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CO_2 Emissions Accounting and Carbon Peak Prediction of China's Papermaking Industry

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Abstract: China has been the world's largest producer and consumer of paper products. In the context of the "carbon peaking and carbon neutrality goals", China's papermaking industry which is traditionally a high energy-consuming and high-emissions industry, desperately needs a nationally appropriate low-carbon development path. From the consumption-side perspective, this paper calculates the CO_2 emissions of China's papermaking industry from 2000 to 2019 by using carbon emission nuclear algorithm, grain-straw ratio, first-order attenuation method, and STIRFDT decomposition model, etc., to further explore the core stages and basic patterns affecting the industry's carbon peaking. The results show that the total CO_2 emissions of China's papermaking industry showed an upward trend from 2000–2013, stable from 2013–2017, and a steady but slight decline from 2017–2019. Meanwhile, the total CO_2 emissions of the full life cycle of paper products in China have decreased to a certain extent in the raw material acquisition, pulp, and paper making and shipping stages, with only the waste paper disposal stage showing a particular upward trend. We find that from 2000 to 2019, China's CO_2 emissions in the pulping and papermaking stage of paper products accounted for 68% of the total emissions in the whole life cycle, of which 59% was caused by coal consumption. Moreover, the scenario prediction shows that improving the energy structure and increasing the waste paper recovery rate can reduce the CO_2 emissions of the industry, and it is more significant when both work. Based on this and the four core stages of CO_2 emissions of the papermaking industry we proposed ways to promote CO_2 emissions peaking of China's paper products.

Keywords: paper and paper products; LCA; CO_2 emissions; carbon peaking

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1. Introduction

Since the 21st century, global problems such as lack of resources, environmental damage, and climate change have become increasingly prominent. China has overtaken the United States as the world's largest CO_2 emitter since 2009 [1], and in 2019, China's CO_2 emissions were higher than the combined CO_2 emissions of the United States and European Union (EU) countries, with a global share of 29.37% [2]. According to China's Intended Nationally Determined Contributions (INDC) commitment, they "Strive to achieve carbon peaking by 2030 and carbon neutrality by 2060". Energy saving and carbon reduction have become essential tasks to help achieve the "carbon peaking and carbon neutrality goals" in the coming period. The papermaking industry presents an energy-intensive sector, which accounted for approximately 1.4% of total national manufacturing energy consumption in 2021 [3]. China is the world's largest producer and consumer of paper and paperboard [4,5], and the types and quantities of paper products are increasing with the growth of the population and the improvement of people's living standards. National paper and paperboard production reaches 112.60×10^6 tons in 2020, up 4.60% from 2019 [6]. Currently, China's papermaking industry is still in the rising stage of industrial development and energy consumption, and the corresponding CO_2 emissions continue to increase with the increase in paper products production [7]. Hence, scientific accounting of CO_2 emissions from the whole life cycle of paper products can provide an information reference for the development of China's paper product CO_2 emission life cycle database and related standard guidelines, which is of positive significance to the green transformation development of the papermaking industry.

Currently, the methods used by scholars to account for CO_2 emissions from the production process of paper products mainly include the carbon emission factor method, input-output method, and life cycle assessment. Fleiter et al., Zhang et al., and Wang et al. [8–10] all used the carbon emission factor method provided in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories to account for the CO_2 emissions generated by the pulp and paper production process of paper companies as well as the industry. Pulping and papermaking are the main processes in paper product production, yet the waste treatment processes are also crucial. Wang et al. [11] measured the CO_2 emissions of pulp making, alkali recovery, and wastewater treatment processes in papermaking enterprises in Shandong and Jiangsu provinces using the carbon emission factor method, and the results showed that CO_2 emissions per unit of straw pulp were the highest, followed by wood pulp, and waste pulp was the lowest. Chen et al. [12] estimated energy consumption and CO_2 emissions of the Chinese papermaking industry from a supply chain perspective supplemented by the energy input/output method, involving the main processes of forest cultivation, logging, pulp, and paper production. Accounting found that the total CO_2 emissions of China's papermaking industry in 2011 was 149.74×10^6 t, with unit CO_2 emissions of about 1543 kg/t paper, much higher than the 200 kg/t paper in the Netherlands and 204 kg/t paper in Sweden in the same period (We need to note that the energy mix in China is very different from that in Europe. China is a country rich in coal resources, but less in oil and natural gas resources, and the development and use of new energy in the overall energy system is not yet in a dominant position, contrary to the widespread use of renewable energy in European plants. Therefore, China is one of a few countries in the world whose energy production and consumption is dominated by coal. These differences are also directly reflected in the difference in carbon emissions from the paper industry). Zhao et al. [13] accounted and analyzed the implicit carbon flows and CO_2 emissions in the production and operation of Stora Enso (Guangxi), an integrated forest-paper enterprise, based on the multi-level input/output method of the forest-pulp-paper supply chain, and proposed relevant ways to reduce CO_2 emissions in the enterprise. In addition, Furszyfer Del Rio et al. [14] presented the main determinants of energy and CO_2 emissions emerging from the papermaking industry and barriers to decarbonization of the papermaking industry based on a socio-technical utilization perspective.

Life cycle assessment (LCA) is a method to quantitatively evaluate the resource consumption and environmental impact of a product throughout its life cycle, from the acquisition of raw materials, the production of the product to the disposal of the product after use, etc. It is a product-oriented environmental load quantification tool and is increasingly used in the papermaking industry. In terms of theoretical exploration, Li et al. [15] used life cycle theory to construct an analytical framework for CO_2 emission accounting of paper products in the papermaking industry; Liu et al. [16] analyzed the carbon source and carbon sink flow of paper enterprises in the context of forest-paper integration; Ma et al. [17] constructed a carbon footprint evaluation system for products in the papermaking industry and evaluated the application of carbon footprint in the papermaking industry and enterprises. Tang and Zheng [18,19] divided the life cycle of paper products into four stages from the perspective of market consumption: input period, growth period, maturity period, and decline period, and based on the characteristics of each stage, the development stages of paper products and their characteristics were judged through the analysis of indexed data such as types of paper products, production volume, consumption, and degree of industry competition, etc. As for empirical studies, Lopes et al. and Dias et al. [20,21] used the LCA method to evaluate the environmental impact of the papermaking industry in Portugal. Gemechu et al. [22] used the LCA method to calculate and analyze the greenhouse gas emissions from virgin wood pulp and waste pulp papermaking processes, and found that waste pulp papermaking produced fewer greenhouse gases. Chen et al. [23] analyzed the 2010 and 2015 life cycle CO_2 emissions of paper products in China. The scope covered in their study was relatively complete, including forest plantation, pulp and paper making, transportation, waste paper recycling and pulp making, incineration, and landfill. However, their analysis did not include non-wood pulp raw materials in the production process, and the CO_2 emissions from the pulp and papermaking process accounted for as much as 86.33% of their results. It is worthwhile to note that the process of paper making is generally divided into two types: wet paper and drying process. Currently, China is still dominated by the former, but the latter is also developing. Different processes are used to produce different types of paper. The types of paper produced in China mainly include corrugated paper, containerboard, printing paper, and newsprint. The array of paper product categories varies from country to country.

In summary, scholars' research results on CO_2 emission accounting in the papermaking industry are relatively abundant and they provide an essential reference for the study of this paper. However, studies on CO_2 emissions of paper products are basically based on the production-side perspective, mainly accounting for CO_2 emissions of the pulp and paper production process. With the development of trade globalization, the import and export trade of paper products has become more and more frequent, and it is easy to ignore the spatial transfer of CO_2 emissions in the trade by accounting only from the production side. At the same time, the existing research also needs to deepen further the determination of the system boundary of the whole life cycle of the papermaking industry. Accordingly, this paper combines the perspective of consumer responsibility to provide a more complete estimation of CO_2 emissions of Chinese paper products from 2000 to 2019, from various stages in the whole life cycle, including raw material acquisition, pulp and paper production, trade and transportation, waste paper disposal, and export. On this basis, the impact of relevant policies on CO_2 emissions in the papermaking industry is discussed at both macro and micro levels, and then specific paths are proposed to promote the industry's "carbon peaking".

2. Materials and Methods

2.1. System Boundary and CO_2 Emission Source Determination

2.1.1. System Boundary

CO_2 emissions from the perspective of consumer responsibility are based on the carbon footprint idea, accounting for the total amount of greenhouse gas emissions from products or services consumed by enterprises and individuals in the process of transportation, production, and consumption, which is equivalent to the production-side CO_2 emissions minus the CO_2 emissions of exported products plus the CO_2 emissions of imported products, where the difference between the CO_2 emissions of imported and exported products is the implied CO_2 emissions of product trade [24–26]. In order to comprehensively and systematically quantify the CO_2 emissions of paper products at all stages of production and consumption, this paper adopts the whole life cycle accounting method and proposes a system boundary for CO_2 emissions accounting of paper products, as shown in Figure 1.

The system boundary is the sub-interface between the system and the environment. The environment of the whole life cycle CO_2 emission system of paper products includes resources and energy input, and CO_2 output. The whole life cycle of paper products is mainly divided into four stages within the system: raw material acquisition stage, pulp and paper stage, waste paper disposal stage, and transportation stage. Considering the data acquisition problem, CO_2 generated by paper and paperboard in domestic consumption is not included in the accounting system. Under the perspective of consumer responsibility, and based on the principle of who consumes who bears, part of the CO_2 emissions from paper and paperboard exported from China (including production and transportation) are borne by the importing country, and this part should be subtracted from the accounting process. In addition, China imports mainly wood pulp and waste paper which are semifinished products, and still need to be processed in China. Thus, the CO_2 emissions from this part are divided into the pulp and paper stage and the transportation stage, which are included in the accounting system.

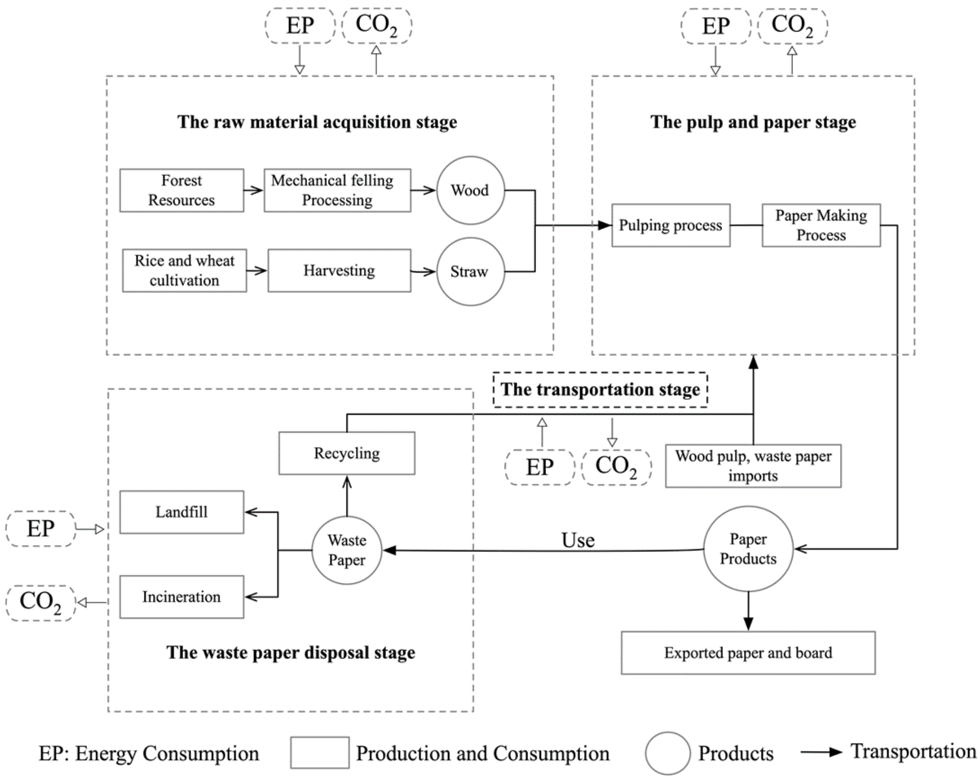

Figure 1. CO_2 emission accounting boundary of paper products in the whole life cycle.

2.1.2. CO_2 Emission Source Determination

(1) The raw material acquisition stage. China's paper raw materials are currently dominated by waste pulp followed by wood pulp, with non-wood pulp consuming the lowest percentage. Non-wood pulp originates from domestic production, while waste pulp and wood pulp originate from domestic production and imports. The CO_2 emissions from the production or import of the three raw materials are defined in Table 1 below.

(2) The pulp and paper stage. This stage is the process of pulp processing to produce paper and paperboard, which involves CO_2 emissions including fuel combustion emissions, chemical decomposition emissions, and electricity and heat consumption emissions. The research boundary of the pulp and paper stage is based on the accounting standards for greenhouse gas emissions from the papermaking industry defined in the "Greenhouse Gas Emissions Accounting Methodology and Reporting Guidelines for Paper and Paper Products Producers in China (for Trial Implementation)". Additionally, the amount of CO_2 emissions due to fuel combustion was accounted for according to Zhang et al. [9], and Peng et al. [27].

(3) The waste paper disposal stage. Drawing on the research results of Gonzalez-Garcia et al., Ghose et al., and Geme chu [22,28,29], the core aspects of raw material input, production, and product output in the transportation phase of paper products are included in the accounting boundary. Among them, raw material input transportation includes pulp raw materials from domestic origin or foreign imports transported to the pulp and paper enterprises and after the use of waste paper recycling transported to the pulp and paper enterprises recycling; product output transportation includes finished paper and paperboard from the production enterprises transported to the paper products suppliers, distributors, individual consumers or export transported to

other countries. Under the consumer responsibility principle, CO_2 emissions from the export transportation of paper and paperboard should be borne by the importing country of paper and paperboard, and this part of CO_2 emissions is not included in the transportation phase of paper products. Due to the availability of data, CO_2 emissions from the export transportation of the product to the consumer are difficult to calculate, and the part of the production process that involves transportation from the workshop is neglected.

(4) The transportation stage. China's waste paper disposal mainly has three ways: landfill, incineration, and recycling [23]. Waste paper recycling and utilization is an important part of the closed-loop material flow of "resource consumption-products-renewable resources" in the papermaking industry, and the CO_2 generated from recycling is included in the transportation stage. For the convenience of estimation, it is assumed that the waste paper is landfilled or incinerated in the open air without fixed concentration points, and methane recovery is not considered in the landfilling process, so the CO_2 released in the landfilling or incineration process is mainly accounted for in the waste paper disposal stage.

Table 1. Three sources of raw materials and definition of CO_2 emissions.

Raw Materials	Origins	Notes
Wood pulp	Domestic timber harvesting and transportation	The proportion of foreign imported wood used for furniture manufacturing is high, and only a small portion of it is used for pulp and paper making, so the CO_2 generated from the transportation of this part of imported wood is negligible. The CO_2 generated in the process of forest plantation can be absorbed by its own photosynthesis, so we do not calculate CO_2 emissions from forest plantation, but only calculate CO_2 emissions from domestic harvesting of wood for pulp and paper production.
	Foreign wood pulp import	Wood pulp imported from abroad is mainly involved in transportation distance and transportation volume, so CO_2 generated from imported wood pulp is included in the transportation phase for calculation.
Non-wood pulp	Domestic production	Among non-wood pulp, rice-wheat straw pulp has always accounted for the highest percentage [6], so we mainly calculate the CO_2 emissions from the rice-wheat straw pulp feedstock acquisition process, and then estimate the CO_2 emissions from the non-wood pulp feedstock acquisition process based on the percentage of rice-wheat straw pulp.
Waste paper pulp	Domestic recycling and foreign import of waste paper	Both domestic waste paper recycling and foreign waste paper import mainly involve transportation, so this portion of CO_2 emissions are included in the transportation phase.

2.2. Calculation Method

2.2.1. Accounting for CO_2 Emissions in the Raw Material Acquisition Stage

Timber Harvesting Process

The acquisition of wood pulp raw materials (wood harvesting process) involves three processes: logging for timber, skidding, and transportation. The accounting of CO_2 emissions from this process is based on the carbon emission factor method of the National Greenhouse Gas Emissions Inventory Guidelines. The formula is as follows.

① Logging and timbering operations:

$$C_h = e_d \times E_h = e_d \times W_h \times W_{ah} \tag{1}$$

In Equation (1), C_h is the CO_2 emission from logging and timbering operation activities (10^6 t), e_d is the CO_2 emission factor of diesel fuel (tCO_2/t), E_h is the energy consumption of logging and timbering (10^6 t), W_h is the volume of paper logging (m^3), and W_{ah} is the average fuel consumption of chainsaw in logging operation (t/m^3).

② Mechanical ropeway skidding operations:

$$C_m = e_d \times E_m = e_d \times W_m \times W_{am} \times L_m \tag{2}$$

In Equation (2), C_m is the CO_2 emission of ropeway skidding operation activity (10^6 t), E_m is the energy consumption of ropeway skidding (10^6 t), W_m is the volume of skidding (m^3), W_{am} is the average fuel consumption of mechanical ropeway skidding (t/m^3.km), and L_m is the length of ropeway (km).

③ Material transport operations:

$$C_l = e_d \times E_l = e_d \times W_l \times W_{at} \times L_l \tag{3}$$

In Equation (3), C_l is the CO_2 emission from the vehicle timber transport activity (10^6 t), E_l is the energy consumption of timber transport (10^6 t), W_l is the volume of timber transported (m^3), W_{at} is the average fuel consumption of timber transport (t/m^3.km), and L_l is the distance of timber transport (km). Assuming no damage to wood during skidding and transportation, i.e., $W_h = W_m = W_l$. The final CO_2 emissions during the wood pulp raw material acquisition stage are $C_w = C_h + C_m + C_l$.

The Process of Obtaining Raw Materials for Rice and Wheat Straw Pulp

Rice-wheat straw pulp is one of the important ways to utilize straw as raw material. CO_2 emissions from this process include: ① CO_2 from the use of agricultural chemicals (fertilizers, pesticides); ② CO_2 from the consumption of diesel fuel for irrigation [30], tilling and harvesting with agricultural machinery, etc. Refer to the grain/straw ratio method. The formula is as follows.

$$C_n = n^{-1} \times \sum_{i=1}^{i} AR_i \times c_i \times A \tag{4}$$

In Equation (4), A is the area of rice planted for papermaking, C_n is the CO_2 emission in the non-wood pulp raw material acquisition stage (10^6 t), n is the ratio of rice-wheat straw pulp production to total non-wood pulp production, AR_i is the i-th agricultural input per hectare of rice planted area (t/hm^2, kW-h/hm^2). According to the statistics of the China Rural Statistical Yearbook, agricultural inputs include nitrogen fertilizer, phosphorus fertilizer, potassium fertilizer, compound fertilizer, herbicide, insecticide, fungicide, diesel, agricultural film, rice seed and electricity. c_i is the CO_2 emission factor of the i-th agricultural input (tCO_2/t, tCO_2/kW-h). CO_2 emissions in the raw material acquisition stage of the final paper product $C_A = C_w + C_n$.

2.2.2. Accounting for CO_2 Emissions in the Pulp and Paper Stage

The pulp and paper stage mainly generates CO_2 emissions from energy consumption. In this paper, the carbon emission nuclear algorithm is used to calculate CO_2 emissions based on the energy consumption of the pulp and paper stage and the CO_2 emission factor of energy, the formula is as follows.

$$C_B = \sum c_j = \sum_{j=1}^{j} e_j \times f_j \tag{5}$$

In Equation (5), C_B is the CO_2 emission of the pulp and paper stage (10^6 t), c_j is the CO_2 emission of various energy sources consumed in this stage (10^6 t), and e_j is the physical quantity of various energy sources consumed (10^6 t, m^3, kW-h). According to the statistical caliber of China Statistical Yearbook, the energy consumed in the pulp and paper stage includes coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity. f_j is the CO_2 emission coefficient of each energy source (tCO_2/t, tCO_2/m^3, $tCO_2/kW\text{-}h$).

2.2.3. Accounting for CO_2 Emissions in the Waste Paper Disposal Stage

The accounting method on transportation CO_2 emissions mainly refers to the idea of the STIRPAT factor decomposition model [31,32], Which is based on constructing an accounting model of energy consumption in the transportation process of paper products, and then combining it with the carbon emission factor method. To account for CO_2 consumption during the transportation of paper products, the formula is as follows.

$$C_T = \sum F \times \frac{K}{F} \times \frac{E_i}{K} \times \mu_i = \sum F \times \frac{K}{F} \times \frac{E_i \times \mu_i}{K} = F \times D \times \frac{C}{K} = \sum F \times D \times \varphi_j \quad (6)$$

In Equation (6), C_T is the total CO_2 emission during the transportation of paper products (10^6 t), F is the freight volume of paper products (10^6 t); K is the turnover of paper products (10^6 t.km), and $\frac{K}{F}$ is the transportation distance of paper products (km), expressed as D; E_i is the consumption of the i-th energy source during the transportation of paper products (10^6 t), and $\frac{E_i}{K}$ is the consumption of various energy sources per 10^6 t of paper products in 1km-transportation (t/10^6 t.km), μ_i is the CO_2 emission coefficient of each energy source, $\frac{C}{K}$ is the CO_2 emission per 10^6 t of paper product in 1km-transportation ($tCO_2/10^6$ t.km), i.e., the CO_2 emission coefficient of transportation mode, expressed as φ_j, j is the jth transportation mode. For the convenience of calculation, φ_j is set constant for each transportation mode.

(1) CO_2 emission accounting method for the transportation process of imported paper raw materials

In international trade, the distance of cargo transportation is mostly measured by the shortest spherical distance between the capitals of the two trading countries [33,34], but this is generally applicable to air transportation methods, and if used as a distance measure for waterway transportation, it will greatly underestimate the actual distance of cargo transportation [35]. Due to the low cost and high volume of waterway transportation, Chinese paper raw material imports are mainly transported by waterway. To make up for the shortcomings of this international transport distance measure, the traditional international trade transport distance is split into the international and domestic distance measures [35], and in this paper, the transport distance of paper raw material import is divided into two parts with the main Chinese port as the transit point, the first part is the international distance transported from the paper raw material exporting country to the main Chinese port, and the second part is the domestic distance transported from the main Chinese port to the paper and paperboard main production provinces in China. The two paper raw materials (pulp and waste paper) source countries are not exactly the same and they are from numerous source countries, hence, for ease of accounting, we only set China's largest port of international trade—Shanghai—for the international distance in the destination, the largest port of paper raw materials exporting countries as the starting place. The actual water transport distance between these two places is the international distance of paper raw materials imports. As for the domestic distance, according to reality, we set Qingdao port, Tianjin port, Shanghai port, Xiamen port, and Shenzhen port as the main ports of paper raw material imports [36]. The main provinces of paper and paperboard production follow the nearest and only principle, i.e., it will be from the nearest port and only from this port to import pulp and waste paper. Therefore, the actual distance between the main ports and the provincial capitals of the main paper and paperboard-producing provinces is the domestic distance. In summary, the formula for accounting for CO_2 emissions during the transportation of imported paper raw materials is as follows.

$$C_I = \sum_{\alpha=1}^{\alpha} F_p \times D_\alpha \times \varphi_1 + \sum_{\beta=1}^{\beta} F_w \times D_\beta \times \varphi_1 + \left(F_p + F_w\right) \times D_N \times \varphi_2 \quad (7)$$

In Equation (7), C_I is the total CO_2 emission of paper raw material import transportation (10^6 t), F_p and F_w are the import volume of pulp and waste paper respectively (10^6 t), and the sum of both is the total import volume of paper raw material (10^6 t), D_α and D_β are the water transportation distance between the largest port of the αth pulp exporting country and the βth waste paper exporting country and Shanghai port respectively (km), and φ_1 is the CO_2 emission coefficient of waterway transportation mode ($tCO_2/10^6$ t.km). Since it is difficult to obtain specific data on the volume of pulp and waste paper transported by the main paper and paperboard producing provinces from each major port, D_N is the average distance (km) of the actual distance between all major ports to the provincial capitals of the main paper and paperboard-producing provinces, and based on the average distance, we set that the domestic transport process is dominated by rail transport, and φ_2 is the CO_2 emission factor of the rail transport mode.

(2) CO_2 emission accounting method for domestic waste paper recycling and transportation process

Paper and paper products are involved in almost every aspect of everyone's life, and within the Chinese region, the consumer market is nationwide, with waste paper generally originating from China's 31 provinces, autonomous regions, and municipalities (Hong Kong, Macau, and Taiwan of China are not counted). The recovered waste paper is transported to 16 paper and paperboard-producing provinces with complicated and irregular transportation routes. Therefore, this paper sets 31 provinces, autonomous regions, and municipalities directly under the Central Government to follow the principle of proximity and uniqueness, i.e., only transport to the nearest major paper and paperboard-producing province. Taking the actual distance between these two provincial capitals as the transportation distance of waste paper recycling, and the transportation mode is also mainly railroad transportation, the CO_2 emission accounting formula of the domestic waste paper recycling transportation process is as follows.

$$C_z = F_w \times D_w \times \varphi_2 \tag{8}$$

In Equation (8), C_z is CO_2 emissions from domestic waste paper recycling transportation (10^6 t). Since specific data on the amount of waste paper shipped to the main paper and paperboard production sites in each province and city are not available, F_w is the total amount of waste paper recovered (10^6 t) and, D_w is the average distance (km) between the source of all recovered waste paper and the provincial capitals of the main paper and paperboard production sites.

2.2.4. Accounting for CO_2 Emissions in the Transportation Stage

In order to ensure the consistency of methods and data sets in the time series and minimize accounting errors, the first-order attenuation method is used to estimate the CO_2 emissions from waste paper open landfill and incineration.

(1) Open landfill

Open-air landfills mainly release CH_4, and the accounting converts CH_4 emissions into CO_2 emissions, with the following accounting formula.

$$C_J = MSW_m \times DOC \times DOC_f \times MCF \times F \times \frac{16}{12} \tag{9}$$

$$C_d = MSW_m \times DOC \times DOC_f \times (1 - MCF \times F) \times \frac{44}{12} \tag{10}$$

In Equations (9) and (10), MSW_m is the volume of waste paper landfill (10^6 t), DOC is the proportion of decomposable organic carbon (%) (how many kg of carbon per kg of landfill waste paper), DOC_f is the proportion of decomposable DOC (%), MCF is the CH_4 correction factor for aerobic decomposition (%), F is the proportion of CH_4 in landfill gas (%), $\frac{16}{12}$ is CH_4/C molecular weight ratio, and $\frac{44}{12}$ is the CO_2/C molecular weight ratio.

(2) Open burning

Assuming that the waste paper is burned completely in the open air, releasing mainly CO_2 gas and producing very little CO, the CO_2 emissions from this part are accounted for by the following formula.

$$C_v = MSW_s \times CF \times FCF \times OF \times \frac{44}{12} \quad (11)$$

In Equation (11), MSW_s is the waste paper incineration volume (10^6 t), CF is the carbon content of waste paper (%), FCF is the fossil carbon percentage of waste paper (%), and OF is the oxidation factor.

2.2.5. Accounting Methods for Export Paper and Paperboard CO_2 Emissions

From a consumer responsibility perspective, CO_2 emissions from the production and other processes of paper and paperboard exported from China should be borne by the importing country and not counted as part of the whole life cycle CO_2 emissions of Chinese paper products. The formula for accounting for CO_2 emissions from this portion of paper and paperboard is as follows.

$$C_O = U_c \times PB \quad (12)$$

In Equation (12), C_O is the CO_2 emissions of paper and paperboard exported (10^6 t), U_c is the CO_2 emissions per unit of paper and paperboard production (t CO_2/t), and PB is the volume of paper and paperboard exported from China (10^6 t).

2.3. List of Data and Sources

(1) The raw material acquisition stage. The amount of wood used in the process of acquiring wood pulp is equivalent to the amount of timber used for paper making, data of which is taken from the "China Forestry Statistical Yearbook 2000–2020" (national production of major timber and bamboo). The average fuel consumption for logging for timber, skidding, and transporting timber was referred to the data in the research results of Yuan Zhou et al. [37], and the cableway length and distance for transporting timber were adopted from the field research conducted by Zhang et al. [38] on southern plantation forests. As for the non-wood pulp acquisition process, non-wood pulp and rice-wheat straw pulp production data were drawn from the "China Papermaking Industry Annual Report (2001–2020). The parameters of the amount of straw resources consumed per unit of rice-wheat straw pulp output were referred to the data of Zhang [39] who investigated the non-wood pulp production lines of Yongfengyu enterprises. Paper straw availability coefficient and straw collectability coefficient were adopted from the research results of Sun et al. and Li Zhongzheng [40,41]. The straw-to-grain ratio (straw coefficient) was selected as the average of the straw coefficient of rice in China by Wang [42]; data on total rice production and total planted area in China during the study period were obtained from the China Rural Statistical Yearbook (2000–2020) [43] (planted and farmed area and production of major agricultural products). Statistics on various agricultural inputs during rice cultivation and cultivation up to harvesting were taken from the National Compilation of Information on Costs and Returns of Agricultural Products (2001–2020) [44]. The CO_2 emission factors of agricultural inputs such as fertilizers, pesticides, agricultural films, and seeds were obtained from the data of Huang et al., Wang et al., and Xue et al. [30,45,46], respectively.

(2) The pulp and paper stage. Energy consumption data for the study period was obtained from the China Statistical Yearbook (2000–2020) [3]. Energy types were classified into nine categories according to the China Energy Yearbook: coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity, and the CO_2 emission coefficients of various energy sources were adopted from the Guide to Provincial Greenhouse Gas Inventory Preparation (for Trial Implementation) [47]. The electricity CO_2 emission

factor is the average value of CO_2 emissions per unit of electricity supply in the six regions of China and Hainan Province in the reference list.

(3) The transportation stage. Data on pulp and waste paper imports and country of import for the study period were obtained from the UN Trade Database https://comtrade.un.org/data (accessed on 25 December 2021). China needs to import large amounts of paper raw materials from abroad. The pulp or paper scrap exporting countries with the highest export volumes and the sum of their export volumes accounting for more than 90% of China's total pulp or paper scrap imports were selected as the main importers of paper raw materials into China. The distance between the largest port of the importing country and the Chinese port of Shanghai was referred to as the water transport distance as indicated on the website of the International Cargo Exchange https://www.searates.com (accessed on 25 December 2021). For the main paper and paperboard-producing provinces, we referred to the "China Papermaking Industry 2000–2020 Annual Report" [6] and selected 16 provinces and cities such as Shandong, Zhejiang, Guangdong, and Jiangsu, whose combined production of paper and paperboard accounted for more than 95% of the total paper and paperboard production in China during the study period. The actual distance data between the main importing ports to the provincial capitals of the main paper and paperboard production areas and to the provincial capitals of main waste paper recycling sites were based on the Baidu map, and ArcGIS was used to calculate the spherical distance between points. The data on waste paper recycling volume were obtained from the China Paper Yearbook (2000–2020) [48], and the CO_2 emission factors of each transportation mode were referred to the "European Communities Trade Mark Association's Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations" [31].

(4) The waste paper disposal stage. There is relatively less literature available about the percentage of waste paper recycling, landfill, and incineration. In our paper, the proportion of landfill and incineration of domestic waste to the total domestic waste disposal in China from 2000 to 2020, respectively, was used as the landfill rate and incineration rate of waste paper, from which the amount of landfill and incineration of waste paper was derived [23]. Data on domestic waste disposal in China during the study period were obtained from the China Statistical Yearbook of Urban Construction (2000–2020) [49] (information on the national urban sanitation subgroup). The data parameters such as DOC_f utilized in the accounting process were referred to as the National Greenhouse Gas Emission Inventory Guidelines and the Provincial Greenhouse Gas Inventory Preparation Guidelines (for Trial Implementation) [47].

Some additional notes are in place here. The China Forestry Statistical Yearbook (2017–2020) no longer separately counts wood used for paper making. The wood used for paper making during 2017–2019 is forecasted by the average year-on-year growth from 2012–2016. For the reason of limitations in data acquisition, the shipping distance from Shanghai port to other regions in Asia is calculated by the average shipping distance from Shanghai port to the largest ports in Japan, South Korea, Thailand, and Singapore. China Urban Construction Statistical Yearbook 2000 does not count the domestic waste landfill rate and incineration rate, and the domestic waste landfill rate and incineration rate in 2000 are extrapolated by the data in 2001.

A list of data parameters and a summary of values used in the whole life cycle carbon accounting of paper products were included in Table 2 below.

Table 2. Summary of data parameters related to CO_2 emissions of paper products.

Data Parameters	Value	Data Parameters	Value
Paper straw availability coefficient (t/t)	0.4500	Coal CO_2 emission factors (tCO_2/t)	1.9003
Straw collectability coefficient (t/t)	0.8300	Coke CO_2 emission factor (tCO_2/t)	2.8604
Grain/straw ratio (t/t)	1.0400	Crude oil CO_2 emission factor (tCO_2/t)	3.0202
Agricultural film CO_2 emission factor (tCO_2/t)	22.7200	Gasoline CO_2 emission factor (tCO_2/t)	2.9251
Rice seed CO_2 emission factor (tCO_2/t)	1.8400	Kerosene CO_2 emission factor (tCO_2/t)	3.0179
Nitrogen fertilizer CO_2 emission factor (tCO_2/t)	1.5300	Diesel CO_2 emission factors (tCO_2/t)	3.0959
Phosphate fertilizer CO_2 emission factor (tCO_2/t)	1.6300	Fuel oil CO_2 emission factor (tCO_2/t)	3.1705
Potash CO_2 emission factors (tCO_2/t)	0.6500	Natural gas CO_2 emission factor (tCO_2/m^3)	0.0022
Compost CO_2 emission factor (tCO_2/t)	1.7700	Electricity CO_2 Emission Factor (tCO_2/kW-h)	0.0010
Herbicide CO_2 emission factor (tCO_2/t)	10.1500	Rail transport CO_2 emission factors (t/t.km)	0.0220
Pesticide CO_2 emission factor (tCO_2/t)	16.6100	waterway transport CO_2 emission factors (t/t.km)	0.0140
Fungicide CO_2 emission factor (tCO_2/t)	10.5700	DOC_f	50%
DOC	40%	F	50%
MCF	50%	FCF	90%
CF	50%	OF	100%

3. Results

3.1. Overall CO_2 Emission Status

The results of accounting for each stage of the whole life cycle of CO_2 emissions of paper products are combined to estimate the CO_2 emissions of the whole life cycle of paper products in China, as shown in Figure 2. The CO_2 emissions of each stage are, in descending order, pulp and paper stage (average share of about 67.95%) > waste paper disposal stage (19.26%) > raw material disposal stage (5.70%) > transportation stage (3.84%) > export paper and board (3.23%). The pulp and paper making and waste paper disposal stages are the main sources of CO_2 emissions for the whole life cycle of paper products, accounting for more than 90%. The growth of CO_2 emissions from exported paper and paperboard means a gradual increase in CO_2 emissions transferred from abroad to China, which not only increases the pressure of energy conservation and emission reduction in China but also exacerbates the contradiction between the lack of paper raw materials and the excess production of paper and paperboard in China's papermaking industry.

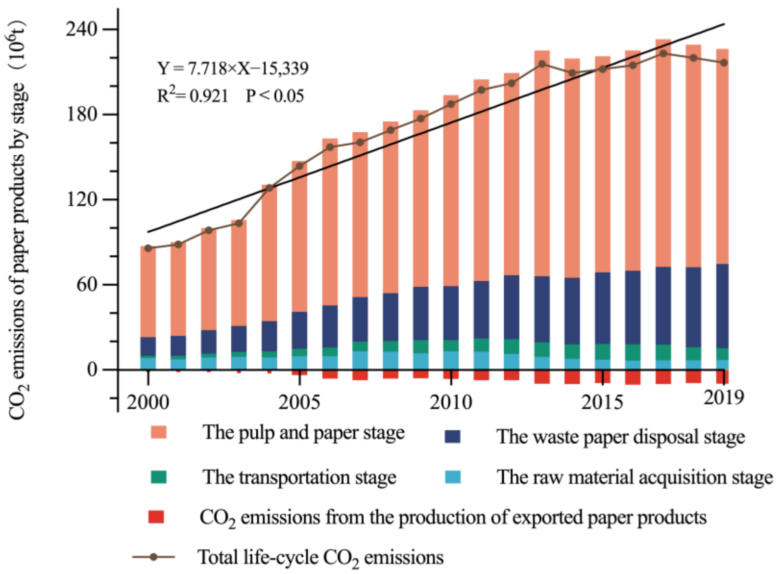

Figure 2. CO_2 emissions from the life cycle of paper products from the perspective of consumer responsibility.

3.2. CO_2 Emission Status of the Raw Material Acquisition Stage

In the raw material acquisition stage, the CO_2 emissions from acquiring non-wood pulp are much higher than those from acquiring wood pulp, see Figure 3. China is also gradually reducing the use of non-wood pulp raw materials, which is in the direction of improving the raw material structure of papermaking in China, and we expect that the CO_2 emissions from acquiring non-wood pulp will continue to show a significant decline.

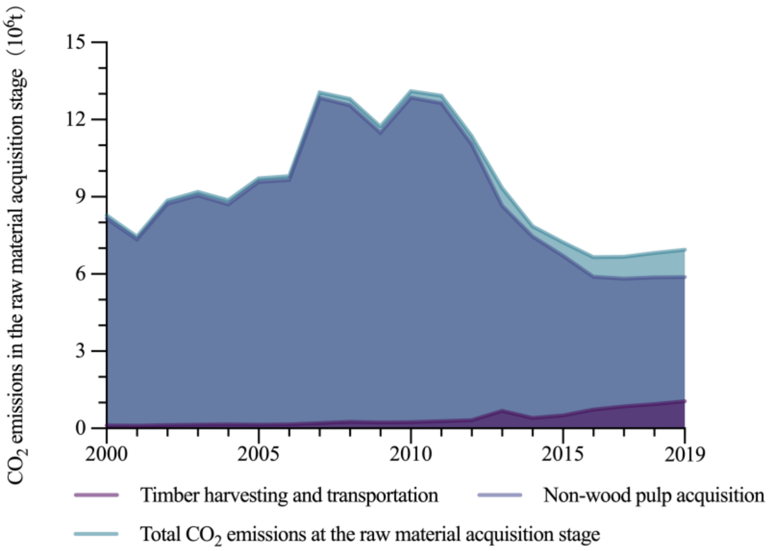

Figure 3. CO_2 emissions from the raw material acquisition stage.

From the accounting results, the CO_2 emissions from wood pulp acquisition rose slightly from 2000–2019, and the opposite for non-wood pulp. Since the CO_2 emissions from non-wood pulp always accounted for the largest proportion, accounting for more than 95% from 2000–2019, the total CO_2 emissions from the raw material acquisition stage continued to decline with the decline in CO_2 emissions from non-wood pulp acquisition. Among them, around 2010, the CO_2 emissions of the raw material acquisition stage rose significantly, mainly due to the continued high prices of imported wood pulp and imported waste paper, resulting in a year-on-year decline in imports and a rise in domestic demand for non-wood pulp. 2013 onwards, the adjustment of the raw material structure of paper production has to some extent reduced the pressure on CO_2 emissions. During the two "2011–2019 Five-Year Plan" period, the proportion of non-wood pulp has been reduced from 13.71% to 6.03% so that the CO_2 emissions of this phase exhibit a certain downward trend. In terms of wood harvesting and transportation, the highest CO_2 emissions are from transporting wood, followed by skidding, and the lowest is from harvesting wood; in terms of CO_2 emissions from various agricultural inputs used in rice cultivation for paper production, fertilizer accounts for 41%, electricity consumption for irrigation accounts for 26%, and CO_2 emissions from diesel and pesticide inputs account for 8–9%, and the CO_2 emissions from the above agricultural inputs in total account for more than 85% of the total emissions from cultivation.

3.3. CO_2 Emissions Status of Pulp and Paper Stage

From an overall perspective, CO_2 emissions from the pulp and paper stage rose from 64.21×10^6 t in 2000 to 151.61×10^6 t in 2019, with an average annual compound growth rate of 4.38% (Figure 4), which is higher than the average annual compound growth rate of 3.79% of China's total CO_2 emissions [2]. While the UK's CO_2 emissions at that stage in 2014 have been reduced by 42% compared to 2008 [50]. Compared to some European countries, CO_2 emissions from the pulp and paper production process in China are still on an increasing trend.

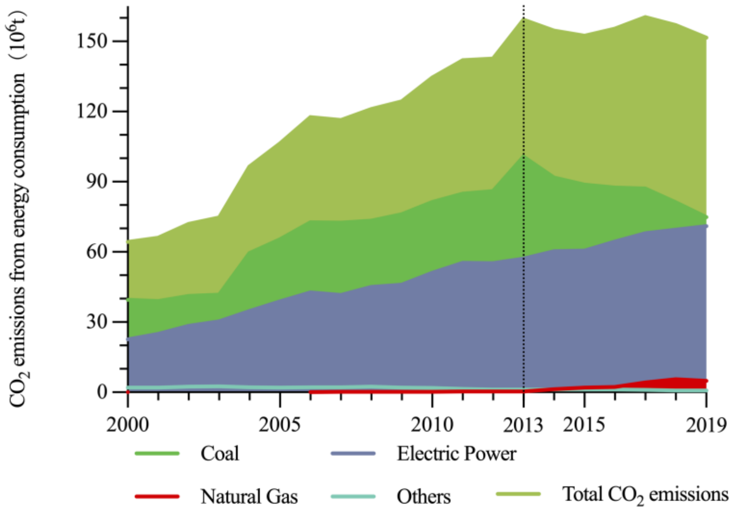

Figure 4. CO_2 emissions from energy consumption in the pulp and paper stage.

Specifically, from 2000–2016, coal, which accounts for more than 75% of total energy consumption, accounted for the highest proportion of CO_2 emissions in the pulp and paper stage, basically remaining at around 60% and still on an upward trend. With the implementation of China's "13th five-year plan" in 2016–2019, the energy structure adjustment has increased, and the proportion of CO_2 emissions from coal in the pulp and paper stage has been reduced to 49.4% by 2019. In 2013, there was a phase peak of CO_2 emissions in the pulp and paper stage, which was attributed to the large increase in coal consumption during this stage, and a slow decline in the Chinese coal price index during the same period, followed by a steep downward trend after the summer, until late in the "12th Five-Year Plan" [51]. The CO_2 emissions share of electricity is above 35%, growing from 22.65×10^6 t in 2000 to 71.04×10^6 t in 2019, with an average annual compound growth rate of 5.88%, higher than that of coal at 3.24%. The sum of CO_2 emissions from coal and electricity accounts for more than 95% of the total CO_2 emissions from the entire pulp and paper stage, while the sum of CO_2 emissions from natural gas and other energy sources accounts for just under 4%. Moreover, according to the European Papermaking Industry Federation CEPI (Confederation of European Paper Industries) [52], data show that in 2016 the European papermaking industry biomass energy consumption reached 58.82%, natural gas consumption accounted for about 33.43%, while coal accounted for only 3.96%. In particular, in the Dutch papermaking industry by 2009 natural gas energy consumption accounted for about 97% [53]. This shows that the energy consumption structure of the pulp and paper stage of China's papermaking industry is still dominated by coal and electricity, and the energy structure adjustment is yet to be strengthened.

3.4. CO_2 Emissions Status of the Transportation Stage

CO_2 emissions from the input of paper raw materials during the transportation phase of paper products mainly include wood pulp, waste paper imports, and domestic waste paper recycling. The results are shown in Figure 5.

Overall, from 2000 to 2020, the total CO_2 emissions from the whole life cycle transportation process of paper products increased from 1.59×10^6 t to a maximum value of 11.16×10^6 t within 2017 and then gradually declined to 8.07×10^6 t in 2020. The high dependence on paper raw material imports is one of the main reasons for the increase in CO_2 emissions during the whole life cycle transportation of paper products. In 2010, CO_2 emissions from transportation declined significantly due to high international pulp and waste paper prices and the accordingly reduced imports of paper raw materials. Comparing the CO_2 emissions of pulp and waste paper import and transportation from 2000–2017, the gap between the two has gradually narrowed. On the one hand, due to the gradual increase in China's waste paper recycling rate, there has been a fluctuating decline in waste paper imports. On the other hand, due to the tight forestry resources, the external dependence on wood pulp remains high and is temporarily difficult to improve, so the CO_2 emissions of wood pulp import and transportation may continue to rise in the future. Influenced by the "Implementation Plan for Prohibiting the Entry of Foreign Waste and Promoting the Reform of Solid Waste Import Management System" released in 2017, the structure of imported raw materials for the papermaking industry is adjusted in 2018–2020, with the gap between pulp and waste paper gradually expanding and showing an opposite pattern to that of 2000–2017. 2000–2020, China's waste paper recycling rate increases from 29.5% to 46.5%, and CO_2 emissions from domestic waste paper recycling transport are slowly increasing, from 0.08×10^6 t in 2000 to 0.41×10^6 t in 2020. Compared with paper raw material import transport, domestic waste paper recycling transport is shorter in distance and the recycling volume is lower than the sum of pulp and waste paper import volume in the same period, resulting in its CO_2 emissions being much lower than the CO_2 emissions from paper raw material import transport in the same period.

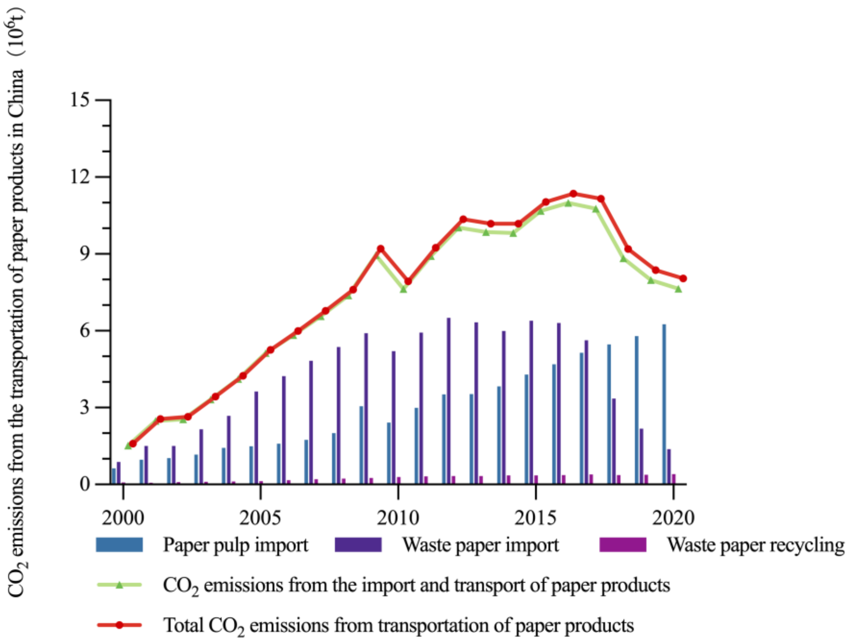

Figure 5. CO_2 emissions from the transportation of Chinese paper products.

3.5. CO_2 Emissions Status of Waste Paper Disposal Stage

The amount of CO_2 released from the waste paper landfill and waste paper incineration segments of the life cycle of paper products in China is shown in Figure 6. At present, the total amount of harmless domestic waste disposal in the country has been rising significantly year by year, and the development trend of incineration volume is similar to it, while the sanitary landfill volume is growing very slowly. In Figure 6, CO_2 emissions from waste paper incineration rise and those from landfill fall, with the former increasing at a compound annual growth rate (CAGR) of 22.17% and surpassing the latter since 2013. The total CO_2 emissions from the waste paper disposal phase also increased, with a CAGR of 7.76%. In comparison, the CO_2 emissions per unit of waste paper landfill are about 0.55 t, while the CO_2 emissions per unit of waste paper incineration are about 1.65 t, so the landfill of waste paper is more conducive to the low carbon development of paper products compared to incineration.

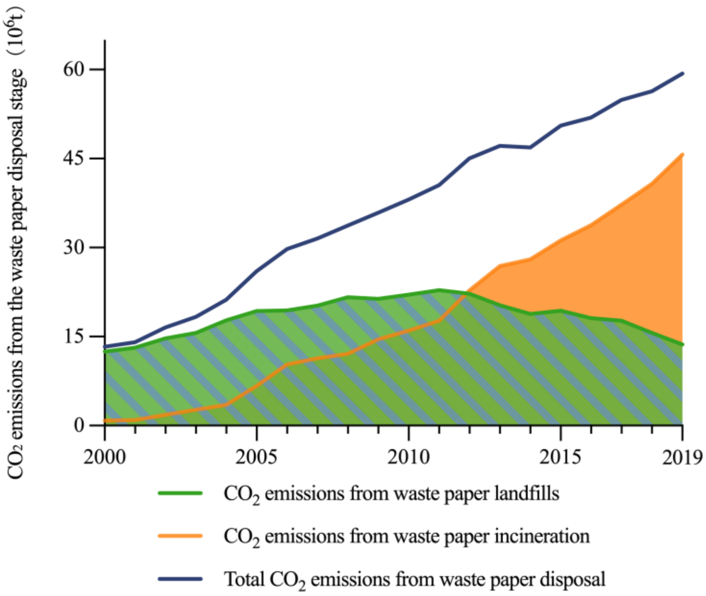

Figure 6. CO_2 emissions from the waste paper disposal of Chinese paper products.

3.6. Export Paper and Paperboard CO_2 Emissions Status

From a consumer responsibility perspective, CO_2 emissions from exported paper and paperboard should be subtracted from the full life-cycle CO_2 emissions of the paper product, which are shown in Table 3.

Table 3. CO_2 emissions from exported paper and board.

Year	Paper and Paperboard Export Volume (10^6 t)	CO_2 Emissions per Unit of Paper and Board Produced (tCO_2/t)	Emissions from the Production of Paper and Paperboard for Export (10^6 t)
2000	0.72	2.11	1.52
2001	0.76	2.06	1.57
2002	0.85	1.90	1.62
2003	1.29	1.74	2.24
2004	1.25	1.95	2.43
2005	1.94	1.90	3.69
2006	3.41	1.81	6.17
2007	4.61	1.58	7.30
2008	4.03	1.52	6.11
2009	4.05	1.44	5.83
2010	4.33	1.45	6.29
2011	5.09	1.43	7.28
2012	5.13	1.39	7.14
2013	6.11	1.58	9.63
2014	6.81	1.48	10.05
2015	6.45	1.42	9.18
2016	7.33	1.43	10.50
2017	6.99	1.44	10.07
2018	6.18	1.50	9.30
2019	6.86	1.41	9.66

3.7. Discussion of the Limitations of Our Analytical Results

The whole-life cycle CO_2 emissions of paper products accounted for in this paper are conservative estimates, and the results of the study are subject to some limitations, mainly including: (1) With regard to the system accounting boundary, CO_2 emissions generated from the consumption of paper and paperboard, CO_2 emissions generated from road construction and repair and production and maintenance of transportation equipment during the whole life cycle transportation of paper products are not included in the accounting system because of the difficulty in obtaining data. (2) In terms of accounting methods, when accounting for CO_2 emissions from domestic waste paper recycling in the transportation stage, it is assumed that the waste paper generated in each of the 16 major paper and paperboard-producing provinces is recycled for pulping within the province, and the distance of this part of waste paper recycling is 0, resulting in negligible CO_2 emissions; the waste paper from the remaining 15 (non-major paper and paperboard producing) provinces is recycled and transported to the nearest major paper and paperboard producing province (region or city), and the distance between the provincial capitals of the two provinces is taken as the distance of waste paper recycling, which may be slightly lower than the actual transportation distance, resulting in lower CO_2 emissions from waste paper recycling and transportation. (3) Some data parameters (such as CO_2 emissions coefficients of different transportation modes) are adopted from relevant European research data, while there are certain differences between the development of China and Europe, which will affect the accuracy of the relevant parameters used. In addition, this paper sets the CO_2 emissions coefficients related to each stage of the study period unchanged, but the corresponding CO_2 emissions coefficients may decrease with the improvement of the technology level in various aspects, which will lead to some errors in the accounting results. (4) Regarding the accounting method of CO_2 emissions used, there are relevant references for CO_2 emissions accounting methods listed in our paper. Among similar studies, CO_2 emissions accounting studies from the perspective of different pulp types are relatively consistent with the results of this paper [7,27]. In addition, the CO_2 emissions trend of the papermaking industry in this article is consistent with the overall situation of CO_2 emissions of the manufacturing industry in China [54], while reflecting the industrial characteristics of low carbon development, transformation, and upgrading of the papermaking industry.

4. Forecast of LCA CO_2 Emissions Scenarios for Paper Products in China

Since the pulp and paper and waste paper disposal stage is the main stage of the whole life cycle of CO_2 emissions of paper products, reduction in CO_2 emissions in the process of pulp and paper and waste paper disposal is the key link to low carbon development of paper products in China. Accordingly, this paper further predicts the whole life cycle of CO_2 emissions of paper products in China from 2020 to 2035 using scenario analysis. Among them, the baseline scenario uses curve fitting to predict CO_2 emissions at each stage of the whole life cycle of paper products, i.e., CO_2 emissions are predicted for each stage of the whole life cycle, and then aggregated into the total CO_2 emissions of the whole life cycle of paper products. Low-carbon scenario I only improves the waste paper recovery rate, otherwise the same as the baseline scenario; low-carbon scenario II only improves the energy consumption structure in the pulp and paper stage, otherwise the same as the baseline scenario; low-carbon scenario III improves both the energy structure and waste paper recovery rate, otherwise the same as the baseline scenario. In terms of scenario parameters, the paper recycling problem is complex and comprehensive, which is reflected in the fact that paper recycling cannot achieve a high recycling rate under the existing circumstances due to the economic structure, paper characteristics, and recycling algorithms in China. In this paper, we set the optimization criteria in the scenario prediction by combining the policy proposal and the impact of the "waste separation" policy on CO_2 emissions in the waste paper disposal stage. Low carbon scenario I sets China's waste paper recycling rate to 74% in 2035 with reference to Europe's waste paper recycling rate of 74% in 2020, and assumes a linear increase in the waste paper recycling rate from 2020 to 2035. For the low carbon scenario II, with reference to the requirements in the outline of the "14th five-year plan" and the 2035 visionary goals for national economic and social development of the People's Republic of China issued by the National Development and Reform Commission, the proportion of non-fossil energy consumption in 2035 is set to be about 20% [55], the proportion of coal consumption is within 49%, natural gas is more than 13%, and oil is about 16% [56]. The total energy consumption of the papermaking industry in this scenario is obtained from the industrial output value and energy intensity, while the energy structure is set to change linearly, where the industrial output value is fitted to the model curve using SPSS software. To avoid the effect of energy intensity effect on CO_2 emissions reduction, the energy intensity is assumed to be the same as in 2016. The scenario projection results are shown in Figure 7.

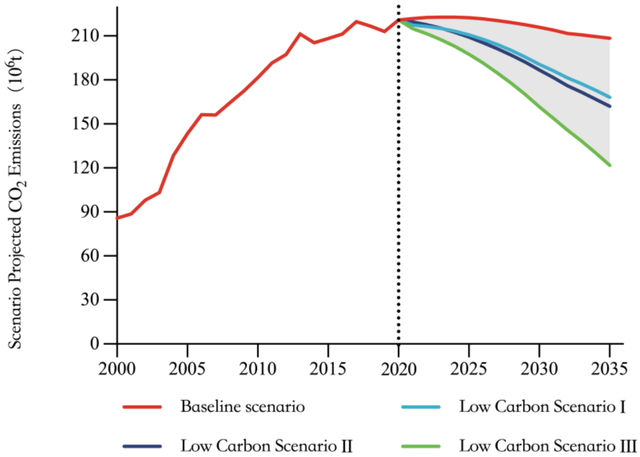

Figure 7. Prediction of CO_2 emissions from life cycle of paper products under the low carbon scenario.

From the predicted results, under the existing policy, CO_2 emissions from paper products in China's papermaking industry will peak around 2025 at about 223 $\times$ 10^6 t, and the peak trend will be very smooth, with CO_2 emissions fluctuating only within 1 $\times$ 10^6 t from 2023 to 2026. In general, improving the energy mix and increasing the recycling rate of waste paper can curb CO_2 emissions throughout the life cycle of paper products. The projections of the baseline scenario show that, under the existing policy background, the systematic and continuous adjustment of the industrial structure of the papermaking industry in China since the "12th Five-Year Plan" has achieved significant results. The emissions reduction effect of low-carbon scenario II based on energy consumption structure is better than that of low-carbon scenario I based on waste paper recycling rate, and the difference in CO_2 emissions reduction between the two is relatively minor. The projection results of low carbon scenario III show that simultaneously improving the energy mix and increasing the waste paper recycling rate are more effective in reducing total CO_2 emissions. Compared with the baseline scenario, the CO_2 emissions reduction of the whole life cycle of paper products from 2021–2035 increases from 49.04 $\times$ 10^6 t to 86.82 $\times$ 10^6 t, which is close to the CO_2 emissions of the pulp and paper stage in 2003–2004, and the emissions reduction contribution rate is also as high as 41.63% in 2035, which is more effective than the effect of low carbon scenarios I and II. In a low-carbon context, the papermaking industry, as a traditional high-energy-consuming and high-emissions industry, can achieve a faster and more effective low-carbon development path.

5. Conclusions

From two dimensions and four stages of reducing CO_2 emissions and increasing carbon sequestration, we propose the following emissions reduction strategy for the whole life cycle of paper products (Figure 8).

(1) The raw material acquisition stage. Combined with the CO_2 emissions accounting and scenario prediction results in this paper, the pulp and paper stage is the stage with the largest share of emissions in the papermaking industry (over 70%). Its energy structure adjustment is the top priority for the low-carbon development of the papermaking industry. Specifically, we propose the following: Firstly, increase the application of cogeneration technology in the papermaking industry. Through cogeneration technology, paper companies can use the steam generated for power generation

in pulp and paper production through temperature and pressure reduction, which can significantly improve the utilization rate of energy and reduce the production costs of paper companies. In this regard, in the European papermaking industry cogeneration power accounted for 96% of the total electricity consumption, China's corresponding proportion on this is less than 50%, hence, the development potential is enormous. Secondly, increase the application of biomass energy. The raw material of the papermaking industry mainly comes from plants. After extracting fiber from plants, in the pulping process by converting the remaining organic matter into biomass energy efficiently, it can significantly reduce the consumption of fossil energy and reduce the emissions of CO_2. In Europe, paper mills have been able to achieve a non-fossil energy consumption ratio of more than 57% by efficiently converting organic matter from paper residues into biomass energy. For example, biodiesel produced by UPM in Finland from the by-products of pulp production can reduce CO_2 emissions by 80% [57]. Some Japanese paper companies make full use of their own biomass resources, while purchasing waste rubber and wood from society and treating municipal waste, so that 100% of their energy consumption is biomass energy, thereby reducing the CO_2 generated by energy consumption.

(2) The pulp and paper stage. This stage requires greater efforts to sort waste in recycling. For example, the three types of waste paper—old newspapers, books, and cardboard boxes—contain different varieties of pulp, and the mechanical and chemical pulp obtained from their recycling has different properties. If a large amount of chemical pulp is mixed into the mechanical pulp, the corrugated boxes produced will become soft and lose their original load-bearing and pressure-resistant capacity. So, the stronger and more detailed the classification of all types of waste paper, the higher the value it will produce. With China's waste paper nearing the limit of recyclable volume, greater recycling and sorting efforts can provide new ideas for reducing CO_2 emissions.

(3) The waste paper disposal stage. Although "the policy of banning waste imports" has led to a significant reduction in CO_2 emissions from imports, the imbalance between supply and demand has led to high prices of waste paper raw materials and serious adulteration, so many paper companies have had to revise their waste paper acquisition quality standards, which has had a series of adverse effects on the papermaking industry. In response to the problem, it is recommended "the policy of banning waste imports" to refine the import of solid waste to avoid "one-size-fits-all". From the perspective of circular economy and environmental protection, China's own exports take away the packaging and instructions and other paper products through the import of the way to recycle is a more scientific and more environmentally friendly choice.

(4) The transportation stage. First, increasing sustainable management of forests. With the certification of forest certification organizations, we can effectively reduce CO_2 emissions by supervising and managing the entire value chain from forest management to paper product production then to consumer recycling. Second, promote the "forest-pulp-paper integration" model, effectively reducing CO_2 emissions from the raw material acquisition stage of the aggregation and transportation operations. Third, promote the optimal rotation period system for forests, choose suitable tree species according to local conditions and maintain a reasonable forest age structure so that the forest can absorb the maximum amount of CO_2. Fourth, to reduce the use of non-wood pulp in the proportion of rice-wheat straw pulp. The use of rice-wheat straw pulp is an important reason for the relatively large proportion of CO_2 emissions in the pulp and paper stage. Promoting the clean production of reed raw materials and other pulp and paper can effectively reduce CO_2 emissions. In addition, the use of bamboo pulp and paper is also an effective path to reduce CO_2 emissions.

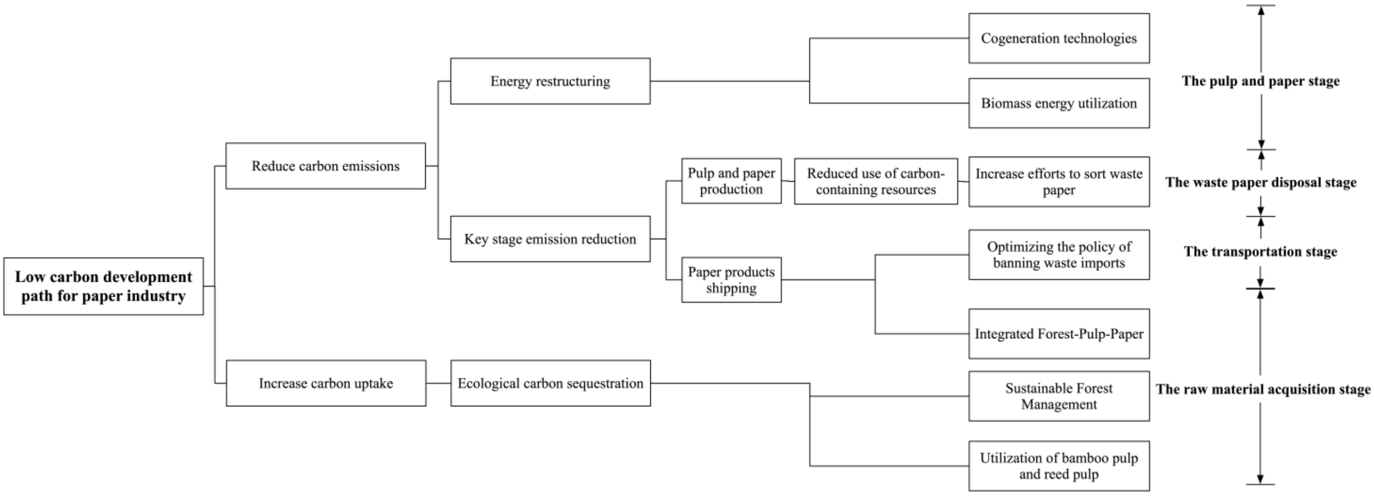

Figure 8. Low carbon development route map for the whole life cycle of papermaking industry.

To achieve the Sustainable Development Goals and the emission reduction targets in the INDC framework for China's papermaking industry we will need to study more aspects beyond our current article's focus on CO_2 emissions. The outlook from "a tree" to "a piece of paper" suggests that the whole industry chain involves more than just CO_2 emissions. In the future, we look forward to conducting more research on forests, natural gas, and biomass to promote sustainable development and achieve clean production.

Nowadays, China's papermaking industry is gradually developing into an industry with recyclable resources, low energy consumption, and low emissions, but there is still a large gap in industrial structure and energy utilization efficiency compared to developed countries' papermaking industry. For a long time to come, China's low-carbon development path must always adhere to the concept of green development, synergize technology, management, finance, and other multiple means.

Author Contributions: J.Y. (Jiameng Yang) conceptualization, formal analysis, validation, supervision; Y.H. methodology, data curation, writing—original draft; J.Y. (Jiarong Ye) investigation, visualization; S.X. writing—original draft; Z.L. formal analysis, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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