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Hybrid Fuels Enhance Sustainability and Economics of Cement Manufacturing

Jinqiang Liang [1], Qi Zhang [1], Jiahui Li [1], Yukun Mei [1], Duiping Liu [2], Jibin Zhou [2], Zhishuang Pan [3], Danzhu Liu [2], Majid Khan [4], He Huang [5,*] and Mao Ye [2,*]

1 Engineering Institute, China University of Petroleum-Beijing at Karamay, Karamay 834000, China
2 Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 834000, China
3 Lanzhou Chemical Research Center of China National Petroleum Corporation, Lanzhou 73000, China
4 University of Science & Technology Beijing, Beijing 100083, China
5 College of Chemical Engineering, Xinjiang University, Urumqi 830017, China
* Correspondence: xjuhuanghe@xju.edu.cn (H.H.); maoye@dicp.ac.cn (M.Y.)

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Abstract: The conventional cement production is characterized by energy-intensive and relies heavily on fossil fuel, resulting in substantial CO_2 emissions. Substituting fossil fuels with alternative energy sources is therefore essential for improving process efficiency and reducing the carbon footprint of cement manufacturing. In this study, six representative alternative fuels—including oily sludge, biomass, waste tires were assessed at thermal substitution rates (TSR) of 10%, 20%, 30%, and 40%. A total of 25 combustion scenarios were modeled were to evaluate their effects on clinker production, CO_2 emissions, energy efficiency, and techno-economic performance. The simulation results show that alternative fuels can not only effectively reduce coal consumption but also improve energy efficiency. Under the same condition of heat value, in the 10% waste tire A substitution scenario, coal consumption is reduced to 17,325 kg/h, and in the 40% waste tire B substitution scenario, coal consumption is reduced to 11,550 kg/h. The oily sludge-based alternative fuels exhibit the most significant enhancement in cement clinker yield, followed by biomass and waste tire B. Waste tire A is similar to the cement clinker output of conventional cement production. In terms of CO_2 emissions, in the 40% oily sludge B substitution scenario, compared with the conventional cement production process, CO_2 emissions are reduced by 118,300 tons, relative to the conventional cement production process, representing a 13.17% reduction. In terms of economic performance, a high proportion of oily sludge substitution can reduce the conventional cement production cost by 392.89 CNY/t to 358.45 CNY/t, reduced by 8.77%. Alternative fuels play a crucial role in significantly enhancing energy efficiency and promoting decarbonization. Notably, oily sludge demonstrates optimal techno-economic performance, providing critical parameters for industrial-scale solid waste co-processing.

Keywords: fuels substitution; cement production; oil sludge; biomass; waste tires; aspen simulation

1. Introduction

As the core material of modern architecture, cement plays an important role in human development and social progress [1–3]. As the pillar industry of modern economic system, the importance of cement production and cement industry is reflected in many dimensions. It not only acts as a fundamental underpinning for the construction sector, but also the core driving force [3,4] of the national industrialization and urbanization process.

China's cement output has consistently maintained its position as the world's largest producer [5]. In 2024, the annual average output of cement in China reached 1.825 billion tons, accounting for 46.97% of the total global cement production.

The traditional cement industry confronts pressing challenges, including high energy consumption, high carbon dioxide emissions and overcapacity. Meanwhile, environmental pollution caused by the cement industry has become increasingly prominent. Energy consumption of cement production accounts for 2~3% of the global industrial energy consumption, with 60~70% derived from coal-fired combustion—a factor that exacerbates fossil fuels depletion and intensifies energy security pressures. The excessive exploitation of mineral resources has resulted in the destruction of mountains and biodiversity loss. Open-pit mining has led to the destruction of vegetation and soil erosion. The restoration cycle is as long as decades. The restoration of mines lags behind. Among the 15,000 limestone mines in China, the greening rate of historical mines remains below 20%. Geological collapse has occurred in some mining areas in China due to over-exploitation. Cement plants are mostly built on mines, and the pollution superposition effect is significant, such as the formation of "pollution corridors" in Hebei and Shandong. The operation cost of facilities such as dust removal and denitrification accounts for 15–20% of the production cost, which is difficult for small and medium-sized enterprises to bear, and the phenomenon of illegal discharge occurs frequently. Therefore, the development of green and sustainable cement production process to reduce the damage of cement production to the environment and resources is an important direction for the future development of cement industry [6]. Energy-saving and emission reduction technologies for cement production mainly include energy efficiency enhancement, fuel substitution and application of alternative raw materials [7–10].

Xing et al. [11] investigated the carbon emissions from the co-disposal of hazardous waste, domestic waste and general solid waste in cement kiln and conventional cement production, and reported that the maximum carbon dioxide emission of conventional cement production was 883.65 kg/t, and the minimum carbon dioxide emission of co-disposal of domestic waste and secondary hazardous disposal waste was 609.79 kg/t. Fuel substitution is sufficiently effective to achieve carbon dioxide emission reduction in cement production. Mancini et al. [12] employed Aspen Plus software to simulate the entire cement production process and assess the feasibility of using waste plastics as alternative fuels under oxy-fuel combustion conditions. Three schemes-air combustion, air combustion coupled with flue gas recirculation, and oxy-fuel combustion with flue gas recirculation were examined, while analyzing their and the energy efficiency and economic performance. Turakulov et al. [13] examined cement production, amine-based CO_2 absorption, membrane-based CO_2 separation, and waste heat recovery systems to assess their techno-economic and environmental impacts. The study defined the design parameters for each unit and quantified the investment and operating costs. Li et al. [14] proposed a hybrid design to optimize the waste-to-energy process by combining hydrothermal treatment of sludge and plasma gasification of medical wastes with waste heat recovery from cement plants. He et al. [15] simulated the process of converting 1 million t/a phosphogypsum into sulfuric acid with co-production of cement, and verified the feasibility of the process of phosphogypsum to sulfuric acid and co-production of cement, which can provide data support for actual production operation and process optimization. Niu et al. [16] focused on a dry-process cement production line with a clinker output of 3000 t/d, employed Aspen Plus software to establish the process flow model of cement production system with oxygen-enriched combustion transformation, and studied the system energy efficiency and CO_2 capture cost of cement clinker production with oxygen-enriched pulverized coal combustion. Based on Aspen Plus, Justin G et al. [17] established a cement calciner model with biomass as an alternative fuel. Poplar was chosen as a representative forestry biomass to substitute 40% of coal. Under the condition of low-temperature gasification in a fluidized bed, the gasification temperature was 550 °C, the equivalence ratio was 0.2, and the moisture content of biomass was 12.5%. The NO emission concentration reached the minimum value of 442.91 mg/m^3. Currently, research on the utilizing oily sludge as a substitute for traditional coal fuel in cement industry mainly focuses on the combustion characteristics of the fuel, the pollutants produced by combustion and the quality of clinker; however, research on the whole process simulation of the cement production process using oily sludge as a coal fuel substitute remains scarce. A few enterprises use oily sludge to substitute part of coal in production, yet the replacement rate remains extremely low [18,19]. In addition, there are still many difficulties in replacing raw materials and fuels, in which the replacement rate of steel slag is only 15%, and the cost of construction waste pretreatment is high (≥¥80 CNY/ton), posing a barrier to resources recycling. Moreover, other hazardous components in the fuel produce secondary pollution after combustion, which causes health risks to the residents around the cement plant.

The application of alternative raw material technology in cement production can not only reduces the exploitation of natural raw materials, but also effectively enables the effective utilization of industrial waste, lowers production costs and environmental impact. Common alternative raw materials include fly ash, slag, steel slag and other industrial by-products. The application of these raw materials in cement production has been widely studied and comprehensively practiced. For example, Ibrahim et al. [20] reviewed the utilization status of industrial by-products in cement production, and pointed out that these alternative raw materials have significant advantages in enhancing cement performance and reducing carbon emissions. Huang et al. [21] further explored the environmental benefits of these alternative raw materials, with a focus on their importance in sustainable cement production. Arne et al. [22] analyzed the application technology and challenges of alternative raw materials in cement production, thereby providing a direction for future research. Li et al. [23] analyzed the carbon emission reduction effect of alternative raw material technology by taking carbide slag, calcium silicate slag and steel slag as examples, and pointed out that alternative raw material technology will become an important emission reduction means for China's cement industry to cope with climate change.

The traditional cement production process is plagued by high energy consumption and substantial carbon emissions. The adoption of fuel substitution technology addresses this challenge and advances the sustainable development of the industry. Numerous alternative fuels are available for the cement industry, among which oily sludge exhibits a high calorific value [24–26] and is rich in inorganic minerals. Replacing traditional fuel coal with oily sludge as a fuel enables energy conservation and increases production efficiency in the cement production process. In this study, the comprehensive performance of six alternative fuels for cement production was systematically evaluated, and a full-process Aspen model of the whole process was established, considering the multi-objective optimization of production, emissions, economics and other key metrics, the optimal alternative scheme based on actual working conditions was proposed. Taking dry-process cement production as a case study, a novel technical route for cement production process was designed, and a process model of cement production was established by Aspen Plus software to simulate the cement production process with six distinct alternative fuels, such as oily sludge, biomass and waste tires. The impacts of fuel substitution ratio and oxygen concentration on energy efficiency, cement output and carbon dioxide emissions were investigated, while the technical and economic performance of various fuels was compared and analyzed. Through detailed process simulation and comprehensive techno-economic analysis, the application potential of various alternative fuels in cement production was evaluated. This study has focused not only on production yields and costs, but also on environmental impacts, especially the reduction of carbon dioxide emissions. Furthermore, sensitivity analysis enhances the practicality of the study and provides valuable insights for the sustainable development of the cement industry. The fuel substitution process for cement production is illustrated in Figure 1.

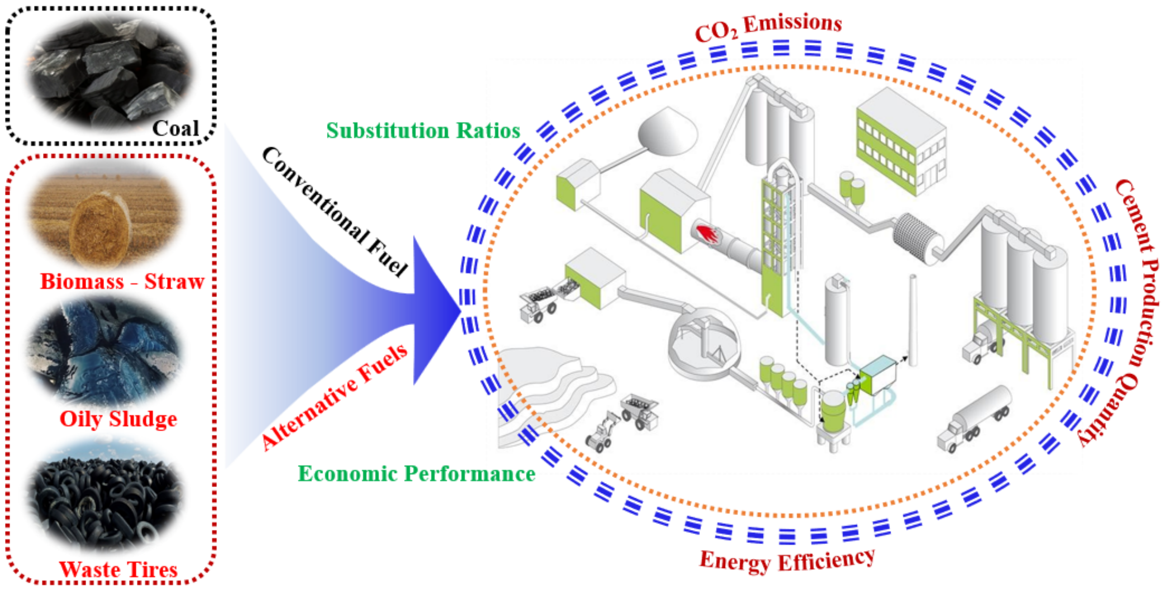


Figure 1. Fuel substitution process for cement production.

2. Process Model

The conventional cement production process involves that raw materials are ground into powdery raw materials by dry grinding before entering the rotary kiln, and are directly sent to the rotary kiln for calcination. Compared with the wet cement production process, the dry cement production process has lower energy consumption and higher production efficiency; thus, it [27] is predominantly adopted in modern cement production. Cement production mainly includes raw material pretreatment, preheating, decomposition, calcination, cooling, grinding, dust removal, transportation, packaging and other auxiliary processes. The detailed cement production process route is shown in Figure 2. Its core equipment includes cyclone preheater, decomposition furnace, rotary kiln, grate cooler and auxiliary production equipment.

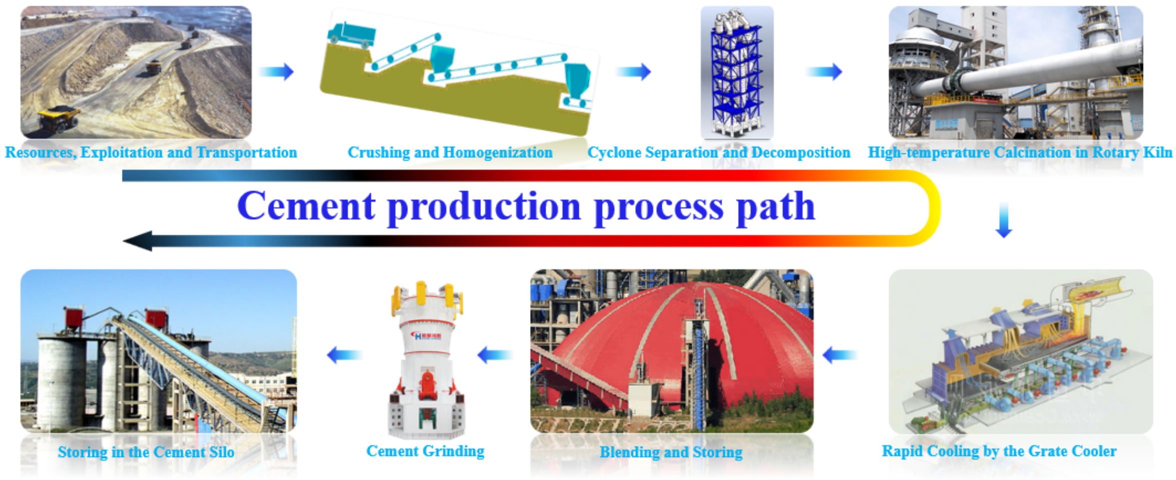


Figure 2. Cement production process route.

2.1. Reaction during Cement Production

The main chemical reactions in the cement production process are shown in formulas (1)–(6) [28], in which formulas (1)–(2) predominantly take place in the decomposition furnace. Magnesium carbonate and calcium carbonate decompose under the heat released by the combustion of pulverized coal, producing substantial amounts of carbon dioxide [29]. The temperature of 600 °C, magnesium carbonate begins to decompose, and at 800 °C, calcium carbonate begins to decompose [30]. Reactions (3)–(6) are solid phase sintering reactions and take place in the rotary kiln, i.e., cement clinker is mainly produced in the rotary kiln. Additionally, in the industrial production of cement, besides Reactions (1)–(6), the combustion heating reaction of fuel also occurs [28–30].

$$600\ ^{\circ}C\sim750\ ^{\circ}C:\ MgCO_3 \rightarrow MgO + CO_2 \Delta H_{1023K} = 1421\ (kJ/kg) \quad (1)$$

$$800\ ^{\circ}C\sim900\ ^{\circ}C:\ CaCO_3 \rightarrow CaO + CO_2 \Delta H_{1173K} = 1655\ (kJ/kg) \quad (2)$$

$$2CaO + SiO_2 \rightarrow 2CaO \cdot SiO_2 (C_2S) \Delta H_{1573K} = -619\ (kJ/kg) \quad (3)$$

$$12CaO \cdot 7Al_2O_3 + 9CaO \rightarrow 7\ (3CaO \cdot Al_2O_3)(C_3A) \Delta H_{1573K} = -347\ (kJ/kg) \quad (4)$$

$$7(2CaO \cdot Fe_2O_3) + 2CaO + 12CaO \cdot 7Al_2O_3 \rightarrow 7\ (4CaO \cdot Al_2O_3 \cdot Fe_2O_3)(C_4AF) \Delta H_{1573K} = -109\ (kJ/kg) \quad (5)$$

$$C_2S + CaO \rightarrow C_3S (C_3S) \Delta H_{1573K} = -1.55\ (kJ/kg) \quad (6)$$

The solid-phase reaction occurs at 900~1300 °C, and C_2S, C_3A, C_4AF and other minerals in the clinker are generated. When the temperature of the material rises to about 1300 °C, C_2S and CaO are dissolved in the liquid phase, and the minimum temperature for the formation of C_3S is 1350 °C. At 1450 °C, the majority of C_3S is formed. The main mineral components of clinker are C_3S, C_2S, C_3A and C_4AF. C_2S (dicalcium silicate) is the primary contributor to the strength of cement clinker in the middle and later stages, C_3S (tricalcium silicate) is the main contributor to the early strength, C_3A (tricalcium aluminate) provides the early strength, and C_4AF (tetracalcium aluminoferrite) reduces the melting temperature of clinker, contributes to the formation of CS and saves energy. After exiting the kiln, clinker is rapidly cooled in a grate cooler effectively maintain its mineral composition and activity [28,30]. After the cooling, clinker is ground with an appropriate amount of gypsum and other materials to produce a finished cement product. The core processes of cement production—raw materials decomposition and clinker—consume considerable amounts of heat. Traditional cement production obtains heat via coal combustion.

2.2. Raw Materials and Fuels

Coal and alternative fuels are dried and pulverized prior to entering the decomposition furnace and rotary kiln. The moisture content of the dried coal powder and alternative fuels is approximately 1.75%. The alternative fuels commonly adopted in the cement industry include waste plastics, municipal solid waste, biomass, oily sludge, waste tires, and related materials. Among these, oily sludge renatures a broad source distribution, primarily including crude oil exploitation, oil and gas transportation, oil refining and other processes. During crude oil exploitation, ground oil sludge and drilling oil sludge are produced, and in the process of oil and gas transportation, tank cleaning sludge will be produced around the dehydration tank and oil storage tank. In the process of oil refining, sewage treatment is needed, and a large amount of refinery sludge will be produced in the oil separation tank, air flotation tank and aeration production tank. Three kinds of oily sludge with different calorific values and one kind of biomass (corn straw) were selected as alternative fuels for simulation analysis. Oily sludge A is the scum from a certain treatment plant in Liaohe Oilfield [24]. Oily sludge B is the tank cleaning sludge from an oil refinery in Jinan City [25]. Oily sludge C is sourced from the Petrochemical Wastewater Treatment Plant of Liaohe Oilfield in Panjin City, Liaoning Province [26]. Biomass is sourced from rubberwood [31,32]. Waste tires encompass two distinct types. The composition analysis is detailed in Table 1.

Table 1. Composition analysis of coal, oily sludge, biomass and waste tires [24–27,31–35] wt%.

Sample	Proximate Analysis			Ultimate Analysis				
	Fixed Carbon	Volatile Matter	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
Coal	56.85	29.21	12.30	71.21	4.23	8.46	1.28	0.74
Oily Sludge A	10.55	54.98	28.79	47.93	6.58	6.64	2.81	1.57
Oily Sludge B	15.06	53.77	31.07	48.40	4.23	10.71	1.53	2.80
Oily Sludge C	9.03	68.88	20.72	63.49	7.91	4.99	0.86	0.67
Biomass	19.20	80.10	0.70	50.60	6.50	42	0.20	0.00
Waste Tires A	30.00	55.00	13.50	75.00	7.00	2.70	0.30	1.50
Waste Tires B	33.84	60.05	6.11	83.07	6.48	1.95	0.47	1.92

The calorific values of the seven fuels were calculated by the average method [25]. The calorific value of coal is 28.19 MJ/kg. Due to the different oil content of different oily sludge, the heat generated by its combustion varies, resulting in distinct measured calorific values. The calorific values of the three selected oily sludges are 23.69 MJ/kg, 20.10 MJ/kg and 31.04 MJ/kg respectively, the calorific values of the oily sludges A and B are lower than those of the coal, the calorific value of the oily sludge C is slightly higher than that of the coal, and the calorific value of the biomass is 18.26 MJ/kg lower than that of the oily sludge A. The average calorific values of waste tires A and B were 34.14 and 36.34 MJ/kg, respectively, which were higher than those of oily sludge C and coal. This study focuses on energy saving and yield increase in the cement production process. Therefore, the ash composition of each fuel after complete combustion is taken into account. The ash of coal, oily sludge and biomass fuel contains SiO_2, CaO, Fe_2O_3 and Al_2O_3, which are the raw materials for cement production. The ash produced by fuel combustion further participates in the solid phase reaction of cement clinker [31–35]. The ash content of the three kinds of oily sludge is 28.79 wt%, 31.07 wt% and 20.72 wt% respectively- significantly higher than that of coal. Therefore, using oily sludge as a replacement for traditional fuels enables production enhancement. However, the industrial analysis of corn straw shows high contents of fixed carbon and volatile matter, with an ash content is only 0.70 wt%. The total mass of the alternative fuel is determined according to the substitution proportion, and the alternative fuel enters the decomposition furnace and the rotary kiln respectively according to 70% and 30% of the mass proportion.

2.3. Model Establishment

Cement production process requires considerable amounts of heat, which is provided by the combustion of pulverized coal in conventional cement production. The combustion of pulverized coal takes place in the decomposition furnace and rotary kiln. The RYield reactor (RYield) and Gibbs reactor (RGibbs) modules are employed to simulate the combustion process. Coal is first decomposed into conventional components (C, H, O, N, S, etc.) And unconventional component ash in the RYield reactor, and the decomposed products enter the RGibbs reactor to reach the reaction equilibrium with the minimum Gibbs free energy. Coal powder and its ash are defined as unconventional substances, and the enthalpy and density of coal are calculated by HCOALGEN and DCOALIGT models, respectively. The ash comprises abundant CaO, SiO_2, Al_2O_3 and Fe_2O_3, which are raw materials for cement production. The ash composition of coal, oily sludge, biomass and waste tires after complete combustion is shown in Table 2 [36–39].

Table 2. The ash composition after complete combustion of coal, oily sludge, biomass and waste tires.

Items	SiO_2	CaO	Fe_2O_3	Al_2O_3	Others
Coal	41.34	10.29	3.45	25.77	19.15
Oily sludge	13.30	6.75	20.15	10.35	49.45
Biomass	13.15	10.25	0.34	0.18	76.08
Waste tires	15.16	6.12	10.08	4.25	64.39

Different oily sludges have different oil content, so the amount of ash produced is different. The composition of ash is closely related to the sources of oily sludges. In this study, the ash composition of oily sludge after complete combustion is assumed to be the same. The ash of oily sludge after complete combustion also contains some heavy metals, such as nickel and vanadium, which originate from the residues of petroleum components. In addition to the four components in Table 2, the ash [40–42] after complete combustion of biomass abounds in potassium carbonate, especially straw biomass, which accounts for about 20–40% of the total ash weight, as well as 2–8% magnesium oxide and 2–10% phosphorus pentoxide. The ash of waste tires after complete combustion is rich in zinc oxide, which mainly derives from the additives of tires and is used to promote vulcanization, representing approximately 40–60% of the total ash mass, and the products after combustion contain sulfur trioxide. The focus of this study is to investigate the impact of fuel substitution ratio and oxygen concentration on energy efficiency, cement production and carbon dioxide emissions, and to compare and analyze the technical and economic performance of different fuels. Therefore, the impact of trace metals on cement production process is not considered; however, in actual production, it is necessary to fully take into account the implications of key process risks such as ash, heavy metal migration and alkali metal skinning on the use of alternative fuels such as sludge.

Taking the production of 1 million tons of cement clinker per year as an example, the annual working time is 8000 h, and the cement production process model was established by Aspen Plus software. The temperature of the decomposition furnace is 900 °C, and the flue gas from the decomposition furnace exchanges heat with the raw materials to preheat the raw materials to 800 °C. The temperature of the rotary kiln is 1450 °C [42–44]. The clinker enters the grate cooler and is cooled by air. The secondary air reaches 1100 °C and the tertiary air reaches 650 °C. Finally, the clinker is cooled to below 90 °C [45,46] after leaving the cooling system. Based on the above design, the simulation flow chart of cement production process is established in Figure 3.

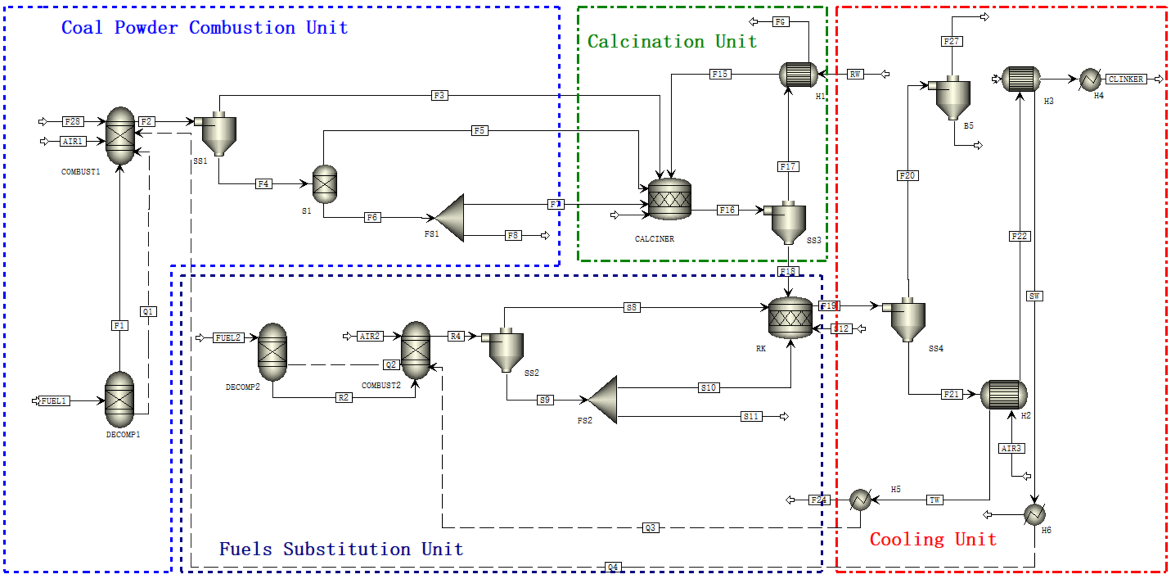


Figure 3. Simulation flow chart of cement production process.

The simulation process mainly includes four parts: raw material pretreatment unit, Pre-Decomposition Unit of decomposition furnace, rotary kiln calcining unit and grate cooler quenching unit. In Figure 3, the blue and purple dashed boxes represent the pretreatment and decomposition units for pulverized coal and alternative fuels, the green dashed box is the rotary kiln calcination unit, and the red dashed box is the grate cooler quenching unit. Cement production mainly includes the processes of raw meal preparation and decomposition, clinker firing and grinding. In the cement production, the raw materials such as limestone, sandstone, steel slag and fly ash are prepared according to the production requirements, and then ground. After raw material preparation and decomposition, the clinker is fired through the rotary kiln of the pre-decomposition furnace. After cooling, the clinker is ground and sent to the clinker silo. The key equipment and its operating parameters are shown in Table 3.

Table 3. List of key equipment parameters.

Equipment	Equipment Number	Model	Operating Parameters
Reactor	Decomp1	RYield	T = 25 °C, P = −50 Pa
Coal Power Decomposition Furnace	Combust1	RGibbs	P = −50 Pa, t = 3~5 s
Reactor	Decomp2	RYield	T = 25 °C, P = −50 Pa
Alternative Fuel Decomposition Furnace	Combust2	RGibbs	P = −50 Pa, t = 3~5 s
Separator	FS1	SSplit	0.81
Limestone Decomposition Furnace	Calciner	RStoic	T = 900 °C, P = −50 Pa, t = 3~5 s
Heat Exchanger	H1	HeatX	T = 800 °C, P = 0.1 MPa
Rotary Kiln	RK	RStoic	T = 1450 °C, P = −50~20 Pa, t = 20~30 min
Grate Cooler	H2	HeatX	T = 1100 °C, P = −30~20 Pa
	H3	HeatX	T = 650 °C, P = −30~20 Pa
	H4	Heater	T = 90 °C, P = −30~20 Pa
	H5	Heater	T = 25 °C, P = −30~20 Pa
	H6	Heater	T = 25 °C, P = −30~20 Pa

3. Results and Discussion

The temperature of calciner in traditional cement production model is 880~900 °C, the temperature of rotary kiln is 1450 °C, the output of clinker is 1.0×10^6 t/a, the cement production scale is of medium scale, the coal consumption is 19,250 kg/h, the calorific value of coal is 28.06 MJ/kg, and the cement output is 1.0×10^6. Coal consumption per unit clinker production is 97.60 kgce/t, which is lower than the national standard for comprehensive coal consumption (103.5 kgce/t) [47]. In order to better describe the six fuels and their substitution ratios, 25 processes were designed based on different combinations, and the corresponding process routes and numbers are shown in Table 4.

Table 4. List of process routes and corresponding numbers.

NO.	Processes	NO.	Processes	NO.	Processes
1	Traditional cement production	10	10% oily sludge C	19	20% Waste Tires A
2	10% oily sludge A	11	20% oily sludge C	20	30% Waste Tires A
3	20% oily sludge A	12	30% oily sludge C	21	40% Waste Tires A
4	30% oily sludge A	13	40% oily sludge C	22	10% Waste Tires B
5	40% oily sludge A	14	10% Biomass	23	20% Waste Tires B
6	10% oily sludge B	15	20% Biomass	24	30% Waste Tires B
7	20% oily sludge B	16	30% Biomass	25	40% Waste Tires B
8	30%oily sludge B	17	40% Biomass		
9	40% oily sludge B	18	10% Waste Tires A		

3.1. Key Stream Results

According to Figure 4, six alternative fuels and four different substitution ratios constitute 25 scenarios. The first scenario is the traditional cement production scenario, and the remaining 24 scenarios are fuel substitution scenarios. The key stream outputs of three key equipment units (calciner, rotary kiln and grate cooler) are analyzed in the Aspen model. The mass flows of key components of the main streams are shown in Figure 4.

Through comprehensive comparison and analysis, it is evident that the quality of the high-temperature cement clinker produced after high-temperature melting and firing in the rotary kiln is consistent with that of the cement clinker cooled by the grate cooler, but is higher than that of the cement raw meal calcined at high temperature in the decomposition furnace, because the ash after fuel combustion in the rotary kiln enters the cement clinker, thereby enhancing its quality. The calorific value of different fuels varies, the fuel quality required under the same calorific value substitution ratio differs, and the ash composition of different fuels after combustion is different, which constitutes the difference of cement clinker quality. The differences in cement clinker quality are reflected in the key stream parameters, as shown in Figure 5.

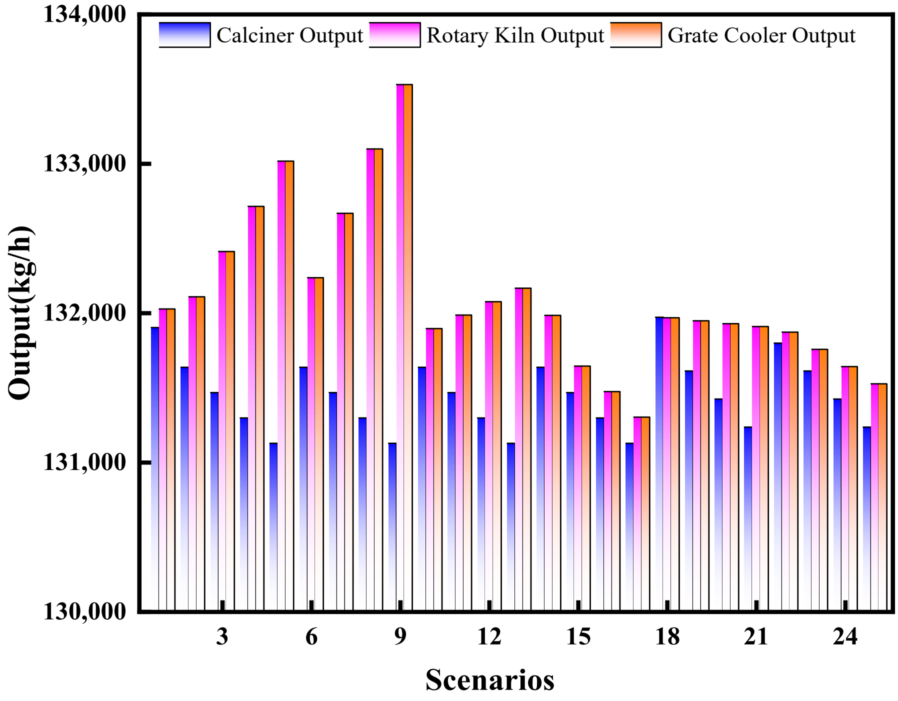
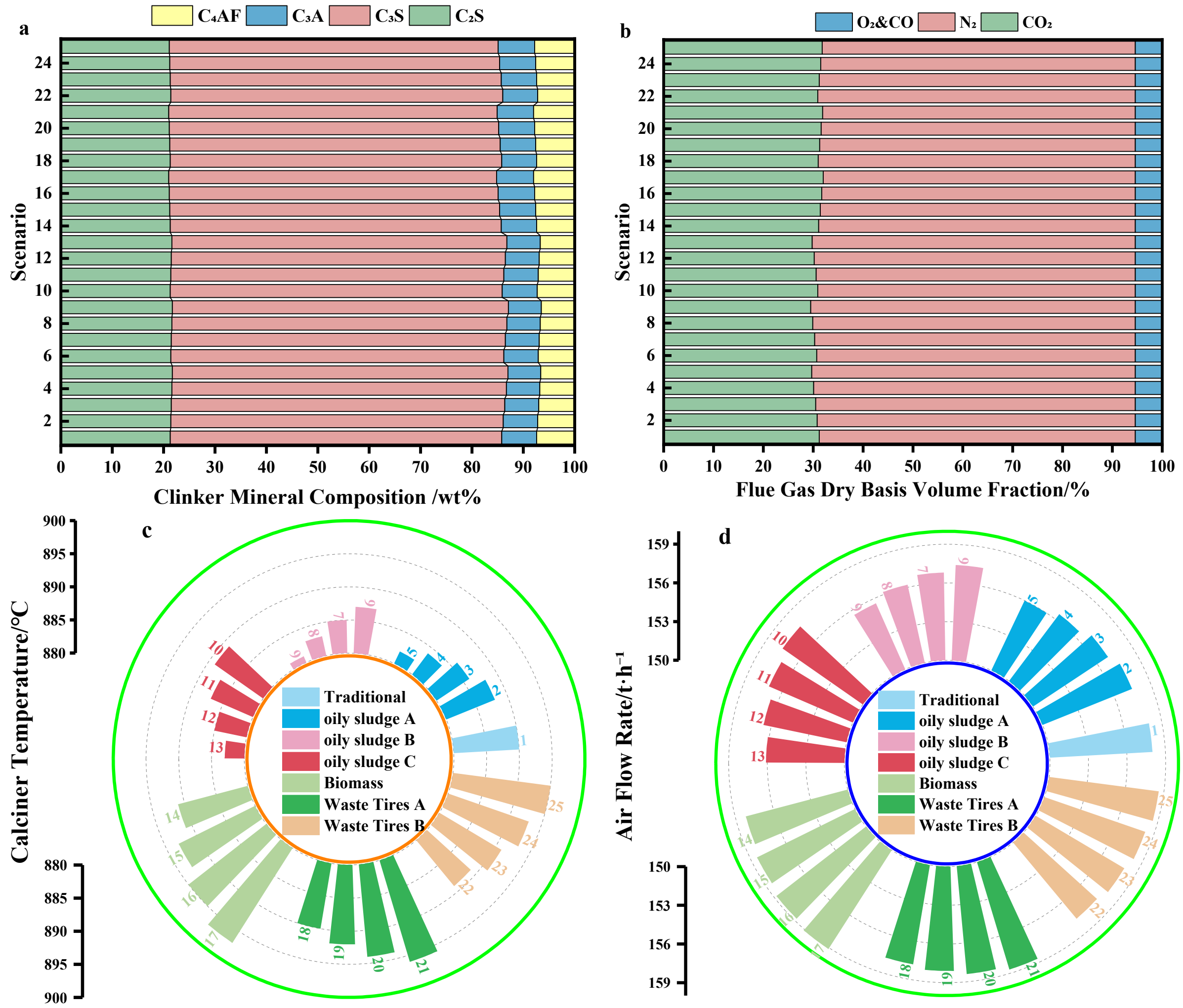


Figure 4. Key stream quality flow rates.



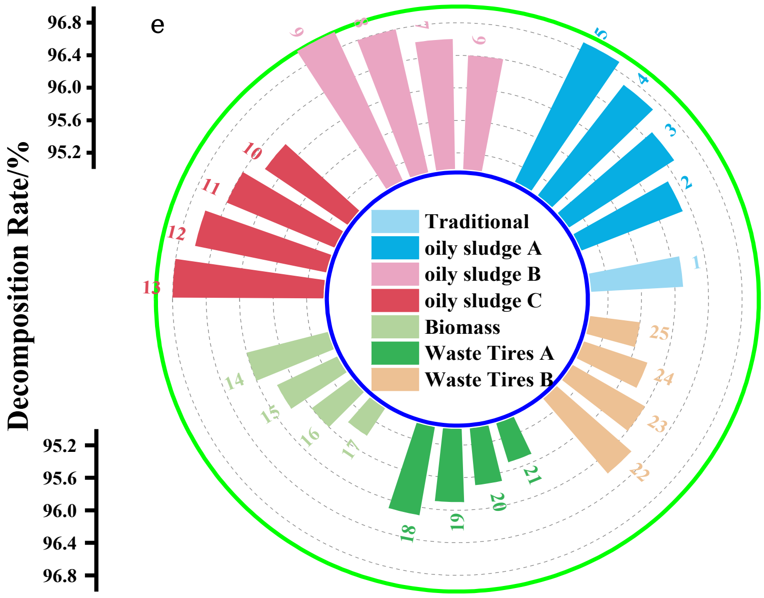


Figure 5. Parameters of Key Stream. (**a**) Clinker Mineral Composition/ wt%; (**b**) Flue Gas Dry Basis Volume Fraction/%; (**c**) Calciner Temperature/°C; (**d**) Air Flow Rate/t·h^{-1}; (**e**) Decomposition Rate/%.

3.2. Energy Consumption

The energy consumption during cement production is mainly concentrated in the stages of pulverized coal combustion, raw meal preheating, clinker calcination and cooling [47–49]. Traditional cement production primarily depends on coal combustion for heat supply, while the application of fuel substitution technology can markedly alter the energy consumption structure, improve energy efficiency and reduce the dependence on traditional coal.

Under the fuel substitution scenario, a portion of coal is replaced by alternative fuels such as oily sludge, biomass or waste tires, as shown in Figure 6. The calorific value and combustion characteristics of different alternative fuels vary, thus exerting a distinct impact on energy consumption. Oily sludge substitution scenario: The calorific value of oily sludge is between 23.24 MJ/kg and 30.69 MJ/kg, and its ash content is high, which can provide a certain amount of heat for cement production. The calorific value of oily sludge A is 23.24 MJ/kg, and the ash content is 28.79 wt%.

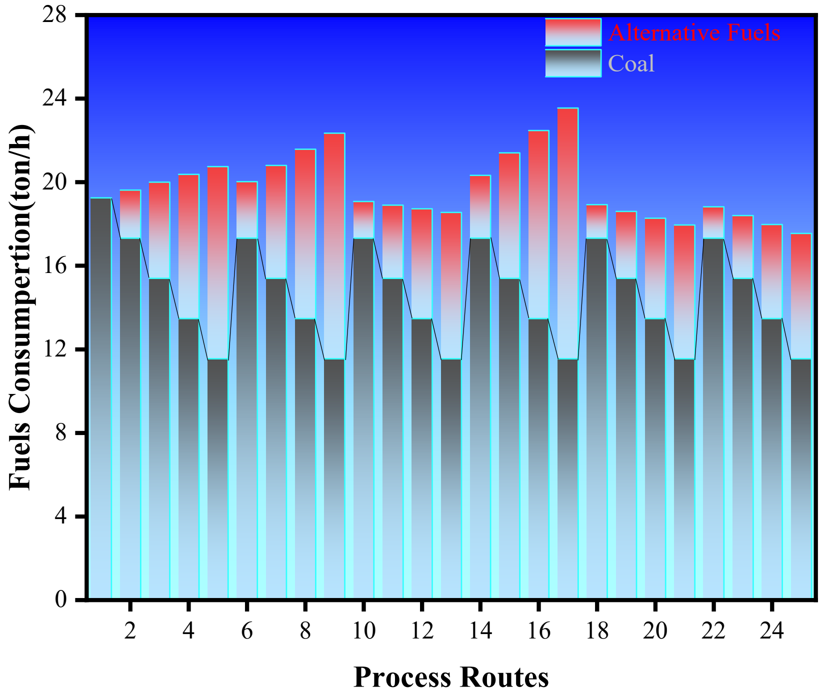


Figure 6. Coal and alternative fuel consumption in different circumstances.

When part of the coal is replaced by oily sludge A, the temperature of the decomposition furnace and the rotary kiln can still be maintained at about 900 °C and 1450 °C, but the coal consumption is reduced. Under the 10% Oily Sludge A substitution scenario, i.e., Route 2 scenario, the coal consumption is reduced to 17,325 kg/h and 2300 kg/h of oily sludge is required. Biomass substitution scenario: The calorific value of biomass is relatively low [50,51], but its ash contains abundant CaO, SiO_2 and other raw materials needed for cement production, which can provide a certain amount of heat for cement production. Taking corn stalk as an example, its calorific value is 18.26 MJ/kg and its ash content is 0.70 wt%. In the 40% biomass substitution scenario, Route 17, the coal consumption is reduced to 11,550 kg/h and the biomass requires 12,000 kg/h. Waste tire substitution scenario: Waste tires A and B have relatively high calorific values of 34.14 MJ/kg and 36.34 MJ/kg respectively, and their ash content contains significant amount of zinc oxide and other components, which can provide a certain amount of heat for cement production. In the 10% waste tire A substitution scenario, i.e., Route 18 scenario, the coal consumption is reduced to 17,325 kg/H and waste tire A requires 1600 kg/H. In the 40% waste tire B substitution scenario, i.e., Route 25 scenario, the coal consumption is reduced to 11,550 kg/h, with 6000 kg/h of waste tire B needed. Alternative fuels with high calorific value can reduce the reliance on the fossil fuel coal while delivering the same calorific value, thereby improving energy efficiency. The application of fuel substitution technology has significantly changed the structure of energy consumption. Some coal is replaced by alternative fuels such as oily sludge, biomass or waste tires, which not only reduces the dependence on traditional fossil energy coal, but also enhances the diversity and sustainability of energy supply.

3.3. Output

The main product of cement production is cement clinker, and its output is one of the important indicators for measuring the efficiency and economy of the production process. During the simulation, the clinker production under different fuel substitution scenarios was analyzed, as shown in Figure 7.

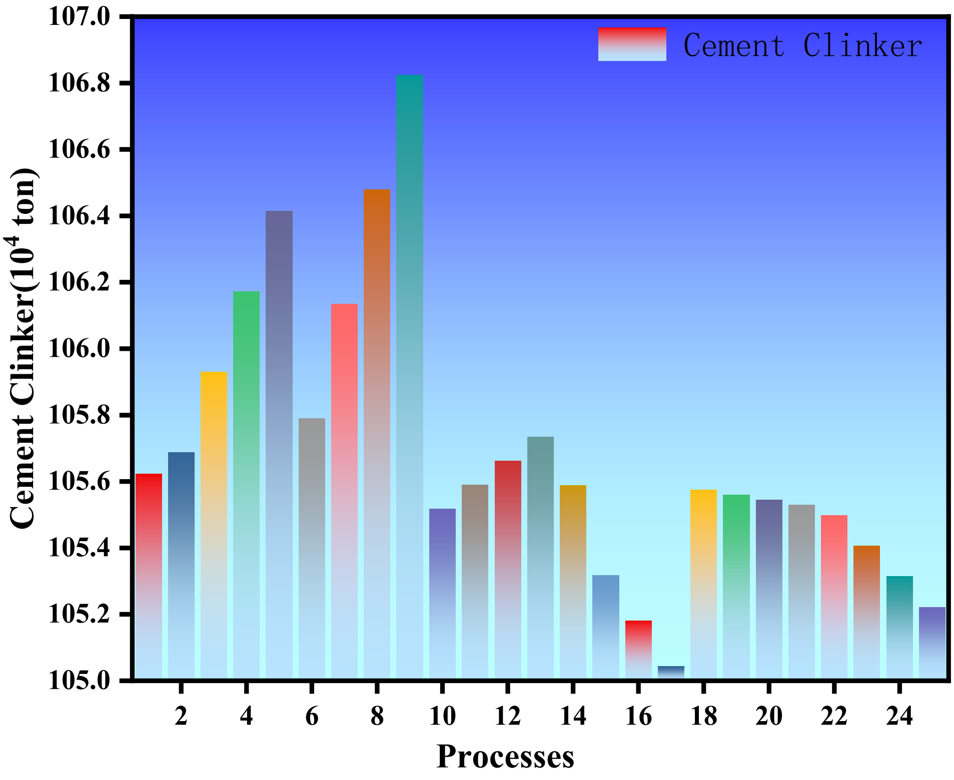


Figure 7. Cement clinker yield.

Based on the comprehensive analysis of the performance of cement clinker production under 25 different scenarios, it can be observed that different types and proportions of fuel substitution schemes have different degrees of impact on clinker production. Among all the scenarios, the highest clinker output is achieved in Scenario 9 (40% oily sludge B substitutions) and the lowest in Scenario 17 (40% biomass substitution), representing a difference of 17.8 thousand tons/year. Based on the current cement clinker market price of 350 yuan/ton, the annual operating income difference under the above two scenarios is approximately 6.23 million yuan.

In terms of fuel type, it is evident that in all oily sludge substitution scenarios, the clinker output is higher than that of the traditional fuel scenario, and as the substitution ratio increases, the output shows an upward trend, especially for oily sludge A and B substitution scenarios. In contrast, biomass alternative fuels show the opposite trend, and the clinker output gradually decreases with the increase of the substitution ratio. In the waste tire alternative path, the clinker output of waste tire path A is basically the same as that of the traditional path; However, the trend of route B is consistent with that of biomass route, that is, with the increase of substitution ratio, the output of clinker decreases gradually.

From the perspective of production operations, higher clinker output typically aligns with the production objectives of the enterprise. Based on the current data analysis, oily sludge pathways A and B exhibit more significant yield improvement, while the yield level of biomass pathways is relatively low. Therefore, in the selection of fuel substitution strategy, if the yield is the primary consideration, the substitution proportion of oily sludge can be increased appropriately, while the substitution proportion of biomass and waste tire B pathway is recommended to be kept within a reasonable range.

3.4. CO_2 Emissions

The carbon content and calorific value of each fuel, including conventional and alternative fuels, were first quantified. For each fuel, we calculated the amount of carbon oxidized to carbon dioxide under complete combustion conditions, and multiplied the amount of fuel used and the carbon content by the combustion efficiency to get the emissions. Notably, combustion efficiency takes into account the energy loss in the actual combustion process and the influence of incomplete combustion. These calculations were integrated into our process model, using Aspen Plus software to perform simulations and evaluate CO_2 emissions under different fuel substitution ratios.

According to the carbon dioxide emission data derived from simulations, variations in CO_2 emissions across different fuel substitution scenarios are analyzed, as shown in Figure 8. These data are critical for assessing the effectiveness of alternative fuels and their substitution ratios in reducing the carbon footprint associated with cement production [52,53].

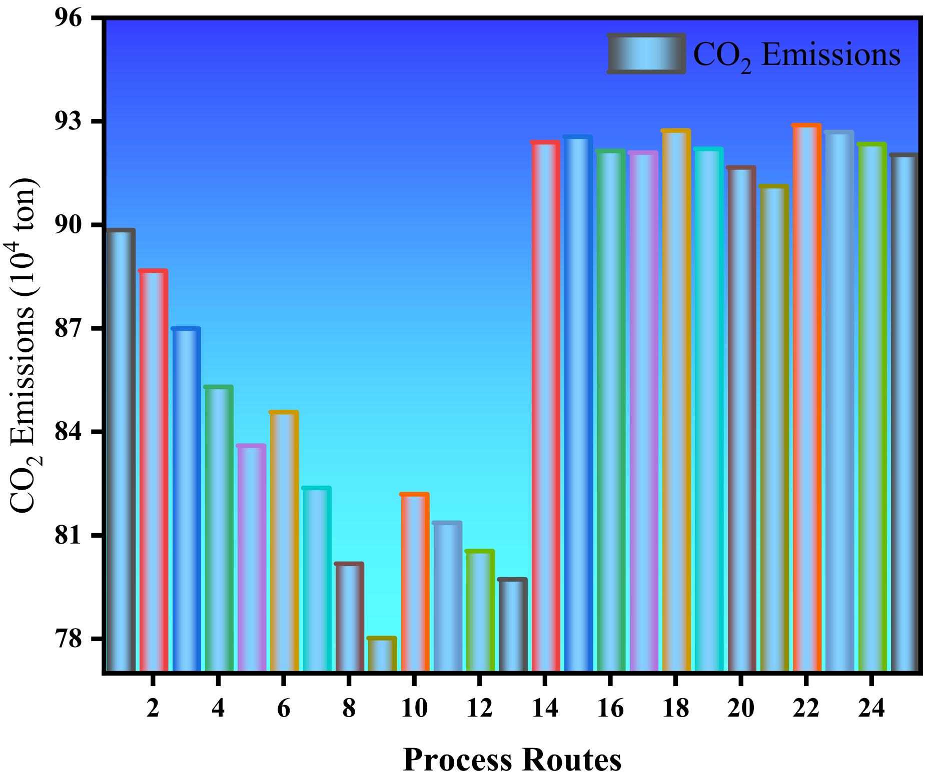


Figure 8. CO_2 emissions in 25 scenarios.

In the traditional cement production process, 1.05 million tons of cement clinker generates approximately 898,500 tons of carbon dioxide. Oily sludge substitution significantly mitigates carbon dioxide emissions- especially under the 40% oily sludge B substitution scenario. Compared with the traditional cement production process, the reduction of carbon dioxide emissions is 118,300 tons, representing a reduction rate of 13.17%. As the oily substitution ratio increase, the carbon dioxide mitigation effect becomes more pronounced. Biomass absorbs carbon dioxide (CO_2) in the atmosphere through photosynthesis during growth, and the amount of CO_2 released during combustion is theoretically equal to the amount absorbed, thus forming a closed cycle. Therefore, from a life cycle assessment (LCA) prospective, the net carbon emissions of biomass combustion can be regarded as close to zero, aligning with the "carbon neutrality". However, in this study, biomass was not evaluated from a full life cycle prospective as an alternative fuel. From the perspective of fuel combustion, biomass and waste tire alternative fuels exhibit basically the same carbon dioxide emission reduction performance, failing to play a carbon dioxide emission reduction effect, and under different proportion of alternative scenarios, carbon dioxide emissions are higher than those of traditional cement production processes. With the increase of the proportion of alternative fuels, carbon dioxide emissions decreased slightly, but the reduction value was small, and the effect of carbon dioxide emission reduction was limited. The comprehensive comparative analysis shows that oily sludge B and C as alternative fuels have the optimal performance in reducing carbon dioxide emissions, showing their potential as environmentally friendly fuels; the emissions under the biomass substitution scenario are slightly higher than those under the traditional scenario, which is related to their chemical composition and combustion characteristics; The emissions of waste tires under scenarios A and B are the highest, so the adoption of oxygen-enriched combustion and back-end capture of high concentration carbon dioxide is conducive to achieving carbon dioxide emission reduction. From the perspective of carbon dioxide emissions, sludge B and C are ideal alternative fuels, especially the high proportion of sludge B replacement scenario, which shows the most prominent mitigation effect.

3.5. Economic Performance

In The economic analysis of cement clinker production process, it is essential to account the fixed-capital investment (FCI), product costs, net present value (NPV), net profit and payback period (PBP) for four key routes, where the fixed asset investment is calculated according to the ratio [54–56], as shown in Table 5.

Table 5. Composition of fixed-capital investment.

Items	Suggestion Percentage	Ratio Factor
Direct investment		
Equipment	25~50% of FCI	45
Installation	6~14% of equipment	10
Instruments and controls	2~8% of equipment	6
Piping	3~20% of equipment	4
Electrical	2~10% of equipment	5
Buildings (including services)	3~28% of equipment	20
Land	1~2% of equipment	5
Indirect investment		
Engineering and supervision	4~21% of direct investment	15
Construction and contractor expenses	6~22% of direct investment	15
Contingency	5~15% of FCI	10
Fixed capital investment	Direct + Indirect investment	100

The prices of raw materials and cement products are summarized in Table 6, in which the oily sludge is hazardous waste, and the negative value indicates the unit price compensation that can be obtained by helping the oily sludge unit to treat the hazardous waste, and the corresponding hazardous waste disposal unit shall obtain the corresponding qualification. The price of limestone comes from the mine owned by the cement plant, and only mining and crushing expenses included.

Table 6. Raw material and product prices [24,25,27,54–56].

Price/($CNY{\cdot}t^{-1}$)						Electricity Price/($CNY{\cdot}(kW{\cdot}h)^{-1}$)
Coal	Oily Sludge	Biomass	Waste Tires	Limestone	Cement Clinker	
500	−1200	350	200	35	500	0.65

When the production scales are comparable the equipment investment can be regarded as the same, and the fixed assets investment remains consistent. The main differences under different fuel substitution scenarios are reflected in the purchase cost of raw materials and their product sales, and the product economic estimates are shown in Table 7.

Table 7. Estimation of product cost.

Component	Economic Assumptions
(1) Raw material	See Table 6
(2) Utilities	Electricity + Water + Air
(3) Operating and maintenance	
(3.1) Operating labor	100,000 CNY/labor/year, 230 labors
(3.2) Direct supervisory and clerical labor	10% of (3.1)
(3.3) Maintenance and repairs	2% of FCI
(3.4) Operating supplies	0.7% of FCI
(3.5) Laboratory charge	1.5% of (3.1)
(4) Depreciation	Life period 20 years, salvage value 6%
(5) Plant overhead cost	5% ((3.1) + (3.2) + (3.3))
(6) Administrative cost	2% of production cost
(7) Distribution and selling cost	2% of production cost
(8) Production cost	(1) + (2) + (3) + (4) + (5) + (6) + (7)

The product cost of cement production mainly includes raw material cost, utility cost, operation and maintenance cost, equipment depreciation cost, management and sales cost, as shown in Figure 9. Among them, oily sludge A and oily sludge B represent the two lowest- cost scenarios under 40% fuel substitution ratio, and their production costs are 273.36 CNY/t and 257.34 CNY/t, respectively. The production route with the highest production cost is the biomass 40% substitution route, at 397.83 CNY/t.

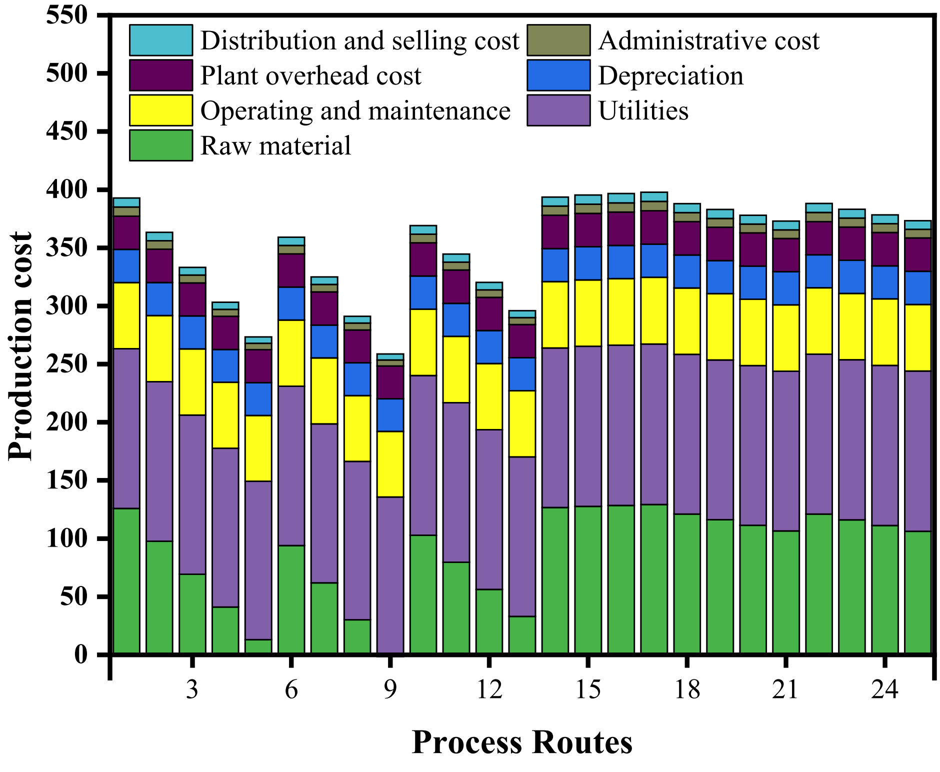


Figure 9. The production costs of different routes of cement.

It can be seen from Figure 9 that the main difference in cement production cost is reflected in the cost of raw materials, of which the cost of traditional cement production process is 392.89 CNY/t, which ranks the highest. High-level oily sludge substitution confers significant advantages in raw materials costs. Under the scenario of 40% substitution of oily sludge, the production cost of cement is 358.45 CNY/t, representing the lowest production cost across all evaluated scenarios. The performance of scrap tires and traditional cement production routes in raw materials is basically the same, and there is a slight difference in production costs, such as utility costs, operation and maintenance costs, equipment depreciation costs, management and sales costs, but the difference is not obvious.

With the global focus on carbon emission reduction, carbon tax, as an important policy tool, has been adopted by many countries and regions. The implementation of carbon tax has a significant impact on the cost structure of cement production enterprises. We adopted an assumed carbon tax rate of 100 CNY/t CO_2 to assess the impact of different tax rates on cement production costs. Carbon emissions under different fuel substitution scenarios According to the analysis results in Section 3.4, there are significant differences in carbon dioxide emissions under different fuel substitution scenarios, as shown in Table 8.

Table 8. Carbon tax calculation for cement production.

Scenario	CO_2 Emissions (10^4 tons/year)	Carbon Tax Cost (CNY/t)	Base Total Cost (CNY/t)	Total Cost with Carbon Tax (CNY/t)
1	89.85	8.99	392.89	401.88
2	85.00	8.50	385.00	393.50
3	80.15	8.02	377.11	385.13
4	75.30	7.53	369.22	376.75
5	70.45	7.05	361.33	368.38
6	84.50	8.45	382.50	390.95
7	79.00	7.90	374.61	382.51
8	73.50	7.35	366.72	374.07
9	68.00	6.80	358.83	365.63
10	83.00	8.30	380.00	388.30
11	77.50	7.75	372.11	379.86
12	72.00	7.20	364.22	371.42
13	66.50	6.65	356.33	362.98
14	88.00	8.80	390.00	398.80
15	86.00	8.60	387.11	395.71
16	84.00	8.40	384.22	392.62
17	82.00	8.20	381.33	389.53
18	89.50	8.95	391.50	400.45
19	88.00	8.80	388.61	397.41
20	86.50	8.65	385.72	394.37
21	85.00	8.50	382.83	391.33
22	90.00	9.00	392.00	401.00
23	88.50	8.85	389.11	397.96
24	87.00	8.70	386.22	394.92
25	85.50	8.55	383.33	391.88

The CO_2 emissions in Table 8 are derived from simulation results under different fuel substitution scenarios. The carbon tax cost (CNY/t) is calculated based on the CO_2 emissions and the carbon tax rate, with the resulting cost allocated to each ton of cement clinker. The total cost with carbon tax equals the base total cost plus the carbon tax cost. The fluctuation of carbon tax rate has a significant impact on the economy of cement production. With the increase of carbon tax rate, the proportion of carbon tax cost in the total cost is gradually increasing. Therefore, cement manufacturers should prioritize low-carbon alternative fuels (e.g., oily sludge) to mitigate carbon tax cost and enhance economic performance.

3.6. Life Cycle Perspective the Alternative Fuel of Environmental Performance Evaluation

This study mainly analyzed the direct CO_2 emissions of alternative fuels in the cement production process in the previous chapters. However, to accurately assess the environmental benefits of alternative fuels, it is necessary to comprehensively calculate the greenhouse gas emissions of fuels in all stages from raw material acquisition, processing and treatment, transportation and storage to final combustion and disposal. Especially for biomass fuels, the determination of their carbon neutrality characteristics is highly dependent on the selection of system boundaries and methodological approaches.

3.6.1. Life Cycle Assessment Methodology and System Boundaries

According to the ISO 14040/14044 standards, this study covers the following key stages:

(1) Raw material acquisition stage

Oil sludge comes from the processes of oil extraction, refining and storage and transportation, and is classified as industrial waste. The carbon emissions in this stage mainly include the energy consumption for collection, initial dewatering and on-site storage. Since oil sludge is a waste product, it is not regarded as the acquisition of traditional raw materials, but rather the environmental load from the generation point to the pretreatment facility is calculated. Biomass is represented by corn stalks and rubber wood chips. This stage includes crop cultivation (fertilizer and pesticide use), forest cultivation, harvesting and initial crushing. According to the Sixth Assessment Report of the IPCC, biomass fixes atmospheric CO_2 through photosynthesis during its growth process, and the calculation of its bio-carbon requires special methodological approaches.

Waste tires, as municipal solid waste, their carbon emissions in the acquisition stage mainly come from collection, classification and pre-treatment crushing, which belong to the downstream links of waste management.

(2) Processing and treatment stage

Oil sludge needs to undergo dewatering, conditioning and drying treatment, with an energy consumption of about 35–50 kWh/t (adjusted based on calorific value); biomass needs to be dried (reducing moisture content from 30% to below 10%), crushed and pelletized, with an energy consumption of about 120–180 kWh/t; waste tires need to be crushed, magnetic separation of steel wires and fiber separation, with an energy consumption of about 80–120 kWh/t.

(3) In the transportation stage, we assume an average transportation distance of 150 km (road transportation), using diesel heavy trucks (30t load), and the emission factors refer to the China Life Cycle Basic Database (CLCD).

(4) The combustion utilization stage includes the combustion of alternative fuels in the decomposition furnace and rotary kiln, the participation of ash in the reaction of clinker minerals, and the resulting direct and indirect emissions (such as electricity consumption).

3.6.2. Comparative Analysis of the Full Life Cycle of Each Alternative Fuel

Based on the above methodology, we compared the full life cycle CO_2 emissions of six alternative fuels at a 40% thermal substitution rate (TSR) (1 ton of clinker), and the following key conclusions can be drawn. Oil sludge-based fuels perform the best among the three alternative fuels. Even without considering the credit for waste disposal, their full life cycle emissions are still 22–26% lower than those of coal. This is mainly due to: high ash content (20–31%) converting part of the fuel carbon into clinker minerals, reducing CO_2 release; internalizing the negative externalities of hazardous waste disposal, avoiding dedicated incineration or landfill disposal emissions. The emission reduction effect of biomass fuels is extremely sensitive to the choice of methodology. In the conservative complete LCA scenario, its emission reduction rate (73.3%) is still significantly higher than that of other fuels, but the absolute emission reduction is limited by: low calorific value (18.26 MJ/kg) leading to high mass flow, large processing and transportation loads; if the supply chain is optimized (such as using solar drying, shortening transportation to within 50 km), the total emissions can be further reduced to 45–55 kg CO_2 e/t clinker, and the emission reduction rate can be increased to over 80%;The emission reduction effect of waste tires is limited (8–11%), mainly because of their: high calorific value (34–36 MJ/kg) resulting in small unit energy mass, high transportation efficiency; However, the high volatile matter and sulfur content (1.5–1.92%) result in relatively high direct emissions during the combustion stage; the energy consumption in the process of separating steel wires and fibers offsets some of the environmental benefits.

3.6.3. Revision and Suggestions for the Original Research Conclusions

The original research stated that "the CO_2 reduction effect of biomass and waste tire alternative fuels is limited", which is partially correct but needs to be refined: if only the combustion stage is considered, biomass does not show a significant advantage; however, from a complete LCA perspective, the full life cycle reduction potential of biomass can reach 70–80%, far exceeding that of oil sludge (22–26%) and waste tires (8–11%). The key premise is that a localized, low-carbon supply chain (radius < 100 km, driven by renewable energy for processing) must be established; otherwise, the environmental benefits will be significantly reduced. Although oil sludge performs well currently, its nature as a by-product of fossil fuel production means that as the energy transition progresses and crude oil extraction decreases, the availability of oil sludge will be limited. In the long term, biomass is a more sustainable strategic choice, but issues of seasonal supply and storage stability need to be addressed.

3.7. Simulation Study on Hybrid Alternative Fuel Replacement Strategies

Building upon the findings from single-fuel substitution experiments, this section investigates the technical feasibility and performance implications of co-utilizing two complementary alternative fuels in cement kiln operations. Given the distinct yet synergistic properties of candidate fuels—including calorific value, ash composition, mineralogical reactivity, and carbon emission profiles—two hybrid fuel schemes were systematically designed and evaluated at a total thermal substitution rate of 40% (to enable direct comparison with single-fuel scenarios):

- Scheme I: Co-substitution of oil sludge B (30% by thermal input) and biomass (10% by thermal input). This combination leverages the high ash content of oil sludge B (31.07 wt%), rich in Fe_2O_3 (20.15 wt%), which promotes C_4AF formation and lowers liquid-phase formation temperature; concurrently, biomass—though low in ash (0.70 wt%)—contributes substantial alkali metal oxides (K_2O: 20–40 wt% of its ash), enhancing melt fluidity and combustion efficiency. Notably, biomass is carbon-neutral over its lifecycle, and its alkaline components further support clinker mineralization.

- Scheme II: Co-substitution of waste tires B (30% by thermal input) and biomass (10% by thermal input). Waste tires B exhibits the highest calorific value among all alternatives (36.34 MJ/kg), offering significant coal displacement potential; however, its low ash content (6.11 wt%) and limited mineral-forming capacity necessitate supplementation with biomass to improve clinker phase development and mitigate production losses. Biomass here serves not only as a carbon-neutral component but also as a source of K_2CO_3 and other fluxing agents that partially compensate for the insufficient ash-derived mineral precursors in waste tires B.

3.7.1. Impact on Clinker Production Yield

Hybrid fuel strategies yield markedly divergent effects on annual clinker output (Figure 10). Scheme I achieves an annual clinker production of 1.042×10^6 t—a 4.2% increase relative to conventional coal-based operation. In contrast, Scheme II yields 0.975×10^6 t annually, representing a 2.5% decline. The superior performance of Scheme I arises from synergistic ash contributions: the Fe-rich ash of oil sludge B facilitates C_4AF crystallization, while the potassium-rich ash of biomass significantly enhances liquid-phase formation kinetics. Conversely, although the ZnO content in waste tires B ash (40–60% of ash mass) exerts a mild fluxing effect, its overall ash volume and compositional inadequacy—particularly the scarcity of CaO and SiO_2 reactive species fail to offset the dilution of raw meal reactivity, ultimately constraining clinker formation and reducing output.

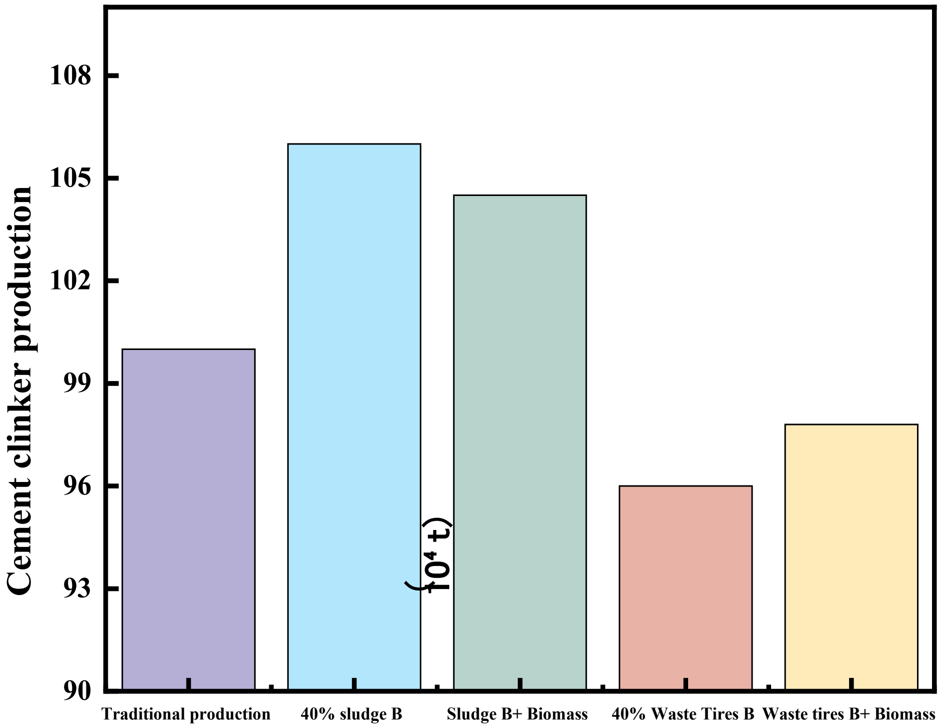


Figure 10. Cement clinker production in mixed alternative fuel.

3.7.2. CO_2 Emission Performance

As illustrated in Figure 11, Scheme I delivers the most substantial greenhouse gas mitigation: annual CO_2 emissions decrease to 7.72×10^5 t, corresponding to a 14.1% reduction versus the baseline (8.985×10^5 t). Scheme II achieves a more modest reduction of 7.1%, lowering emissions to 8.35×10^5 t. The superior decarbonization efficacy of Scheme I stems from three interrelated mechanisms: (i) oil sludge B possesses lower carbon intensity per unit energy than coal; (ii) its high ash content partially substitutes carbonate-bearing raw materials (e.g., limestone), thereby suppressing process-related CO_2 emissions from calcination; and (iii) the biogenic carbon in biomass entails net-zero operational emissions. By contrast, waste tires B contains a high fixed carbon fraction (83.07 wt%), resulting in elevated carbon emission intensity per MJ—despite its high calorific value—thereby limiting the net abatement potential of Scheme II.

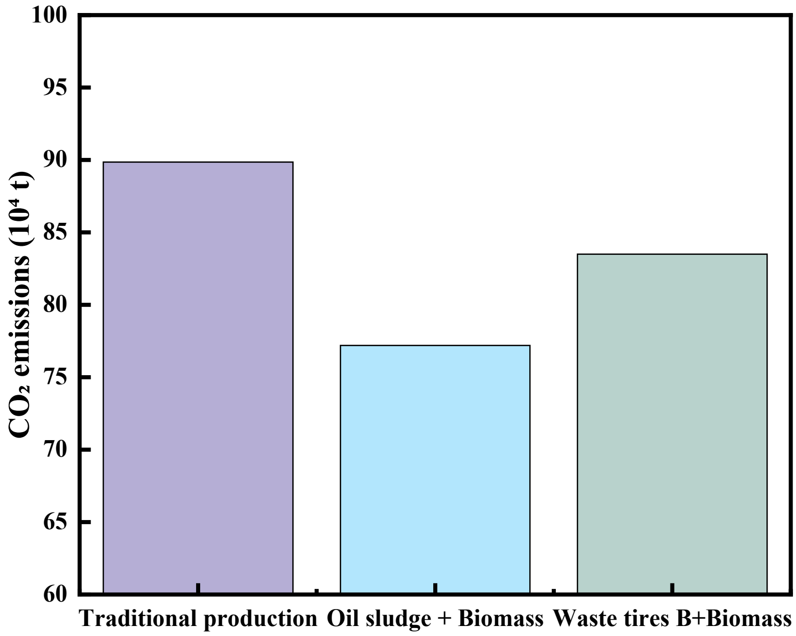


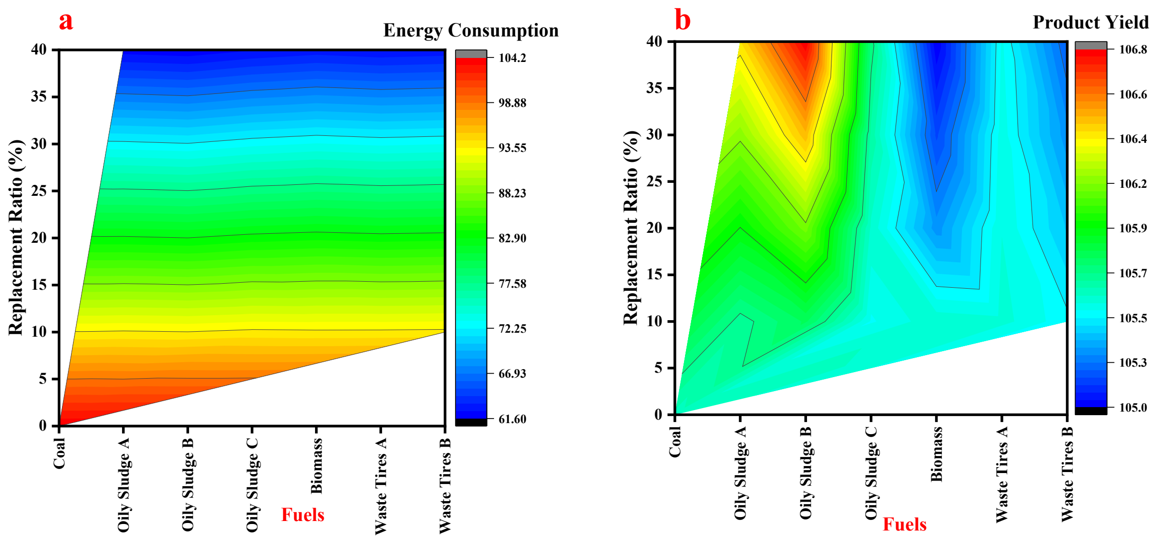
Figure 11. CO_2 emissions in mixed alternative fuel.

3.7.3. Synthesis and Strategic Implications

The hybrid fuel approach successfully exploits functional complementarity among alternative fuels to enhance the sustainability and operational robustness of cement production. Scheme I emerges as the optimal configuration, delivering simultaneous improvements of 14.1% in CO_2 reduction, 4.2% in clinker yield, and 12.9% in production cost savings. Its deployment requires securing a reliable, year-round supply chain for oil sludge B and implementing a seasonal biomass storage system to ensure consistent feedstock quality and availability. Scheme II, while achieving the highest coal displacement rate (42.9%), is constrained by its inherently high carbon intensity and insufficient ash-derived mineral precursors—leading to suboptimal emission reductions and marginal clinker output gains. Consequently, its overall economic viability remains inferior to conventional operation under current assumptions. The core synergy mechanisms underlying effective hybrid fuel utilization are threefold: (1) calorific value complementarity between high-energy and low-energy fuels; (2) raw material substitution complementarity between high-ash and low-ash fuels; and (3) carbon origin complementarity between fossil-derived and biogenic carbon sources.

3.8. Multi-Factor Objective Optimization

Energy consumption, cement clinker production, carbon dioxide emissions, and annual revenue represent key parameters examined in this study, as shown in Figure 12. Lower energy consumption, higher production, reduced carbon dioxide emissions, and high revenue are the core objectives pursued by enterprises.



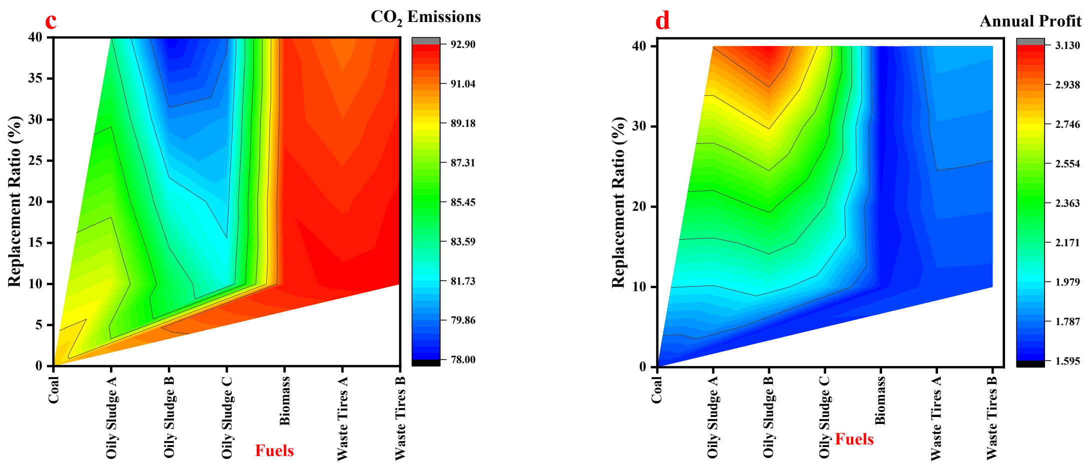
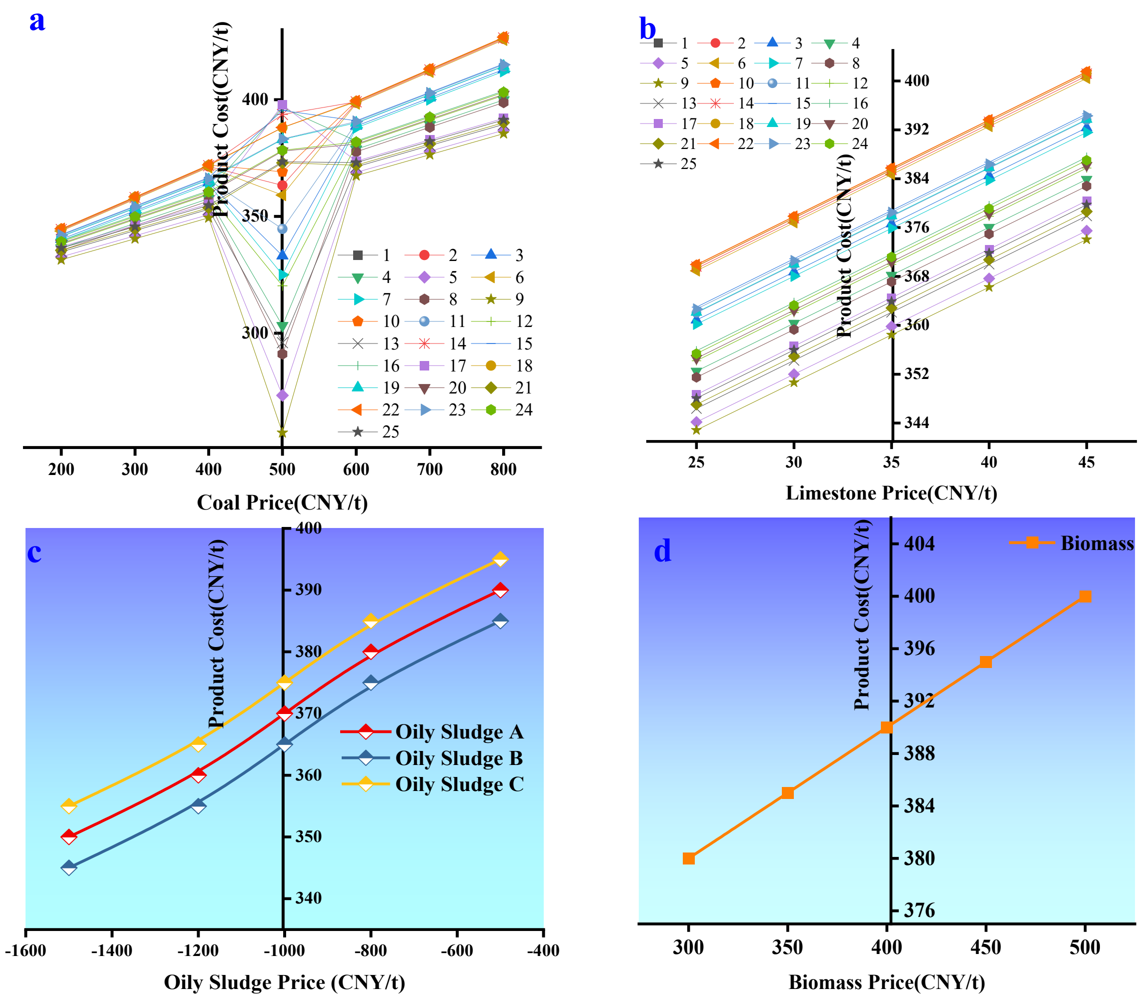


Figure 12. multi-parameter target optimization: (**a**) Energy Consumption; (**b**) Product Yield; (**c**) CO_2 Emissions; (**d**) Annual Profit.

Through comprehensive comparison, it can be found that low energy consumption appears in the high proportion of fuel substitution, in the fuel substitution of 6, oily sludge has the effect of increasing cement clinker production, the high proportion of oily sludge B and C has the effect of emission reduction, and the path with the highest annual income is the high proportion of oily sludge A and B.

3.9. Sensitivity Analysis

Sensitivity analysis plays a critical role in the economic performance analysis of the cement industry. By analyzing how variations in key variables influence project outcomes, it enables evaluation of the project under uncertainty, as shown in Figure 13.



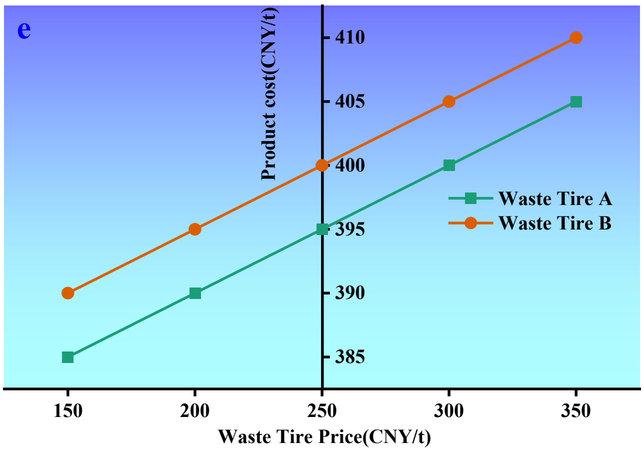


Figure 13. Economic sensitivity analysis: (**a**) coal price; (**b**) limestone price; (**c**) oily sludge price; (**d**) biomass price; (**e**) waste tires price.

From the sensitivity analysis, it can be seen that with the increase of the price of limestone, the production cost of cement increases, and there is a linear positive correlation between them. Under the same fuel substitution scenario, the coal price also exerts an influence on the production cost of cement clinker, but due to the combined effect of different fuel substitution ratios and alternative fuel prices, the coal price and the production cost of cement show different fluctuations. Overall, with the increase of coal price, the production cost of cement increases gradually, and the fuel substitution ratio increases. The impact of coal prices has weakened, and the impact of alternative fuel prices has gradually increased. Therefore, lowering raw materials and fuels prices, as well as increasing the proportion of low-cost alternative fuels, such as oily sludge, is conducive to reducing cement production cost.

It can be seen from Figure 11 that the fluctuation of oily sludge price has the most pronounced influence on cement production cost and net profit, followed by biomass, while waste tires have a relatively modest effect. This indicates that when selecting alternative fuels, the impact of their price fluctuations on production costs and economic benefits should be fully considered to ensure the economy and sustainability of cement production. Fluctuations in alternative fuel prices have a significant impact on the economics of cement production. Fluctuations in the prices of alternative fuels such as oily sludge, biomass and waste tires can lead to changes in the cost and net profit of cement production. In practical production, close monitoring of alternative fuels price volatility and rational selection of both alternative fuels and their substitution ratios are critical to minimizing production costs and enhancing economic efficiency.

At the same time, governments and enterprises should take measures to stabilize the supply and price stability of alternative fuels, thereby facilitating the sustainable development of the cement industry. Additionally, account must be taken of the impact of the change in hazardous waste subsidy policies and seasonal cost fluctuations of biomass on the economy viability. National subsidy policy is being phased out, while local subsidies (such as special subsidies for hazardous waste disposal) have emerged as the key variables to maintain the economy of the project. Biomass fuel costs have significant seasonal and regional fluctuations (such as bad weather leading to a decline in recycling and a surge in prices), which are the main uncertainties in profit margins. The above factors affecting production costs will have a significant influence on the rate of return of the project.

4. Conclusions

Addressing the challenges of high energy consumption, elevated carbon dioxide emissions and environmental pollution in the cement industry, we conducted numerical simulations of six fuels substitution scenarios. Specifically, a co-disposal of three different sources of oily sludge, biomass and two different compositions of waste tires to replace the traditional fossil fuel coal between 10% and 40% in the cement industry production was explored. The main conclusions are as follows.

Alternative fuels can effectively reduce coal consumption and enhance energy efficiency. On the premise of providing the same heating value, the coal consumption is reduced to 17,325 kg/h in the 10% scrap tire A replacement scenario and to 11,550 kg/h in the 40% scrap tire B replacement scenario. The alternative fuel oily sludge can significantly increase the cement clinker production, the alternative fuel biomass and waste tire B reduce the cement clinker production, and the cement clinker production of waste tire A is basically equivalent to that of traditional cement production. From the perspective of fuel substitution ratio, the higher the substitution ratio of oily sludge, the better, while the lower the substitution ratio of biomass and waste tires, the better. Oily sludge fuel substitution can well reduce carbon dioxide emissions, especially in the case of oily sludge B substitution ratio of 40%, compared with the traditional cement production process, carbon dioxide emissions are reduced by 118,300 tons, and carbon dioxide emissions are reduced by 13.17%. Fuel substitution can reduce the production cost of cement, though cost-saving efficacy varies among fuels. High-rate oily sludge substitution can reduce the production cost of traditional cement from 392. 89 CNY/t to 358. 45 CNY/t, reducing the production cost by 8. 77%.

With the increasing global demand for mitigating greenhouse gas emissions and enhancing energy efficiency, it will become increasingly important to use multi-source alternative fuels (such as biomass, industrial and domestic wastes) to replace traditional fossil fuels in cement production. Through numerical simulation, the process route is optimized, the thermal efficiency and economic viability of diverse alternative fuels are predicted, and their potential effects on cement production and environmental impact are evaluated, which will help to formulate more environmentally friendly and cost-effective cement production strategies and promote the sustainable development of the industry.

The alternative fuel blending solution can achieve complementary characteristics among different alternative fuels and optimize the overall performance of cement production. The synergy of blended fuels is mainly reflected in: the calorific value complementarity between high-calorific value and low-calorific value fuels, the raw material substitution complementarity between high-ash and low-ash fuels, and the carbon emission complementarity between fossil carbon and bio-carbon fuels.

Author Contributions

J.L. (Jinqiang Liang): Conceptualization, Funding acquisition, Writing—original draft. Q.Z.: Methodology, Investigation, Data curation. J.L. (Jiahui Li): Methodology, Investigation, Data curation. Y.M.: Investigation, Data curation, Formal analysis. D.L. (Duiping Liu): Investigation, Data curation, Formal analysis. J.Z.: Investigation, Data curation. Z.P.: Data curation. D.L. (Danzhu Liu): Investigation, Data curation, Formal analysis. M.K.: Investigation, Data curation. H.H.: Investigation, Data curation, Formal analysis. M.Y.: Methodology, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

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

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Nomenclature

CO_2	Carbon Dioxide
CNY	China Yuan
FCI	Fixed Capital Investment
LCA	Life Cycle Assessment
NNC	No-Nitrogen Combustion
NPV	Net Present Value
PBP	Payback Period
TSR	Thermal Substitution Rates

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