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Article

Study on prediction model of nitrogen emission in the production stage of residential building materials—A case study of Guangdong province

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Abstract: This study aims to reduce nitrogen emissions from residential buildings and establishes a prediction model for nitrogen emissions during the production of building materials. The calculation boundary, content, and method of nitrogen emission in the production stage of residential building materials are accurately analyzed. Based on the nitrogen emission data of 20 residential buildings in Guangdong, the composition and distribution characteristics of nitrogen emission in the production stage of building materials are analyzed. The coupling relationship between building design parameters and building materials' nitrogen emissions is established using linear regression and ridge regression. 10 kinds of nitrogen emission prediction models based on the design parameters of residential buildings in the production stage of building materials were established and verified. The results show that the linear model M3, based on the number of floors above and below ground, the area width and depth, and the ridge regression model M5, based on the number of floors above and below ground, the area width and depth, and the total number of main functional rooms, have good fitting and prediction performance, respectively. The linear regression model M6, based on the number of floors above and below ground, the area width and depth, and the total number of rooms, has the best fitting and prediction performance. M3, M5, and M6 can accurately predict the nitrogen emission composition and distribution characteristics of building materials in residential building design and lay a foundation for future research on nitrogen emission evaluation and calculation methods and nitrogen emission reduction technology strategies.

Keywords: nitrogen emission; residential building; building material; production stage

1. Introduction

The carbon and nitrogen emissions of residential buildings in the operation and building materials production stages account for a large proportion of the entire life cycle of the building. According to the construction requirements and standards of green buildings, building materials and the indicators of building heat consumption have been controlled to a certain extent. More mature carbon emission evaluation, calculation methods, and emission reduction technologies have been developed for residential building materials in the production and operation stages. Still, for living building materials, there is little research on the relationship between nitrogen emission evaluation methods and design parameters of residential buildings in the production and operation stages.

At present, at the urban level, Malik [1] and others have established a multi-regional input-output database and evaluated the driving factors of nitrogen emissions by analyzing six determinants: nitrogen efficiency (nitrogen emissions per unit output), production formula (interdepartmental dependence), final demand composition (household consumption basket), final demand destination (consumption and investment balance), wealth (final consumption per capital), and population. Wu et al. [2] built a driving force analysis model based on the STIRPAT framework. Using spatial measurement methods, they quantitatively estimated the driving effect of population and land urbanization on ammonia nitrogen emissions. Wu et al. [3] proposed a fuel reprocessing method based on coal preheating to reduce NOx emissions. Liu et al. [4] used the WRF-EMEP model to quantitatively analyze the nitrogen emissions of three typical urban agglomerations in the Beijing Tianjin Hebei region, the Yangtze River Delta, and the Pearl River Delta through the standard deviation ellipse (SDE) "center of mass" migration method. McCourt and MacDonald [5] pointed out that the nitrogen footprint quantifies consumer-driven active nitrogen emissions. They provided an illustrative case study to estimate the drivers of local nitrogen emissions in Canada from the national nitrogen budget, nitrogen emission inventory, and statistical data. Jiang et al. [6] analyzed the socioeconomic drivers that can reduce NOx emissions based on satellite observation technology and spatial econometric models. Pan et al. [7], based on satellite data and long-term ground observation, proposed that reducing ammonia emissions is increasingly important for improving China's air quality. Xian et al. [8], based on the theory and connotation of pollution nitrogen footprint and greywater footprint, analyzed the main factors that increase the urban greywater footprint and studied the methods to give priority to quickly improve the reuse rate of urban domestic sewage and comprehensively improve the nitrogen removal rate of urban sewage.

At the architectural level, Cai et al. [9] studied the distribution behavior of nitrogen atoms in stainless steel by atomic probe tomography. Shan and Ren [10] determined oxygen and nitrogen in steel based on the inert gas melting infrared absorption method and the inert gas melting thermal conductivity method to ensure the accuracy of oxygen and nitrogen content analysis in steel. Shen et al. [11] designed an automatic detection method for the concentration of lower nitrogen oxide pollutants by applying photocatalyst materials in buildings. Li et al. [12] detected the mass concentration of nitrite ions in concrete by three methods, namely spectrophotometer, color difference determination, and direct arbitration. Their research has laid a foundation for the later research on nitrogen reduction of building materials; Tang [13], Zhao [14], Ma, and others [15] studied the method of reducing nitrogen oxide emissions of cement enterprises through staged combustion denitrogenation technology and SNCR denitrogenation technology. Zhu [16] reduced nitrogen oxide emissions of iron and steel enterprises by developing the method of short-process steelmaking. Yao et al. [17] pointed out that controlling nitrogen oxides is the key to reducing nitrogen oxides in steel, providing technical support for further reduction of nitrogen oxides in steel.

In the civil engineering industry, China has not yet formulated a standard prediction system for building nitrogen emissions; the primary data method is still the inventory statistics method. Therefore, based on the bill of quantities and construction drawings of the actual project, this study establishes a method to obtain the nitrogen emissions (dependent variables) of building materials through the design parameters (independent variables) of residential buildings and studies the composition and distribution of nitrogen emissions of primary building materials. At the same time, this study uses the data processing and analysis methods of linear regression and ridge regression, and the prediction model of nitrogen emission in the production stage of building materials for residential building design parameters is established.

2. Calculation of nitrogen emission from building materials in residential buildings

2.1. Research object

The research object is determined to be 20 residential buildings with cast-in-situ reinforced concrete shear wall structures in Guangdong, as shown in **Table 1**. The information of 20 north-south residential buildings is described. The energy conservation design of the enclosure structure of all residential buildings is based on the Energy Conservation Design Standard for Residential Buildings in Hot Summer and Warm Winter Areas (JGJ75-2012). The thermal insulation materials are rock boards and glass wool boards; the external windows are plastic steel; and the filler wall is mainly shale bricks.

2.2. Computing method

According to the China Statistical Yearbook, the China Industrial Economic Statistical Yearbook, the China Mining Yearbook, the National Standard Announcement of the People's Republic of China, and other statistical data are used to calculate the nitrogen emission of the building materials involved in this study during the production stage and determine the nitrogen emission factor according to relevant research [18,19]. As the construction year of the research object is only more than ten years, which has not reached the service life, the nitrogen emission of building materials recycled in the demolition phase is not considered in this study.

Table 1. 20 Basic information about residential buildings.

Building number	Building category	Number of elevator households	Building area/10,000 m^2	Floors above ground	Floors below ground	Building height/m	Standard layer area/m^2	Figure Coefficient	Number of rooms on a standard floor	Average window-to-floor ratio	Building surface area/m^2
1	I	Two elevators and four high-rise buildings	11,474.58	25	2	72.34	325.94	0.28	11	0.11	9919.42
2	I	Two elevators and four high-rise buildings	13,403.50	25	2	72.26	348.02	0.27	12	0.16	10,524.05
3	I	Two elevators and four high-rise buildings	14,410.91	26	2	76.73	348.02	0.27	12	0.17	11,268.97
4	I	Two elevators and four high-rise buildings	14,673.14	26	2	76.73	351.54	0.24	12	0.18	10,718.68
5	II	One elevator, two households, high-risen dependent unit	3242.70	9	2	27.58	248.03	0.30	9	0.16	2713.15
6	II	One elevator, two households, high-rise independent unit	1704.23	9	2	20.73	175.94	0.34	7	0.25	1771.81
7	II	One elevator, two households, high-rise independent unit	3560.11	9	2	27.91	271.78	0.30	9	0.19	2941.85
8	II	One elevator, two households, high-rise independent unit	3518.71	9	2	27.58	268.62	0.29	9	0.23	3095.43
9	II	One elevator, two households, high-rise independent unit	3294.31	10	2	28.23	253.87	0.30	7	0.23	2776.99
10	II	One elevator, two households, high rise, three units, row	7045.77	8	2	25.43	642.10	0.29	21	0.20	5874.99
11	II	One elevator, two households, high rise, three units, row	7512.97	9	2	27.43	627.56	0.28	21	0.24	6268.82
12	II	One elevator, two households, high rise, three units, row	9137.41	9	2	29.28	728.39	0.25	21	0.20	7398.10
13	II	One elevator, two households, high rise, three units, row	3913.15	6	2	19.81	618.38	0.30	20	0.23	3495.65
14	II	One elevator, two households, high rise, three units, row	6246.98	7	2	27.91	628.14	0.31	21	0.25	5340.83
15	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.28	21	0.21	5386.36

Table 1. (*Continued*).

Building number	Building category	Number of elevator households	Building area/10,000 m^2	Floors above ground	Floors below ground	Building height/m	Standard layer area/m^2	Figure Coefficient	Number of rooms on a standard floor	Average window-to-floor ratio	Building surface area/m^2
16	II	One elevator, two households, high rise, three units, row	7298.73	7	2	21.79	720.34	0.24	26	0.23	5359.44
17	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.27	21	0.19	5431.72
18	II	One elevator, two households, high rise, three units, row	6951.14	7	2	21.79	713.08	0.33	21	0.22	6074.98
19	II	One elevator, two households, high rise, three units, row	6772.86	7	2	21.79	674.24	0.34	14	0.24	4559.35
20	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.31	21	0.20	6646.18

3. Calculation results and analysis

3.1. Prediction model research methods

This study calculates the use of primary building materials and nitrogen emissions of each building based on the construction drawings and bill of quantities of 20 residential buildings. At the same time, it completes data cleaning, curve evaluation, linear regression, and ridge regression analysis according to the design parameters of residential buildings in different stages. Finally, it forms the nitrogen emission prediction model of building materials in the production stage.

3.2. Characteristics of building material consumption and nitrogen emission in residential buildings

In this study, according to the density of different building materials, the amount of them is uniformly converted into quality. Among the 20 residential buildings, the average mass of concrete, cement mortar, shale brick, and steel accounted for 79.52%, 10.96%, 5.56%, and 3.66% of the building materials calculated for nitrogen emissions; the total mass of thermal insulation materials and enclosure structures accounted for 0.3%; and the average mass of waterproof coatings, mineral wool decorative acoustic panels, etc. accounted for less than 0.1% of the total mass of all building materials. The building material quality of concrete, cement mortar, shale brick, and steel in the unit building area is 1355.26 kg/m^2, 182.86 kg/m^2, 90.07 kg/m^2, and 66.06 kg/m^2, respectively.

Table 2 analyzes the change in nitrogen emission intensity of different building materials. Because the use positions of building materials in residential buildings differ, nitrogen emission intensity is calculated per-unit building area for all building materials except transparent envelope. In contrast, nitrogen emission intensity is calculated per unit material area for a transparent envelope. It can be seen that the average nitrogen emission intensity of concrete is the highest, about 67.83 kg/m^2; the average nitrogen emission intensity of cement mortar is the second, about 49.20 kg/m^2; the average nitrogen emission intensity of steel and transparent enclosure is the third and fourth, respectively, about 43.09 kg/m^2 and 26.73 kg/m^2; the average nitrogen emission intensity of insulation materials and shale brick is the fifth and sixth, respectively, about 4.90 kg/m^2 and 1.93 kg/m^2.

Table 2. Basic information of 20 residential buildings.

Building number	Shale brick	Concrete	Transparent enclosure	Cement mortar	Thermal insulation materials	Steel products
1	1.42	69.92	17.86	60.03	3.79	26.79
2	0.95	93.08	18.66	50.22	6.07	28.00
3	0.97	61.60	30.52	50.11	4.21	60.78
4	1.01	92.13	22.27	50.84	5.94	33.41
5	1.81	62.71	23.71	47.41	3.83	35.57
6	3.23	63.77	19.60	51.33	4.05	26.40
7	1.65	68.49	19.21	48.39	3.79	28.82
8	2.34	67.66	19.57	70.38	3.91	29.36

Table 2. (*Continued*).

Building number	Shale brick	Concrete	Transparent enclosure	Cement mortar	Thermal insulation materials	Steel products
9	1.54	65.13	30.11	52.24	3.79	45.16
10	2.09	64.04	29.36	53.21	4.81	44.04
11	1.80	62.48	30.32	40.82	4.18	62.48
12	1.72	65.12	30.48	47.57	3.03	66.72
13	3.98	71.74	30.48	81.44	6.02	50.72
14	2.80	64.76	30.50	45.59	5.77	45.75
15	2.40	63.24	30.50	26.98	4.36	45.75
16	1.84	63.18	30.27	42.51	6.50	50.41
17	1.58	65.81	30.05	51.11	6.77	45.08
18	1.94	63.21	30.39	30.74	5.52	45.58
19	1.67	63.97	30.39	44.05	5.90	45.58
20	1.90	64.52	30.28	39.04	5.79	45.42

Generally, the total nitrogen emission of building materials per unit building area of 20 residential buildings is 96.76–156.80 kg/m^2, and the average nitrogen emission is 126.78 kg/m^2. Among them, the proportion of nitrogen emissions from concrete, cement mortar, and steel is large, 36.79%, 30.50%, and 17.02%, respectively, accounting for a total of residential buildings and 84.31% of total nitrogen emission emissions of building materials. The nitrogen emissions of the transparent enclosure, thermal insulation materials, and shale bricks account for 5.00%, 3.59%, and 3.15%, respectively.

It can be seen from the above analysis that the nitrogen emission factor of primary building materials such as concrete, cement mortar, and steel is high, and the consumption of concrete, cement mortar, and steel in residential buildings with reinforced concrete shear wall structures is very large. Therefore, for residential buildings to apply for green building evaluation marks, the space scale of residential buildings must be considered in the civil engineering industry. Reduce the waste of building materials. At the same time, the durability and recycling of building materials must be considered to reduce the maintenance and replacement of building materials. Moreover, due to the high thermal performance requirements of thermal insulation materials and transparent enclosures, thermal insulation materials and transparent enclosures with low nitrogen emission factors must be considered in the civil engineering industry.

3.3. Design parameters and nitrogen emission of building materials

For residential buildings, the factors that affect the total nitrogen emissions of building materials mainly include the shape, number, and distribution of each space inside the building. From the architectural design perspective, the shape and quantity include the design parameters such as the total building area, building cover area, building surface area, and the total height of the building. number of floors, etc. The design parameters for the distribution of various spaces inside the building include the number and corresponding area of various functional rooms on the standard floor.

Considering the above factors, based on the essential information in **Table 1**, this study supplements the basic parameters of residential building design. It refines the analysis parameters used to describe the nitrogen emissions of building materials. Then, using SPSS software, the correlation analysis is conducted on 24 basic parameters of residential building design and 15 analysis parameters describing the nitrogen emissions of building materials, as shown in **Table 3** and **Figure 1**. Then, nitrogen emission prediction models based on different design parameters are established using the following two prediction methods. The two prediction methods are respectively: the first one is house type design parameters, namely, the shape and quantity of buildings, the distribution of each space inside buildings, house type functions, and other parameters; the second one is building material parameters, namely, the amount of concrete, cement mortar, steel, transparent enclosure, and other building materials.

Table 3. 24 parameters for residential building design and 15 parameters for describing nitrogen emission from building materials.

Number	Parameters for residential building design	Number	Parameters for residential building design (A20–A24) Parameters for describing nitrogen emission (A25–A39)
A0	Number of floors above ground	A20	Total number of rooms in public areas
A1	Number of floors below ground	A21	Standard layer width
A2	Number of standard stairs	A22	Standard layer depth
A3	Number of standard floor households	A23	Perimeter of standard layer
A4	Total number of households	A24	Average window wall ratio
A5	Total building area	A25	Total nitrogen emission intensity of building materials
A6	Standard floor area	A26	Total nitrogen emission building materials
A7	Building surface area	A27	Nitrogen emission of shale brick
A8	Figure coefficient	A28	Nitrogen emission intensity of shale brick
A9	Number of bedrooms on standard floor	A29	Nitrogen emission concrete
A10	Total number of bedrooms	A30	Nitrogen emission intensity of concrete
A11	Number of toilets on a standard floor	A31	Nitrogen emission from steel
A12	Total number of toilets	A32	Nitrogen emission intensity of steel
A13	Number of rooms on a standard floor	A33	Nitrogen emission of cement mortar
A14	Total rooms	A34	Nitrogen emission strength of cement mortar
A15	Number of main functional rooms on the standard floor	A35	Nitrogen emission from insulation materials
A16	Total number of main functional rooms	A36	Nitrogen emission intensity of insulation materials
A17	Number of indoor rooms on a standard floor	A37	Nitrogen emission of transparent enclosure
A18	Total number of indoor rooms	A38	Nitrogen emission intensity of transparent enclosure 1
A19	Number of rooms in the public area of the standard floor	A39	Nitrogen emission intensity of transparent enclosure 2

Note: A38 and A39 in **Table 3** are nitrogen emissions per unit building area and nitrogen emissions per unit material area, respectively.

Figure 1 shows that the separators have four kinds of correlations: extremely significant positive correlation 0.95, significant positive correlation 0.90–0.95, positive correlation 0.85–0.90, and negative correlation.

A1	0.12																																						
A2	-0.54	0.10																																					
A3	-0.70	0.10	1.00**																																				
A4	0.36	0.16	0.39	0.43																																			
A5	0.37	0.18	0.39	0.42	0.98**																																		
A6	-0.44	0.31	0.93**	0.93**	0.43	0.46																																	
A7	0.37	0.18	0.39	0.42	0.99**	0.97**	0.41																																
A8	0.14	-0.52	-0.48	-0.51	-0.29	-0.37	-0.67	-0.27																															
A9	-0.48	0.19	0.97**	0.97**	0.38	0.41	0.96**	0.36	-0.56																														
A10	0.39	0.18	0.40	0.42	0.98**	0.99**	0.46	0.96**	-0.35	0.44																													
A11	-0.52	0.16	0.99**	0.99**	0.42	0.41	0.94**	0.41	-0.51	0.97**	0.41																												
A12	0.41	0.17	0.42	0.43	1.00**	0.98**	0.44	0.99**	-0.29	0.41	0.99**	0.43																											
A13	-0.36	0.26	0.93**	0.94**	0.44*	0.44*	0.94**	0.43*	-0.75	0.93*	0.44*	0.93**	0.44*																										
A14	0.37	0.18	0.39	0.42	0.99**	0.98**	0.42	0.97**	-0.33	0.38	0.97**	0.40	0.99**	0.48																									
A15	-0.53	0.20	0.97**	0.97**	0.40	0.43	0.95**	0.38	-0.59	1.00**	0.44	0.97**	0.40	0.93**	0.52*																								
A16	0.37	0.18	0.39	0.42	0.98**	1.00**	0.45	0.96**	-0.33	0.43	1.00**	0.40	0.98**	0.46	0.97**	0.43																							
A17	-0.43	0.28	0.94*	0.94**	0.46	0.47*	0.93**	0.45	-0.03	0.93**	0.46	0.93**	0.46	0.99**	0.51*	0.93**	0.46																						
A18	0.36	0.17	0.38	0.42	0.99**	0.98**	0.41	0.97**	-0.33	0.39	0.97**	0.39	0.99**	0.47	1.00**	0.37	0.97**	0.46*																					
A19	0.30	0.02	0.48*	0.50*	0.94*	0.93*	0.51*	0.93*	-0.32	0.46	0.93*	0.48	0.94*	0.53	0.93*	0.46	0.93*	0.49	0.93*																				
A20	0.39	0.18	0.40	0.42	0.99**	0.98**	0.43	0.97**	-0.34	0.39	0.97**	0.41	0.99**	0.49	1.00**	0.39	0.97**	0.48*	1.00*	0.93*																			
A21	-0.56	0.26	0.94*	0.94*	0.52	0.42	0.97**	0.40	-0.72	0.95**	0.42	0.94*	0.39	0.91*	0.40	0.95**	0.41	0.91*	0.40	0.48*	0.40																		
A22	0.17	-0.14	0.41	0.46	0.69*	0.67	0.43	0.71*	-0.17	0.33	0.65	0.39	0.69*	0.40	0.66*	0.33	0.66	0.36	0.67	0.78	0.67	0.43																	
A23	-0.45	0.20	0.93*	0.93*	38.13	0.39	0.96**	0.39	-0.55	0.91*	0.39	0.93*	0.38	0.91*	0.39	0.90*	0.39	0.84	0.39	0.48	0.39	0.97**	0.49																
A24	-0.45	-0.11	0.14	0.15	-0.36	-0.37	0.07	-0.36	0.04	0.11	-0.38	0.11	-0.36	0.10	-0.34	0.11	-0.37	0.11	-0.34	-0.31	-0.34	0.03	-0.32	0.05															
A25	-0.11	-0.56	-0.13	-0.14	-0.28	-0.32	-0.25	-0.20	0.33	-0.24	-0.33	-0.17	-0.28	-0.15	-0.25	-0.24	-0.33	-0.16	-0.25	-0.17	-0.25	-0.22	0.04	-0.13	0.14														
A26	0.39	0.18	0.40	0.42	0.98**	0.98**	0.45	0.99**	-0.34	0.40	0.97**	0.41	0.98**	0.48	0.99**	0.40	0.97**	0.48	0.99**	0.88	0.99**	0.41	0.73	0.41	-0.35	-0.21													
A27	-0.15	-0.15	0.62*	0.69*	0.54*	0.50*	0.55*	0.53	-0.08	0.56	0.51	0.63	0.55	0.49	0.48	0.56	0.52	0.47	0.48	0.62	0.48	0.54	0.57	0.56	-0.01	-0.10	0.48												
A28	-0.72	-0.30	0.24	0.25	-0.59	-0.59	0.12	-0.59	0.11	0.21	-0.57	0.20	-0.59	0.05	-0.61	0.21	-0.58	0.07	-0.61	-0.47	-0.61	0.13	-0.34	0.12	0.61	0.24	-0.61	0.13											
A29	0.37	0.18	0.40	0.42	0.97**	0.98**	0.47	0.97**	-0.35	0.41	0.96**	0.41	0.97**	0.48	0.97**	0.41	0.97**	0.47	0.97**	0.93*	0.97**	0.44	0.75	0.44	-0.41	-0.24	0.99**	0.48	-0.64										
A30	0.14	-0.61	-0.10	-0.10	0.11	0.10	-0.17	0.16	0.27	-0.20	0.06	-0.15	0.11	-0.15	0.13	-0.20	0.07	-0.16	0.13	0.25	0.13	-0.10	0.05	-0.03	-0.15	0.65	0.17	0.00	-0.18	0.21									
A31	0.35	0.17	0.38	0.42	0.98**	0.99**	0.43	0.97**	-0.33	0.40	0.99**	0.39	0.98**	0.46	0.99**	0.40	0.98**	0.53	0.99**	0.93*	0.99**	0.38	0.66	0.38	-0.31	-0.25	0.99**	0.49	-0.56	0.98**	0.11								
A32	0.19	-0.59	-0.31	0.33	-0.01	-0.01	-0.44	0.05	0.51	-0.36	-0.03	-0.35	-0.01	-0.40	0.00	-0.36	-0.03	-0.39	0.00	0.03	0.00	-0.41	0.08	-0.38	0.20	0.60	0.04	0.02	0.05	0.00	0.59	0.03							
A33	0.40	0.09	0.37	0.39	0.95**	0.94*	0.39	0.97**	-0.26	-0.37	0.93*	0.38	0.96**	0.45	0.97**	-0.37	0.94*	0.44	0.97**	0.93*	0.97**	0.36	0.72	0.38	-0.40	-0.07	0.97**	0.52	-0.60	0.97**	0.23	0.97**	0.12						
A34	0.39	-0.50	-0.33	-0.35	-0.37	-0.40	-0.46	-0.33	0.38	-0.40	-0.41	-0.33	-0.37	-0.33	-0.33	-0.40	-0.41	-0.33	-0.33	-0.32	-0.33	-0.40	-0.20	-0.33	-0.07	0.87*	-0.33	-0.21	0.15	-0.35	0.44	-0.36	0.49	-0.16					
A35	0.28	0.15	0.49	0.52	0.91*	0.93*	0.54	0.93*	-0.41	0.49	0.93*	0.49	0.93*	0.57	0.93*	0.49	0.93*	0.55	0.93*	0.93*	0.93*	0.49	0.75	0.53	-0.36	-0.21	0.93*	0.48	-0.49	0.93*	0.17	0.93*	-0.11	0.85	-0.35				
A36	-0.37	-0.15	0.34	0.37	-0.16	-0.13	0.30	-0.13	-0.33	0.31	-0.15	0.31	-0.16	0.36	-0.15	0.31	-0.15	0.35	-0.15	-0.07	-0.15	0.31	0.09	0.33	0.12	0.30	-0.11	-0.05	0.38	-0.12	0.14	-0.14	-0.15	-0.11	0.15	0.16			
A37	0.31	0.44	0.41	0.44	0.87*	0.89*	0.50	0.90*	-0.48	0.45	0.90*	0.42	0.81	0.55	0.93*	0.45	0.82	0.54	0.93*	0.73	0.93*	0.41	0.49	0.41	-0.09	-0.35	0.83	0.36	-0.50	0.80	-0.12	0.93*	-0.11	0.77	-0.49	0.77	-0.09		
A38	0.01	0.24	-0.21	-0.22	-0.31	-0.31	-0.15	-0.29	-0.13	-0.22	-0.34	-0.22	-0.31	-0.04	-0.25	-0.22	-0.33	-0.05	-0.25	-0.34	-0.25	-0.27	-0.43	-0.24	0.65	0.16	-0.26	-0.36	0.18	-0.34	-0.26	-0.25	0.10	-0.29	0.06	-0.33	0.08	0.08	
A39	-0.08	0.47	0.00	-0.00	-0.22	-0.18	0.16	-0.25	-0.56	0.06	-0.18	0.03	-0.22	0.22	-0.15	0.06	-0.19	0.21	-0.15	-0.18	-0.15	0.08	-0.32	0.06	0.11	-0.14	-0.16	-0.35	-0.01	-0.18	-0.39	-0.16	-0.46	-0.21	-0.09	-0.16	0.15	0.15	0.52
	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35	A36	A37	A38

Figure 1. The analysis chart of the correlation between the design parameters of residential buildings and the nitrogen emission of building materials.

Among them, (1) The parameters with extremely significant positive correlation are:

Total nitrogen emission of building materials (A26) and total number of households (A4), total building area (A5), building surface area (A7), total number of bedrooms (A10), total number of toilets (A12), total number of rooms (A14), total number of main functional rooms (A1 6), total number of indoor rooms (A18), total number of rooms in public areas (A20), concrete nitrogen emission (A29) Between steel nitrogen emission (A31) and cement mortar nitrogen emission (A33), 2) concrete nitrogen emission (A29) and total number of households (A4), total building area (A5), building surface area (A7), total number of bedrooms (A10), total number of toilets (A1 2), total number of rooms (A14), total number of main functional rooms (A1 6), total number of indoor rooms (A18) Between the total number of rooms in the public area of residential buildings (A20), steel nitrogen emissions (A31), and cement mortar nitrogen emissions (A33), 3) between steel nitrogen emissions (A31) and the total number of households (A4), total building area (A5), and building surface area(A7), total number of bedrooms in residential buildings (A10), total number of toilets in residential buildings (A12), total number of rooms in residential buildings (A14), total number of main functional rooms in residential buildings (A16), total number of indoor rooms in residential buildings (A18), total number of rooms in public areas in residential buildings (A20), cement mortar nitrogen emissions (A33), 4) cement mortar nitrogen emissions (A33) and total number of households (A4),building surface area (A7) Total number of toilets in residential buildings (A12), total number of rooms in residential buildings (A14), total number of rooms in residential buildings (A18), and total number of rooms in public areas in residential buildings (A20).

(2) The parameters with significant positive correlation are: 1) the total nitrogen emissions of building materials (A26) and the number of rooms in the public area of the standard floor (A19), the nitrogen emissions of insulation materials (A35), 2) the nitrogen emissions of steel (A31) and the number of rooms in the public area of the standard floor (A19), the nitrogen emissions of insulation materials (A35), the nitrogen emissions of transparent enclosures (A37), 3) the nitrogen emissions of cement mortar (A33) and the total building area (A5) Between the total number of bedrooms in residential buildings (A10), the total number of main functional rooms in residential buildings (A16), and the number of rooms in public areas of standard floors (A19), 4) the nitrogen emission of insulation materials (A35) and the total number of households (A4), the total building area (A5), the building surface area (A7), the total number of residential buildings (A12), the total number of rooms in residential buildings (A1 4) Between the total number of main functional rooms (A16), the total number of indoor rooms (A1 8), the number of rooms in the public area of the standard floor (A1 9), the total number of rooms in the public area of the residential building (A20), and the concrete nitrogen emissions (A29), 5) the nitrogen emissions of the transparent enclosure (A37) and the total number of rooms in the residential building (A14), the total number of indoor rooms in the residential building (A18), and the total number of rooms in the public area of the residential building (A20).

(3) The parameters with negative correlation are: 1) between shape coefficient (A8) and other design parameters, 2) between average window wall ratio (A24) and other design parameters, 3) between nitrogen emission intensity of transparent

enclosures (A38, A39) and other design parameters; 4) between total nitrogen emission intensity of building materials (A25) and other design parameters; 5) between nitrogen emission intensity of shale bricks (A28) and other design parameters. 6) Between the nitrogen emission strength of cement mortar (A34) and other design parameters, and between the nitrogen emission strength of insulation materials (A36) and other design parameters.

To sum up, the increase in building volume will reduce the shape coefficient of residential buildings but, at the same time, increase the total building area of residential buildings, so the total nitrogen emission of building materials will increase. In contrast, the total nitrogen emission intensity of building materials will decrease. At the same time, because the consumption of building materials and nitrogen emissions of transparent enclosure structures account for a small proportion, the average window wall ratio has a limited impact on the total nitrogen emissions of building materials. In addition, the nitrogen emission intensity is directly proportional to the nitrogen emission coefficient. Compared with the total nitrogen emission of building materials, the nitrogen emission intensity of building materials is not closely related to the design parameters of residential buildings, which is insufficient to provide a practical reference for the low nitrogen design of residential buildings.

4. Prediction model and validation of nitrogen emission from building materials

4.1. Prediction model of total nitrogen emissions of building materials-prediction based on house-type design parameters

In this study, the relationship between 12 highly significant positive correlation parameters and the total nitrogen emissions of building materials was conducted in linear, logistic, and quadratic terms (4 of the 12 design parameters are selected as representatives in **Figure 2**). The results show that the design parameters have a significant linear relationship with the total nitrogen emissions of building materials, which can be directly used to build a linear regression model.

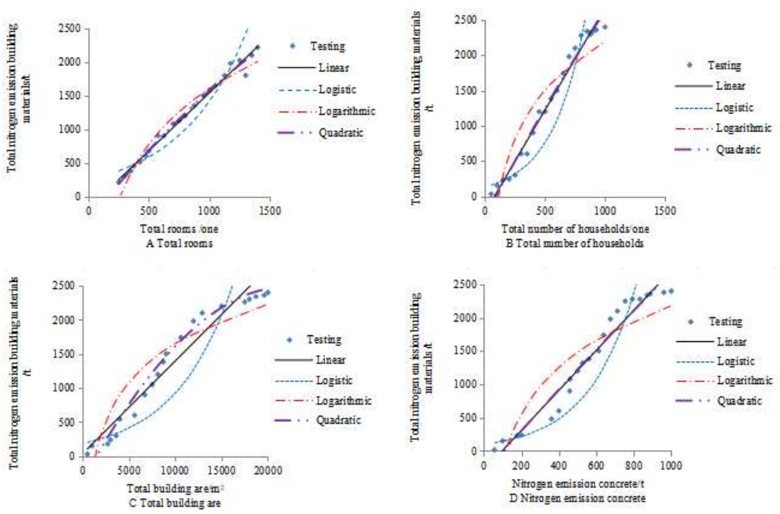

Figure 2. The curve evaluation results between design parameters of residential buildings and total nitrogen emission of building materials.

The rooms on the standard floor of the residential building include the main functional rooms (bedroom and living room) and the secondary functional rooms (such as toilets, kitchens, and staircases). In the design of residential buildings, the living room and dining room can be combined and designed with the number of households equivalent to the standard floor, so the total number of main functional rooms of residential buildings is equal to the product of "the number of floors above the ground of residential buildings" and "the sum of the number of bedrooms on the standard floor and the number of households on the standard floor." At the same time, because the window-to-floor ratio of residential buildings is variable, the exterior area of residential buildings changes in a particular range, and the value is not unique. Therefore, this study uses other parameters of residential building design to evaluate the exterior area of residential buildings.

According to the curve fitting in **Figure 3**, the combined variable based on the width and depth of the standard floor and the number of floors above the ground of the residential building, as well as the quadratic curve of the combined variable, can describe the exterior area of the residential building, and its linear and nonlinear equations can be substituted into the fitting process of the prediction model of total nitrogen emissions of building materials. To further refine the main design parameters that affect the nitrogen emissions of building materials in the process of fitting the prediction model of total nitrogen emissions of building materials, this study uses an advanced method to remove insignificant independent variables and uses a ridge regression model to reconstruct the design parameters with collinearity characteristics.

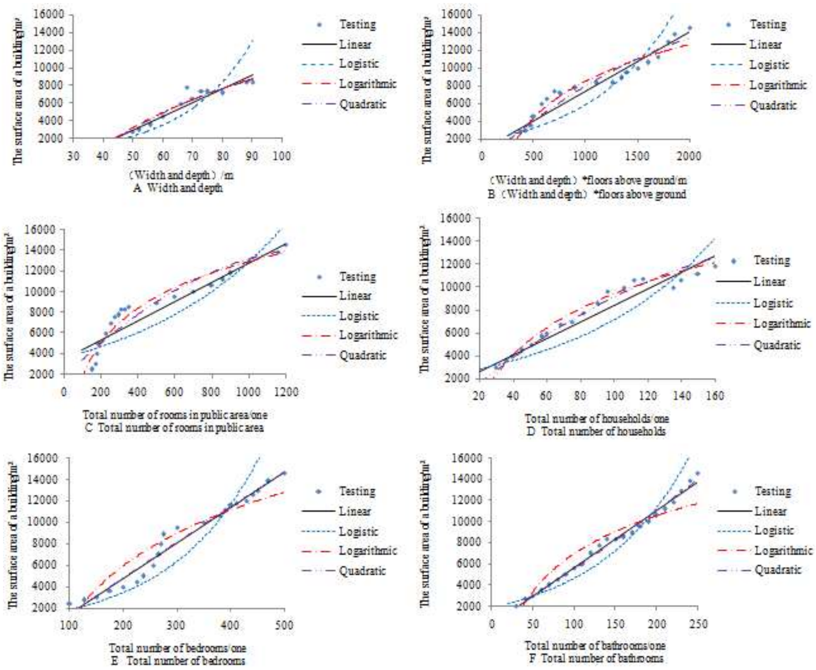

Figure 3. The curve evaluation result of residential building design parameters and exterior surface area.

In this study, Equations (1)–(6) represents the establishment of a prediction model for the total nitrogen emissions of six building materials (based on the design parameters of the house type):

$$G1 = 396.90 * S + 179{,}617.37 \quad (1)$$
$$G2 = 0.82 * (N1 + N2)^2 * (w + d)^2 + 5550.26 * (N1 + N2) * (w + d) - 832{,}949.88 \quad (2)$$
$$G3 = 3451.96 * (N1 + N2) * (w + d) + 9632.11 * (w + d) - 474{,}303.08 \quad (3)$$
$$G4 = 2293.79 * (N1 + N2) * (w + d) + 9916.80 * (w + d) + 5450.36 * N3 * N1 - 313{,}796.61 \quad (4)$$
$$G5 = 2096.76 * (N1 + N2) * (w + d) + 9985.25 * (w + d) + 4562.21 * N4 * N1 - 279{,}195.76 \quad (5)$$
$$G6 = 3533.96 * (N1 + N2) * (w + d) + 12{,}350.15 * N5 - 3633.50.76 \quad (6)$$

S is the total building area (m^2), *w* and *d* are the face width and depth (m) of the standard floor, *N*1 and *N*2 are, respectively, the number of floors above and below the ground of the residential building, *N*3, *N4,* and *N*5 are respectively the number of bedrooms, rooms with main functions, and the total number of rooms in the standard floor of the residential building, and *G*1 to *G*6 are the total nitrogen emissions in the production stage of building materials of models M1 to M6 (kg).

M1 to M6 are built based on house-type design process parameters (**Table 4**). M1 is a model based on the total area of residential buildings as a variable, which can only be applied to the total nitrogen emissions of building materials in the planning stage of residential building projects. M2 to M6 use multiple combined variables to replace the surface area of buildings. Combination variables of M2 to M6 are based on the internal space scale of residential buildings (including the number of bedrooms on the standard floor, the number of main functional rooms, and the total number of rooms). Except for M1, the adjusted R^2 is greater than or equal to 0.986, which is a good fit. Therefore, the project planning, scheme design, preliminary expansion design, detailed design, and other processes of this residential building can provide a reference for low nitrogen emissions of residential buildings.

Table 4. The fitting of the model for predicting the total nitrogen emission of building materials-the prediction according to the parameters of household design.

Model	Variable	Construction method	Adjusted R^2
M1	*S*	Linear regression	0.916
M2	*N*1, *N*2, *w*, *d*	Nonlinear regression	0.986
M3	*N*1, *N*2, *w*, *d*	Linear regression	0.989
M4	*N*1, *N*2, *w*, *d*, *N*3	Ridge regression $K = 0.008$	0.989
M5	*N*1, *N*2, *w*, *d*, *N*4	Ridge regression $K = 0.008$	0.989
M6	*N*1, *N*2, *w*, *d*, *N*5	Linear regression	0.987

4.2. Indirect prediction model of total nitrogen emissions from building materials

The total nitrogen emission of concrete, cement mortar, steel, and transparent enclosure structures accounts for 89.31% of the total nitrogen emission of building materials. According to the significance of design parameters and the degree of optimization of model fitting, regression models of nitrogen emissions from concrete (Mh1 and Mh2), steel (Mg1 and Mg2), and cement mortar (Mss) are established, respectively. Mc1 and Mc2 are represented by Equations (7) and (8), Ms1 and Ms2 are represented by Equations (9) and (10), and Mass is represented by Equation (11):

$$\mathrm{Gh1} = 1385.30 * (N1 + N2) * (w + d) + 3980.80 * (w + d) - 242{,}373.03 \quad (7)$$
$$\mathrm{GGh2} = 1401.30 \times (N1 + N2) * (w + d) + 116{,}03.86 * N4 - 193{,}878.00 \quad (8)$$

$$\mathrm{Gg1} = 715.39 \times (N1 + N2) * (w + d) - 48{,}019.30 \quad (9)$$

$$\mathrm{Gg2} = 363.80 * (N1 + N2) * (w + d) + 1197.95 * N5 * N1 + 5087.86 \quad (10)$$

$$\mathrm{Gss} = 1085.28 * (N1 + N2) * (w + d) + 21{,}755.86 \quad (11)$$

Gh1, Gh2, Gg1, Gg2, and Gss represent the nitrogen emissions (kg) in the corresponding building material production stage. At the same time, this study builds an aggression model (Mt) for nitrogen emissions of transparent enclosures based on the perimeter of standard floors, number of floors above ground, and average window wall ratio of residential buildings:

$$Gt = 107.86 * Sc + 21{,}282.16 \quad (12)$$

$$Sc = 3.26 * [2.96 * (w + d) - 20.50] * N1 * Q - 39.16 \quad (13)$$

Gt is the nitrogen emission in the production phase of transparent enclosures (kg), *Sc* is the total area of windows in residential buildings (m^2), and *Q* is the average window wall ratio.

It can be seen from **Table 5** that Equations (14)–(17) represent the establishment of a prediction model for total nitrogen emissions of four building materials (based on the prediction of building material parameters):

$$G7 = \frac{\mathrm{Gh1} + \mathrm{Gg1} + \mathrm{Gss}}{90.90\%} + Gt \quad (14)$$

$$G8 = \frac{\mathrm{Gh1} + \mathrm{Gg2} + \mathrm{Gss}}{90.90\%} + Gt \quad (15)$$

$$G9 = \frac{\mathrm{Gh2} + \mathrm{Gg1} + \mathrm{Gss}}{90.90\%} + Gt \quad (16)$$

$$G10 = \frac{\mathrm{Gh2} + \mathrm{Gg2} + \mathrm{Gss}}{90.90\%} + Gt \quad (17)$$

The above prediction model estimates the total nitrogen emission of building materials through concrete, steel, cement mortar, and transparent enclosure structures. This may reduce the fitting accuracy to a certain extent but can significantly reflect the nitrogen emission distribution and change the characteristics of the primary building materials.

Table 5. Prediction model of total nitrogen emission from building materials and the fitting of the combination part-prediction according to the parameters of building materials.

Model	**Variable**	**Construction method**	**Adjusted R^2**
Mh1	*N*1, *N*2, *w*, *d*	Linear regression	0.996
Mh2	*N*1, *N*2, *w*, *d*, *N*5	Linear regression	0.996
Mg1	*N*1, *N*2, *w*, *d*	Linear regression	0.991
Mg2	*N*1, *N*2, *w*, *d*, *N*5	Ridge regression = 0.006	0.993
Mss	*N*1, *N*2, *w*, *d*	Linear regression	0.956
Mt	*N*1, *w*, *d*, *Q*	Linear regression	0.88
M7	Mh1, Mg1, Mss, Mt	Combination	0.986
M8	Mh1, Mg2, Mss, Mt	Combination	0.987
M9	Mh2, Mg1, Mss, Mt	Combination	0.986
M10	Mh2, Mg2, Mss, Mt	Combination	0.987

According to the above analysis, 10 models can fit the total nitrogen emissions of building materials in 20 residential buildings well (**Figure 4**). In contrast, since M1 has only one independent variable and is only based on the total building area, M2 is a nonlinear model established based on spatial shape parameters. The fitting effect of these two models is not as good as that of the other 8 models; M3–M5 requires a few independent variables, which can be used in different stages of architectural design. Compared with the other nine models, M6 has the most minor errors but requires the most independent variables, so it requires very high depth for architectural design.

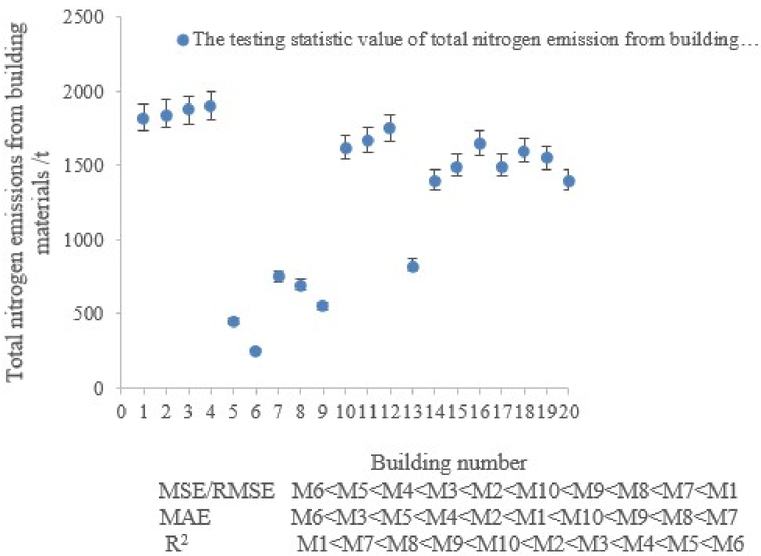

Figure 4. The fitting effect of the regression model.

4.3. Model validation of total nitrogen emissions from building materials

Based on selecting 20 residential buildings, this study selects 5 additional residential buildings (see **Table 6**); the prediction performance of the 10 models was analyzed from the following four aspects: mean square error MSE, root mean square error RMSE, mean absolute error MAE, and prediction goodness R^2.

Table 6. 5 validates design information of residential buildings and total nitrogen emissions from building materials.

Building number	S/m^2	$N1$	$N2$	w/m	d/m	Q	$N3$	$N4$	$N5$	Total nitrogen emissions from building materials/kg
21	9460.8	15	2	38.59	12.50	0.20	10	14	34	1,239,716.4
22	10,858.5	16	3	32.078	15.48	0.17	10	17	43	1,296,906.2
23	10,152.1	22	3	24.596	14.53	0.16	8	13	33.54	1,161,517.9
24	7386.4	20	2	20.4	14.96	0.20	7	9	22.95	821,896.17
25	14,356.1	21	2	42.0993	15.31	0.21	12	17	46.98	1,554,730.8

The verification results are shown in **Table 7** and **Figure 5**. It can be seen from the verification results of M1 and M2 that the prediction performance of M1 and M2 is poor, which indicates that only the total building area and spatial shape parameters of residential buildings cannot accurately provide practical guidance for the low nitrogen design of residential buildings. It can be seen from the verification results of M4 that the prediction performance of M4 is not ideal. This indicates that the total nitrogen emission of building materials cannot be accurately predicted through the internal space scale of residential buildings and the number of standard bedrooms in each building. It can be seen from the verification results of M3 and M5 that the error of M3 and M5 is low, and the prediction performance is good, which indicates that the spatial shape and internal spatial scale of residential buildings can be used to predict the total nitrogen emissions of building materials. It can be seen from the verification results of M6 that the error of M6 is the lowest. With the deepening of the conceptual design of residential buildings, M6 can provide the most ideal data support for the optimal design of residential buildings. At the same time, the prediction level from M7 to M10 is similar, so nitrogen emission of the primary building materials used can be targeted and analyzed in combination with the internal space design of residential buildings.

Table 7. 10 predictive performances of models.

Model	MSE	RMSE	MAE	R^2
M1	279,586.51	518.07	471.45	0.71
M2	297,587.44	537.27	400.67	0.76
M3	196,867.92	433.68	373.92	0.88
M4	207,197.58	434.31	382.98	0.80
M5	166,531.35	399.84	341.79	0.90
M6	181,954.79	420.12	365.28	0.96
M7	216,216.22	446.57	405.38	0.79
M8	211,772.69	457.15	405.45	0.78
M9	219,956.42	452.38	405.12	0.77
M10	210,976.31	462.46	405.75	0.78

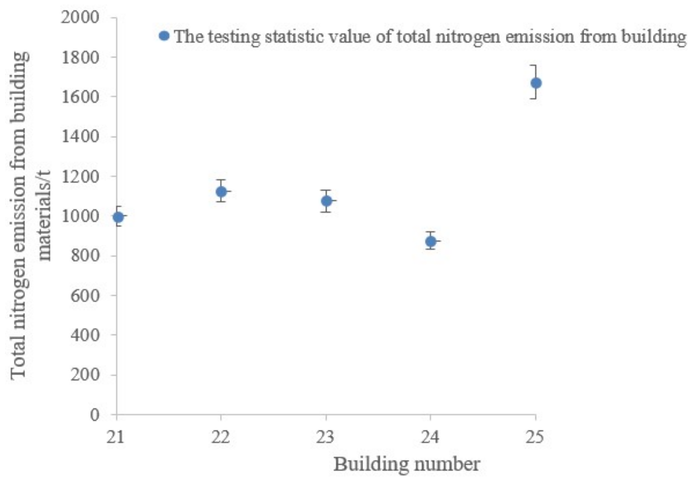

Figure 5. Model predictive performance validation based on 5 residential buildings.

5. Improvement for future research

Lifecycle Assessment: Expand the analysis to encompass nitrogen emissions from all lifecycle stages of building materials. This would offer a more holistic view of the environmental impact and better guide sustainable building practices.

Broaden Geographic Scope: Conduct similar studies in different regions to validate the findings and increase their generalization. This would help in understanding regional variations in building practices and environmental conditions.

Complexity of Models: While the regression models are statistically sound, their practical implementation may require specialized knowledge. Simplifying these models or providing user-friendly tools could enhance their usability for industry practitioners.

6. Conclusions

In this study, 20 residential buildings with cast-in-reinforcement concrete shear wall structures were taken as examples to analyze the total nitrogen emissions of building materials in the production process. The research shows that the proportion of nitrogen emissions from concrete, cement mortar, steel, and transparent enclosure structures accounts for 89.31% of the total nitrogen emissions from building materials. Although the nitrogen emission factor of concrete, cement mortar, and steel is low due to the large number of materials used in the overall construction process, to reduce the nitrogen emission, the shape and volume of buildings and the division form of internal space structure must be accurate in the design process. Using building materials with the best durability should be considered to maximize recycling of building materials. For a transparent enclosure structure, it is necessary to reasonably select low-nitrogen emission building materials based on green building design specifications and standards.

In this study, nitrogen emission prediction models based on different design parameters are established according to the following two prediction methods (house type design parameters and building material parameters), and 10 kinds of nitrogen emission prediction models are established and verified through the design parameters of different residential buildings. These 10 models can provide a reference for low nitrogen emissions of residential buildings in different stages of project planning, scheme design, preliminary expansion design, and deepening design of residential buildings. Among them, the prediction levels from M7 to M10 are similar, and the nitrogen emission of the primary building materials used can be targeted based on the internal space design of residential buildings. The linear model M1, based on the total building area, and the nonlinear model M2, based on the number of floors above and below ground, surface width, and depth, have poor prediction performance and significant errors. The prediction performance of the ridge regression model M4 based on the number of floors above and below ground, the width and depth of the area, and the total number of bedrooms is not ideal. Linear model M3 based on the number of floors above and below ground, face width, and depth, and ridge regression model M5 based on the number of floors above and below ground, face width and depth, and the total number of main functional rooms have good fitting and prediction performance. The linear regression model M6, based on the number of floors above and below ground, the width and depth of the area, and the total number of rooms, has the best fitting and prediction performance. M3, M5, and M6 can accurately predict the nitrogen emission composition and distribution characteristics of building materials in residential building design and lay a foundation for future research on nitrogen emission evaluation and calculation methods and nitrogen emission reduction technology strategies.

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

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