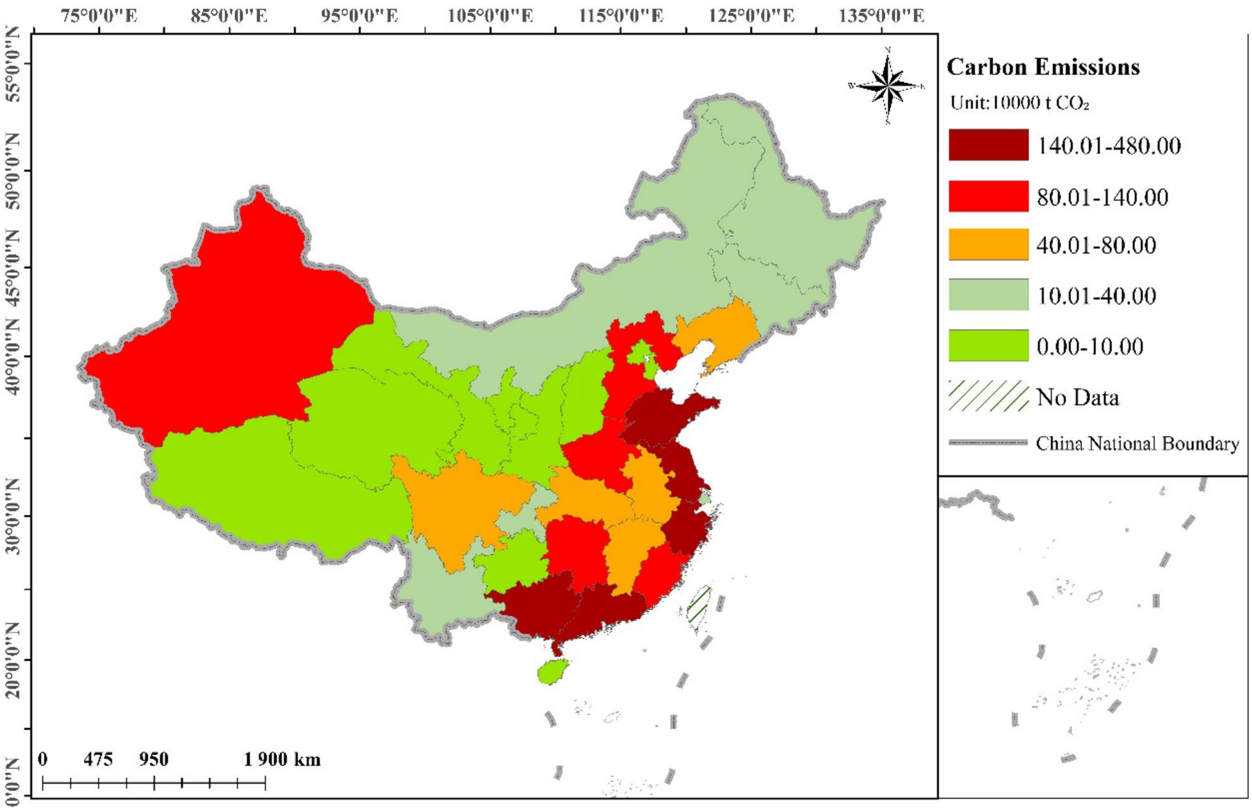

Fig. 6 Spatial distribution pattern of CO_2 emissions of China's wood and bamboo processing industry in 2019

processing industry shows significant spatial heterogeneity. The spatial distribution pattern of CO_2 emissions of China's wood and bamboo processing industry is highly consistent with the industrial spatial layout. That is, the more developed the wood and bamboo processing industry of the provinces and regions, the higher the CO_2 emissions. In general, the CO_2 emissions of southeast coastal areas and Xinjiang province are higher than other provinces and regions.

Regarding CO_2 emissions intensity, highest value occurs in Xinjiang province (738.50 tons CO_2 per million of corrected production value), and lowest value occurs in Anhui province (7.35 tons CO_2 per million of corrected production value). The average CO_2 emissions intensity of high emission areas, medium–high emission areas, medium emission areas, medium–low emission areas and low emission areas are 22.16 tons CO_2 per million yuan of corrected production value, 164.52 tons CO_2 per million yuan of corrected production value, 24.73 tons CO_2 per million yuan of corrected production value, 28.83 tons CO_2 per million yuan of corrected production value and 48.54 tons CO_2 per million yuan of corrected production value, respectively. In general, the higher the CO_2 emissions of wood and bamboo processing industry of the provinces and regions, the lower the CO_2 emissions intensity (except for Xinjiang province). It is well-known that higher CO_2 emissions intensity indicates lower energy efficiency. Therefore, this is because that the more developed the wood and bamboo processing industry of the provinces and regions, the higher the production efficiency, which results in higher energy efficiency and lower CO_2 emissions intensity. Concretely speaking, the differences on energy efficiency and CO_2 emissions intensity of wood and bamboo processing industry among different provinces and regions in China are mainly due to the comprehensive factors including technology level, industrial structure, energy consumption structure, resource endowment, enterprise scale and enterprise management level, etc.

Mitigation path

Although the CO_2 emissions level of China's wood and bamboo processing industry is low, the potential for reducing emissions is still great. First, the consumption of electricity is a key factor in CO_2 emissions of the wood and bamboo processing industry in China,

Table 3 CO_2 emissions of the wood and bamboo processing industry of Chinese provinces and regions in 2019

Ranking	Provinces and regions	CO_2 emissions/10^4 t CO_2	Percentage/%	Grading	CO_2 emission intensity/ t CO_2 per million yuan of corrected production value
1	Shandong	471.1817	21.89	High emission areas	26.60
2	Jiangsu	296.5315	13.78		19.05
3	Guanxi	170.1291	7.90		10.11
4	Guangdong	147.0453	6.83		31.55
5	Zhejiang	140.3495	6.52		23.50
6	Hunan	92.3512	4.29	Medium–high emission areas	20.48
7	Xinjiang	89.6964	4.17		738.50
8	Fujian	89.2604	4.15		7.57
9	Henan	85.5066	3.97		29.32
10	Hebei	83.2411	3.87		26.74
11	Sichuan	76.0913	3.53	Medium emission areas	34.55
12	Anhui	71.6002	3.33		7.35
13	Hubei	60.6788	2.82		18.09
14	Jiangxi	56.7755	2.64		16.42
15	Liaoning	46.0505	2.14		47.25
16	Jilin	34.8721	1.62	Medium–low emission areas	22.41
17	Heilongjiang	34.4125	1.60		35.07
18	Shanghai	22.0168	1.02		67.31
19	Yunnan	20.5205	0.95		14.52
20	Inner Mongolia	15.6114	0.73		18.01
21	Chongqing	12.6502	0.59		15.63
22	Shaanxi	8.3538	0.39	Low emission areas	42.24
23	Guizhou	8.0325	0.37		13.27
24	Hainan	7.6471	0.36		38.76
25	Tianjin	5.5907	0.26		54.92
26	Ningxia	2.2308	0.10		114.73
27	Shanxi	1.8982	0.09		38.76
28	Gansu	1.0314	0.05		103.00
29	Beijing	0.6122	0.03		11.48
30	Qinghai	0.5502	0.03		19.70

as discussed earlier. Thus, wood and bamboo processing enterprises could select electricity generated from low-carbon energy to reduce CO_2 emissions, such as wind power, solar power, nuclear power, or biomass energy. According to the IPCC guidelines, biogenic carbon emissions from wood and bamboo processing residues are carbon neutral. Therefore, enterprises should autonomously generate electricity from these residues. Second, the energy utilization efficiency of production process should be further improved. China's wood and bamboo processing industry mainly consists of small and micro enterprises, whose production equipment is old-fashioned. Hence, those backward manufacturing equipment with low energy efficiency that is highly polluting should be eliminated gradually. Meanwhile, the manufacturing equipment with high energy efficiency level should be promoted. Third, cleaner production technologies should be used to produce subsystems with high CO_2 emission levels, such as veneer drying and compositing subsystems for plywood manufacturing [14], fiber preparation subsystems in fireboard manufacturing [23], a wood chip production subsystem for particleboard manufacturing [22], and timber drying [50]. In other words, enterprises need to further reduce energy consumption and emissions in those subsystems.

Research limitations

Some limitations of this study should be discussed. This study only considered energy-related CO_2 emissions, and CO_2 emissions from chemical reactions that occur during production were not included. The effects of chemical reactions are very small compared to energy consumption. The mitigation path only considered CO_2 emissions. Other factors, such as cost, technological applicability, and other environmental impacts need to be studied in the future.

Conclusion

This study considered the energy consumption and CO_2 emissions of China's wood and bamboo processing industry from 2000 to 2019 using IPCC Tier-2 methodology. Energy consumption reached a maximum of 312,900.35 TJ in 2012. Energy usage decreased by 8.86% per year after 2012. The energy consumption structure tended toward low carbon. Energy intensity dropped from 1.39 TJ per million yuan of corrected production value in 2000 to 0.15 TJ per million yuan of corrected production value in 2019. The energy consumption intensity of China's wood and bamboo processing industry is far lower than the average level of the national industry.

Another key finding was that the CO_2 emissions of the entire industry peaked at 31,148.1 thousand tons of CO_2 in 2012. Raw coal and electricity had the largest contribution to CO_2 emissions over the period, followed by heat, diesel oil, gasoline, and natural gas. The CO_2 emissions intensity declined about 7.16 times during this time, from 140.04 tons CO_2 per million yuan of corrected production value to 19.62 tons CO_2 per million yuan of corrected production value. Compared with cement industry, iron and steel industry, papermaking industry, petroleum and petrochemical industry in China, wood and bamboo processing industry show remarkable advantage in terms of carbon emission intensity. The distribution of CO_2 emissions of China's wood and bamboo processing industry shows significant spatial heterogeneity. The spatial distribution pattern of CO_2 emissions is highly consistent with the industrial spatial layout. Emissions could be reduced using clean power, improving the energy utilization efficiency of production process, and adopting cleaner production technologies.

This study contributes to current studies in the following ways. It is the first study to quantify the CO_2 emissions of the wood and bamboo processing industry at a national scale. Furthermore, this study considered the contribution rates of different kinds of energy and the intensity of the CO_2 emissions. Finally, this study systematically proposes a mitigation path for the wood and bamboo processing industry, which will be valuable for other countries.

Abbreviations

MDF	Medium-density fiberboard
PB	Particleboard
HB	Hard fiberboard
OSB	Oriented structural board
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle assessment
CDE	Carbon dioxide emission
AD	Activity data
EF	Emission factor
NCV	Net calorific value
EC	Consumption of energy
CC	Carbon content
OF	Carbon oxidation rate
CEI	Carbon dioxide emission intensity
PV	Production value

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Author contributions

WLL: first author, conceptualization, methodology, data analysis, writing—original draft, and writing—review and editing. LC: writing—review and editing. XFD: corresponding author, supervision and writing—review and editing. All authors read and approved the final manuscript.

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Data availability and Code availability

Data generated or analyzed during this study are included in this published article.

Declarations

Competing interests

The authors have no competing interests.

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