



Emission inventory of air pollutants from residential coal combustion over the Beijing-Tianjin-Hebei Region in 2020

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Abstract

To investigate the atmospheric pollutant emission from residential coal combustion (RCC) in BTH region in 2020, based on the bottom-up methodology, a high spatial and temporal resolution air pollutant emission inventory was established. The results showed that the emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs in BTH region in 2020 were 19.58, 15.67, 2.98, 8.33, 296.96, 3.51, 36.67, and 5.87 million tons, respectively. Chengde contributed the most PM_{2.5}, BC, OC, and VOCs in BTH region, accounted for 11.48%, 13.71%, 11.52%, and 12.72%, respectively. While Shijiazhuang contributed the most PM₁₀, CO, NO_x, and SO₂ in BTH region, accounted for 11.55%, 11.60%, 11.55%, and 12.10%, respectively. The spatial distribution characteristics of pollutants showed that high emissions concentrated in northern, eastern, and southern areas of BTH region. Based on the time distribution factor obtained from the long-term follow-up survey data of RCC of households in BTH region, the annual emissions of different cities were allocated according to the temporal resolution of monthly, daily, and hourly. It was found that for each pollutant, the highest emissions appeared in January; the higher emissions occurred in mid-December, early January, and mid-February; and the peak emission appeared at 8:00, 11:00, 18:00, and 21:00. Furthermore, the uncertainty analysis of the emission inventory was carried out by using the Monte Carlo method. This study provides a more high temporal and spatial resolution emission inventory of RCC for air quality model, which can accurately simulate regional pollutant emission scenarios.

Keywords Residential coal combustion · Air pollutants · Emission inventory · High resolution · Temporal and spatial distribution · Beijing-Tianjin-Hebei region

Introduction

The haze events in winter heating period have aroused great concern (Yi et al., 2014; Zhang et al., 2014). Beijing-Tianjin-Hebei (BTH) region lies between North China and Northeast China, containing Beijing, Tianjin, and 11 prefecture-level cities in Hebei Province (Fig. 1). In 2020, the heavy haze events frequently occurred in BTH region, and the heavy

haze days accounted for 3% of the total days (BEES, 2020; TEES, 2020; HPEES, 2020). PM_{2.5} (particles with aerodynamic equivalent diameter less than 2.5 microns in ambient air) as the main pollutant in the heating season of BTH region, excessive PM_{2.5} concentration has become an urgent environmental problem (Zhang et al., 2021a; Zhao et al., 2020). In 2020, cities in BTH region accounted for 40% of the top 10 cities with the worst air quality (CEB, 2020).

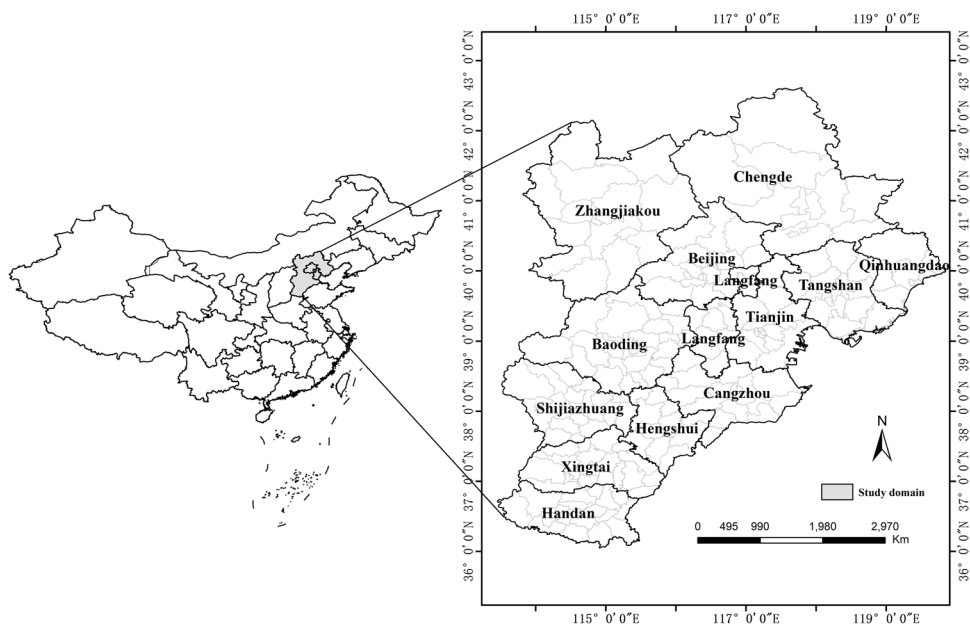
Residential coal was widely used for household heating in rural areas and was considered as an important source of pollutant emission (Zhang et al., 2021b; Zhang et al., 2022a; Wen et al., 2023). Different from the power plants and industrial sectors, there is no corresponding pollutant removal technology in the residential sector. In the use process, residential coal has the characteristics of high pollution intensity, low emission height, and dense population in emission areas, which is considered to be an important reason for the aggravation of air pollution in the heating season (Zhi et al., 2017; Shen et al., 2019). Therefore, it

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Fig. 1 Study domain



is essential to study the impact of RCC used for household heating on air pollution for formulating scientific and effective pollution prevention and control measures. The current emission inventory uses the statistical data of China Energy Statistical Yearbook to evaluate pollutant emissions in the residential sector (Tian et al., 2018; Shen et al., 2012). However, the existing statistical yearbooks differ greatly from the actual consumption of residential coal, and there is great uncertainty (Pan et al., 2016; Meng et al., 2019). Therefore, it is of great significance to establish the emission inventory of RCC pollutants in residential sector according to the actual survey data.

From 2010 to 2020, many scholars have conducted a series of studies on the energy consumption and pollutant emissions from rural residential sector in BTH region (Zhou et al., 2020; Peng et al., 2019; Cai et al., 2018). However, the traditional time allocation method based on the average annual emissions to monthly, daily, and hourly emissions is not consistent with the actual emission situation of RCC (Liu et al., 2016). Meanwhile, the traditional spatial allocation method with population density as the weight factor is quite different from the actual situation (Fu et al., 2013; Cao et al., 2011; Qi et al., 2017; Liu et al., 2018a; Cheng et al., 2017). This study conducted a series of studies on the use of residential coal. This study established the latest high temporal and spatial resolution emission inventory from RCC in BTH region, and used the Monte Carlo method to analyze the uncertainty of emission inventory. This study provides a reliable pollutant emission database for air quality model to simulate the regional air pollution, which is of great significance to the prevention and control of air pollution in BTH region.

Method and data

Emission inventory

Based on the survey of residential coal consumption activities and the optimal emission factors (EFs) determined in literature, the air pollutant emissions from RCC were calculated by the bottom-up method. The air pollutant emission inventory of RCC developed in this study includes PM_{10} , $PM_{2.5}$, BC, OC, CO, NO_x , SO_2 , and VOCs. According to the population of rural residents in Beijing Statistical Yearbook, Tianjin Statistical Yearbook, and Hebei Economic Yearbook in 2020 at the county level, the emission was calculated (NBSC, 2021). The air pollutant emission inventory of RCC was calculated according to the following formula.

$$E_i = A \times (B \times EF_{i,j} + R \times EF_{i,k}) / 1000 \quad (1)$$

where E_i represents the RCC emission (t) for pollutant i , including PM_{10} , $PM_{2.5}$, BC, OC, CO, NO_x , SO_2 , and VOCs; A represents the residential coal consumption (t); B represents the proportion of briquette utilization (%); $EF_{i,j}$ represents the emission factors (kg/t) for briquette combustion of pollutant i ; R represents the proportion of raw coal utilization (%); and $EF_{i,k}$ represents the emission factors (kg/t) for raw coal combustion of pollutant i .

Activity level

Research showed that the actual coal consumption in the household was quite different from the statistical data in

the Statistical Yearbook (Liu et al., 2017a; Li et al., 2018). Therefore, this study used the product of the annual per capita residential coal consumption estimated by Back Propagation (BP) neural network and the rural resident population in BTH region to calculate the residential coal consumption (Li et al., 2021). The surveys for the utilization ratio of briquette and raw coal in BTH region were carried out. Table S1 summarizes the use proportion of briquette and raw coal, and the residential coal consumption of counties of BTH region.

Emission factors

Relevant researches have shown that the EFs of air pollutants from RCC depend on the characteristics of coal and stove (Chen et al., 2015; Liu et al., 2018b), and they vary greatly in different combustion stages (Sun et al., 2014). In addition, the coal composition and sampling and testing methods also affect the EFs results. The production of CO is mainly related to the combustion efficiency. The fuller the combustion, the higher the heat load of the stove, the lower the CO concentration (Liang et al., 2017), which is related to the highly volatile content of coal (Carter et al., 2014). The emission of SO₂ from RCC is positively correlated with the sulfur content of coal and negatively correlated with the sulfur content of ash (Sun et al., 1988). Table S2 summarizes the air pollutant EFs of some field experiments and published data (Tian et al., 2018; Zhou et al., 2020; Peng et al., 2019; Cai et al., 2018; Cheng et al., 2017), and Table 1 shows the EFs used in this study.

Temporal allocation

The time distribution factor refers to the proportion of pollutants from RCC in the corresponding emission time (Shen et al., 2020). Due to the characteristics of unorganized and low-altitude emissions, it is difficult to carry out real-time monitoring of pollutant emissions from RCC. Considering that the emission of pollutants from RCC is directly related to the consumption of residential coal, this study reflects the proportion of pollutants from RCC in the corresponding time according to the long-term follow-up survey data of residential coal combustion (daily coal addition time and coal addition amount) of households in BTH region, and obtains the emission characteristics of monthly, daily, and hourly variation of pollutants from RCC. The time distribution factor is calculated using the following formula.

$$K_i = \frac{A_i}{\sum A_i} \tag{6}$$

$$E_{i,j} = K_{i,j} \times E_{y,j} \tag{7}$$

where K_i is the i (monthly/daily/hourly) distribution factor, A_i is the i (monthly/daily/hourly) residential coal consumption (t), $\sum A_i$ is the i (monthly/daily/hourly) residential coal consumption in total (t), $E_{i,j}$ is the j (PM₁₀/PM_{2.5}/BC/OC/CO/NO_x/SO₂/VOCs) emission (t) corresponding to the i (monthly/daily/hourly) distribution factor, and $E_{y,j}$ is the annual emission (t) of j (PM₁₀/PM_{2.5}/BC/OC/CO/NO_x/SO₂/VOCs).

Spatial allocation

The spatial distribution factor refers to the proportion of pollutant emissions from RCC in the total pollutant emissions in each grid (Sun et al., 2019). According to the air pollutant emissions from RCC and the vector map data of cities, districts, and counties in BTH region, the spatial distribution factor is constructed. The air pollutant emissions from RCC are distributed by ArcGIS software, and the spatial distribution characteristics of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs emission from RCC in BTH region are obtained. The spatial distribution factor is calculated using the following formula.

$$S_{x,y} = \frac{E_{x,y}}{\sum_{x=1,y=1}^{x=m,y=n} E_{x,y}} \tag{8}$$

where $S_{x,y}$ is the spatial distribution factor for the grid corresponding to the horizontal and vertical coordinates (x,y), $E_{x,y}$ is the pollutant emission (t) for the grid corresponding to the horizontal and vertical coordinates (x,y), m and n are the total number of grids in the horizontal and vertical coordinates, respectively, and $\sum_{x=1,y=1}^{x=m,y=n} E_{x,y}$ is the total emission of pollutants (t) from RCC in each grid.

Uncertainty analysis

As shown in Eq. (1), the emission of air pollutants from RCC depends on the EFs of pollutant and the activity levels of residential coal (Zheng et al., 2021). Due to the characteristics of emission sources, the activity level of residential coal is not easy to calculate. In addition, differences exist between

Table 1 EFs of RCC used in this study (g/kg)

| Coal type | PM ₁₀ | PM _{2.5} | BC | OC | CO | NO _x | SO ₂ | VOC |
|-----------|------------------|-------------------|------|------|--------|-----------------|-----------------|------|
| Raw coal | 9.67 | 8.05 | 1.92 | 4.31 | 145.74 | 1.73 | 16.85 | 3.44 |
| Briquette | 4.19 | 3.07 | 0.24 | 1.61 | 64.3 | 0.75 | 8.97 | 0.77 |

yearbook statistics and the actual situation (Tao et al., 2018). Uncertainty inevitably exists in the air pollutant emissions from RCC. In this study, the Monte Carlo method was used to calculate the uncertainty of air pollutant emission from RCC (Zhang et al., 2022b). The principle of Monte Carlo method is to quantify the uncertainty of the corresponding output by repeated random sampling of model input parameters (EPA, 1997). The random sampling error is calculated using the following formula.

$$RSE_- = (E_{5\%} - E_{ave}) / E_{ave} \quad (9)$$

$$RSE_+ = (E_{95\%} - E_{ave}) / E_{ave} \quad (10)$$

where RSE_- is the relatively negative random sampling error, $E_{5\%}$ is the emission of pollutant (t) at 5% confidence level, E_{ave} is the average pollutant emission (t), RSE_+ is the relatively positive random sampling error, and $E_{95\%}$ is the emission of pollutant (t) at 95% confidence level.

Results and discussion

Estimates of air pollutant emissions in 2020

The air pollutant emissions from RCC were calculated according to the method described in the “Emission inventory” section. Table S3 lists the coal consumption and air pollutant emissions of the different cities. In 2020, the residential coal consumption for household heating in BTH region was 2889.04 million tons. It is estimated that the total coal consumptions in Beijing, Tianjin, and Hebei were 377.67, 311.14, and 2200.23 million tons, respectively. They were approximately 11, 13, and 1.7 times higher than the

results in the China Energy Statistical Yearbook, respectively (CESY, 2020; CESY, 2021). Many residential energy consumption surveys’ results showed that the current statistical data seriously underestimated the use of residential coal (Zhou et al., 2020; Peng et al., 2019; Cheng et al., 2017). In the study of urban coal consumption of RCC, Shijiazhuang coal consumption is highest, accounting for 14% of the total coal consumption in BTH region. Beijing (13%), Tianjin (11%), and Baoding (12%) also had higher coal consumption. The statistical methods for data collection, reporting, and validation by national statistical offices in China are not always consistent, which causes the difference between the statistical yearbook and the actual situation (Peng et al., 2019).

Figure 2 shows the city-level emission from RCC in BTH region in 2020. The total emissions of PM_{10} , $PM_{2.5}$, BC, OC, CO, NO_x , SO_2 , and VOCs were 19.58, 15.67, 2.98, 8.33, 296.96, 3.51, 36.67, and 5.87 million tons in BTH region, respectively. CO and SO_2 are the major contributors of emissions from RCC, of which about 76% come from CO and 9% come from SO_2 , while other emissions are mainly from PM_{10} and $PM_{2.5}$. Similar results can also be found in other studies (Zhong et al., 2018a; Bai et al., 2020; Zhu et al., 2020). The incomplete combustion of residential coal leads to high CO emissions. Different from coal consumption in industrial combustion, RCC is still the focus of SO_2 emission reduction policy in the future due to the lack of corresponding control measures. From city-level perspective, the total pollutant discharge in Beijing, Tianjin, and Hebei reached 31.68, 39.52, and 318.35 million tons, respectively. Tianjin, Baoding, Chengde, and Shijiazhuang all contributed more than 10% of the total pollutant emissions from RCC in BTH region. It is worth noting that Chengde contributed the most $PM_{2.5}$, BC, OC, and VOCs in BTH region, which

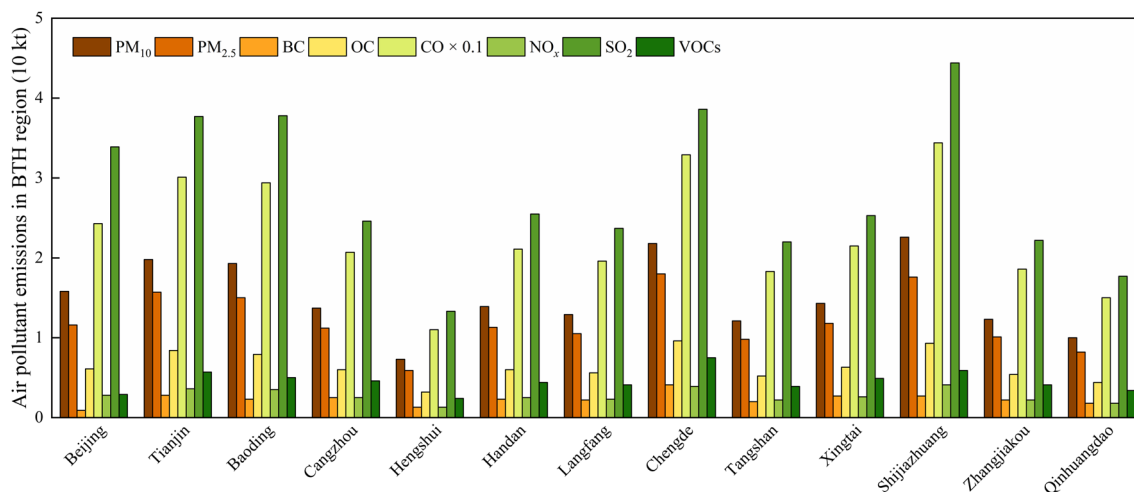


Fig. 2 Air pollutant emissions from RCC in BTH region in 2020

accounted for 11.48%, 13.71%, 11.52%, and 12.72%, respectively, while Shijiazhuang contributed the most PM₁₀, CO, NO_x, and SO₂ in BTH region, which accounted for 11.55%, 11.60%, 11.55%, and 12.10%, respectively. The results are directly related to the data of residential coal activity level and the proportion of two types of coal used in this study. Specifically, the utilization ratios of briquette and raw coal in BTH region were derived from the survey results (Table S1). The proportion of briquette used in Shijiazhuang is 0.74, which is twice the average proportion of briquette used in BTH region (0.41 in average). The proportion of raw coal used in Chengde is 0.84, which is one time the average proportion of briquette used in BTH region (0.59 in average). As for the activity level, Shijiazhuang contributed the largest residential coal consumption (14%) and Chengde contributed the highest raw coal consumption (13%), which is related to the rural resident population and per capita annual coal consumption. It can be obtained from Table S1 that the population of rural residents in BTH region is 4501.5 million. Among them, Shijiazhuang accounted for 15% (695.5 million) and Chengde accounted for 7% (302.1 million) (NBSC, 2021). In addition, the reason for the large emission of pollutants from RCC may be related to the differences in economic development level, income level, and energy supply in the study area (Wang et al., 2017; Silveira et al., 2017; Qiu et al., 2018). Our 2020 BTH region estimated OC, CO, and NO_x emissions were similar to those in 2013 obtained by Cheng et al. (2017), while our estimated PM₁₀, PM_{2.5}, BC, and VOCs emissions were lower than their results. Considering that the base years were too far apart, the emission in this study is much lower than that in other researches (Zhi et al., 2017; Cai et al., 2018; Cheng et al., 2017; Ru et al., 2015). In conclusion, the pollutant emission in various regions was

affected by the coal consumption, the use proportion of briquette and raw coal, and the EFs of pollutants, which was the same as the findings of Peng et al. (2019).

Table 2 shows the comparison of our estimated emissions of air pollutant from RCC with other results. In 2020, the estimated PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs emissions in Beijing, Tianjin, and Hebei in our study were 1–74, 1–14, and 2–16 times of those in Cheng et al. (2017), respectively. For Beijing, the 2020 estimated OC and SO₂ emissions were 92% and 45% higher than the 2010 estimated emissions in Peng et al. (2019), while our VOCs emission was lower than their results. As for PM_{2.5}, BC, and NO_x, the emissions were similar to their research results. Except that the emissions of NO_x and VOCs in Tianjin were close to those of Peng et al. (2019), the emissions of other pollutant were higher than their research. Unlike Tianjin, the estimated emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, and VOCs in Hebei were 29–68% of the emissions in 2010 in Peng et al. (2019). The main reasons such as the research base years, residential coal consumption, estimation methods, rural population, and coal usage from 2010 to 2020 are equally critical to the emissions of this study and other research results.

Uncertainty analysis

In order to evaluate the uncertainty of emission inventory of air pollutants from RCC over BTH region, we used the Monte Carlo method to analyze the uncertainty of air pollutant emissions with reference to Zhong et al. (2018b). Firstly, the input parameter (coal consumption) was set to logarithmic normal distribution function, the standard deviation was set to 0.44 according to Li et al. (2021), the input

Table 2 Comparison of estimated air pollutant emissions from RCC with other studies (10 kt)

| Region | Year | Pollutant emissions | | | | | | | | References |
|---------|------|---------------------|-------------------|-------|-------|--------|-----------------|-----------------|-------|--------------------|
| | | PM ₁₀ | PM _{2.5} | BC | OC | CO | NO _x | SO ₂ | VOCs | |
| Beijing | 2010 | | 1.31 | 0.21 | 0.05 | | 0.33 | 1.87 | 1.02 | Peng et al., 2019 |
| | 2012 | | 1.71 | 0.38 | 0.74 | | 0.41 | 0.37 | | Ru et al., 2015 |
| | 2013 | 4.74 | 3.76 | 1.05 | 1.54 | 69.08 | 0.78 | 5.32 | 1.65 | Cheng et al., 2017 |
| | 2013 | | 4.64 | 1.12 | 1.86 | | 0.83 | 6.97 | 1.16 | Zhi et al., 2017 |
| | 2015 | | 3.47 | | | | 1.15 | 4.31 | 2.93 | Cai et al., 2018 |
| | 2020 | 0.09 | 0.04 | 0.00 | 0.02 | 0.33 | 0.26 | 0.26 | 0.05 | Cheng et al., 2017 |
| Tianjin | 2020 | 1.58 | 1.16 | 0.09 | 0.61 | 24.29 | 0.28 | 3.39 | 0.29 | This study |
| | 2010 | | 0.99 | 0.15 | 0.32 | | 0.22 | 0.96 | 0.82 | Peng et al., 2019 |
| | 2013 | 3.00 | 2.39 | 0.67 | 0.98 | 43.81 | 0.49 | 3.37 | 1.05 | Cheng et al., 2017 |
| | 2020 | 0.26 | 0.17 | 0.02 | 0.10 | 1.57 | 0.28 | 0.57 | 0.24 | Cheng et al., 2017 |
| Hebei | 2020 | 1.98 | 1.57 | 0.28 | 0.84 | 30.14 | 0.36 | 3.77 | 0.57 | this study |
| | 2010 | | 32.55 | 6.06 | 12.63 | | 4.23 | 23.85 | 16.97 | Peng et al., 2019 |
| | 2013 | 50.20 | 39.89 | 11.18 | 16.33 | 732.05 | 8.25 | 56.36 | 17.54 | Cheng et al., 2017 |
| | 2020 | 2.76 | 1.61 | 0.16 | 0.93 | 14.64 | 4.33 | 6.56 | 2.21 | Cheng et al., 2017 |
| | 2020 | 16.01 | 12.93 | 2.61 | 6.89 | 242.53 | 2.87 | 29.51 | 5.00 | This study |

parameter (use the proportion of briquette and raw coal) was set to logarithmic normal distribution function with a standard deviation of 0.10 (Zhao et al., 2011), and the input parameter (emission factor) was set to triangular distribution function (Hua et al., 2016). Then, the samples were randomly selected from the set probability density distribution function, and the samples were brought into the output of the model. The average and standard deviation of the output results were used to describe the uncertainty of the quantitative results.

After 10,000 repeated calculations, the uncertainty range of air pollutant emission inventory of RCC in BTH region was simulated under the 95% confidence interval, as shown in Table 3. The uncertainty range of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs were −35.55 to 45.96%, −50.22 to 55.65%, −48.18 to 51.84%, −58.44 to 73.13%, −35.25 to 40.03%, −41.40 to 47.50%, −32.48 to 33.07%, and −51.43 to 59.92%, respectively. The results were similar to the uncertainty results of atmospheric pollutants generated by RCC in BTH region in 2013 of Cheng et al. (2017). The random errors of each pollutant showed slight asymmetry, which was related to the skew distribution of input parameters of the model (Zhang et al., 2019).

Temporal and spatial distribution

Temporal distribution

According to the time distribution factor obtained based on the long-term follow-up survey data of RCC of households over BTH region, the annual emissions of different cities were distributed to the temporal resolution of monthly, daily, and hourly. The monthly, daily, and hourly distribution factors of pollutants are shown in Table S4–S6. The monthly distribution of air pollutants from RCC over BTH region is shown in Figs. S1–S8. It was found that the highest emissions appeared in January, and the emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs reached

61,122.76t, 48,851.56t, 9219.32t, 25,980.34t, 927,188.56t, 10,952.88t, 114,686.96t, and 18,217.24t, respectively. Conversely, low emissions occurred from May to October in each city, accounted for less than 14%. Chengde and Qinhuangdao contributed significantly to air pollutant emissions in November and April, which entered the heating period earlier than other cities in the BTH region. The daily emissions of pollutants during the heating period (1 November 2019 to 16 April 2020) are shown in Figs. S9–S15. Pollutant emissions in the heating period mostly concentrated in mid-November to mid-March, and the emission peaks occurred in mid-December, early January, and mid-February. Shijiazhuang, Chengde, Baoding, and Tianjin contributed more to pollutant emissions. The daily emissions of pollutants were highest on February 9, 2019; the total emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs in BTH region reached 2192.15t, 1756.58t, 337.03t, 934.49t, 33,240.50t, 392.82t, 4095.24t, and 661.10t, respectively. Studies have shown that the temperature change and holiday factors will affect the emission of pollutants (Zhu et al., 2013). The emission characteristics of hourly variations on February 9, 2019 (Fig. S16–S23), showed that peak emission of pollutants appeared at 8:00, 11:00, 18:00, and 21:00 in BTH region, and the total emission of each pollutant reached 4472.52t, 2610.94t, 2849.09t, and 4806.69t. It can be seen that the hourly emission characteristics of RCC are closely related to the living factors such as residential coal usage habits, and working and rest.

Spatial distribution

The spatial distribution of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs emission from RCC in BTH region in 2020 is shown in Fig. 3. It can be seen that PM₁₀ and PM_{2.5} emissions in BTH region (Fig. 3(a)–(b)) were mainly concentrated in the northern, eastern, and southern regions, such as Chengde, Beijing, Tianjin, Tangshan, Cangzhou, Shijiazhuang, and Handan. The emission intensity in the western region of BTH was relatively low, and the PM₁₀ and PM_{2.5} emissions in most counties were not more than 0.08 million tons and 0.10 million tons. The high emission areas of BC and VOCs (Fig. 3(c) and (h)) were mainly concentrated in Chengde, Tianjin, Cangzhou, and some southern counties. The highest OC, CO, and NO_x emission areas (Fig. 3(d)–(f)) were Jizhou and Baodi districts of Tianjin, Weichang district of Chengde, and Haigang district of Qinhuangdao. Since Beijing and Tianjin use anthracite balls uniformly sold by the government, the CO emission factor of this coal type is high, resulting in large CO emission after combustion (Shen et al., 2015). The high emission areas of SO₂ (Fig. 3(g)) were mainly concentrated in the central and northern of BTH region, such as Tongzhou district of Beijing, Jizhou and Baodi districts of Tianjin, Weichang district of Chengde, and Haigang district of

Table 3 Uncertainty analysis of emission inventory from RCC in BTH region

| Pollutants | Emission (10 kt) | | | RSE (%) | |
|-------------------|------------------|------------|------------|------------------|------------------|
| | 5% | 95% | Average | RSE ₋ | RSE ₊ |
| PM ₁₀ | 16,748.80 | 37,934.59 | 25,989.26 | −35.55 | 45.96 |
| PM _{2.5} | 10,320.97 | 32,269.19 | 20,731.90 | −50.22 | 55.65 |
| BC | 1725.34 | 5055.25 | 3329.35 | −48.18 | 51.84 |
| OC | 5329.23 | 22,201.83 | 12,824.10 | −58.44 | 73.13 |
| CO | 235,238.30 | 508,731.12 | 363,290.38 | −35.25 | 40.03 |
| NO _x | 2527.03 | 6360.22 | 4312.15 | −41.40 | 47.50 |
| SO ₂ | 24,687.71 | 48,652.64 | 36,560.98 | −32.48 | 33.07 |
| VOCs | 3510.75 | 11,559.90 | 7228.34 | −51.43 | 59.92 |

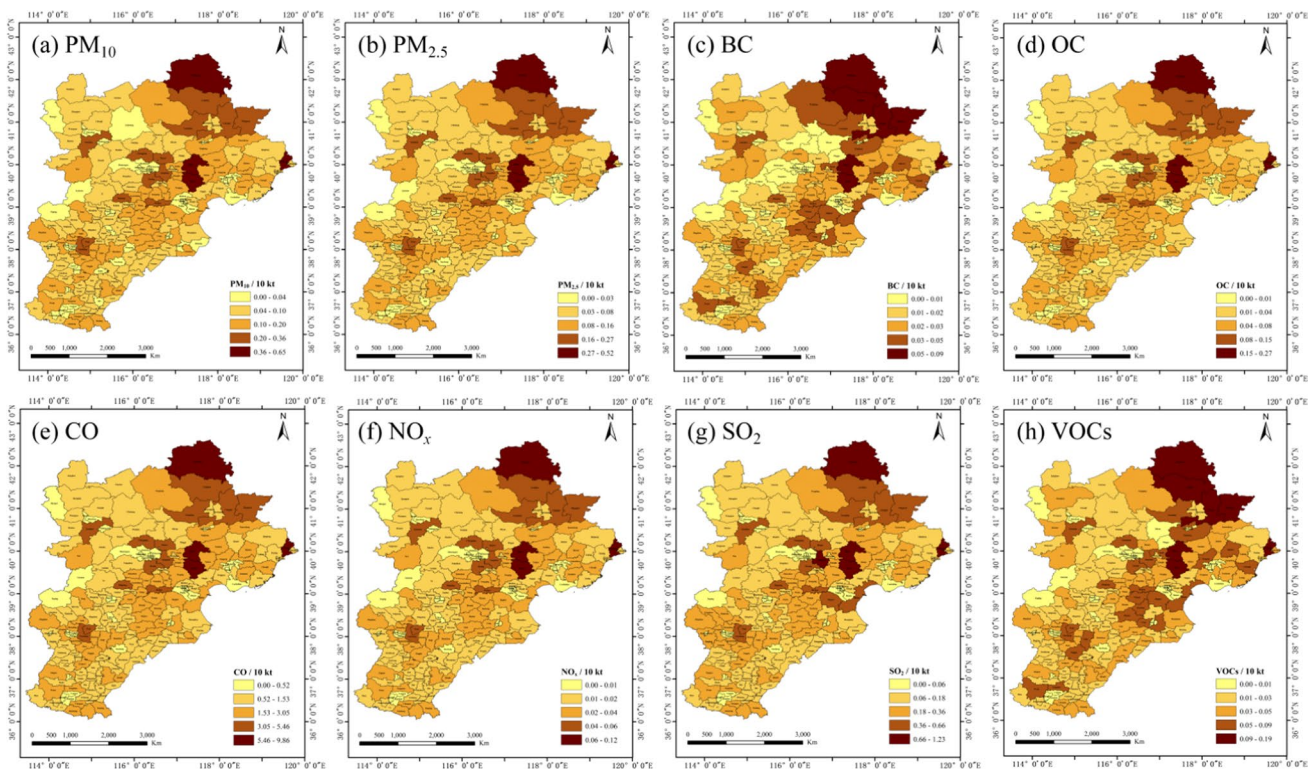


Fig. 3 Spatial distribution of pollutant emissions from RCC in BTH region

Qinhuangdao. Also noteworthy is that the emissions of PM_{10} , $PM_{2.5}$, BC, OC, CO, NO_x , SO_2 , and VOCs in Baodi district of Tianjin were 0.65, 0.52, 0.09, 0.27, 9.86, 0.12, 1.23, and 0.19 million tons, respectively, showing a high intensity of pollutant emission. As described in the “Method and data” section of this study, the emission of pollutants from RCC depends on the level of residential coal activity, the proportion of different coal types, and the pollutant EFs selected in this study. It can be seen from Table S1 that the consumption of residential coal in Beijing, Tianjin, Baoding, Chengde, and Shijiazhuang is very considerable. Especially in Shijiazhuang, the consumption of residential coal reached 402.88 million tons (14%); the consumption of raw coal in Chengde reached 173.43 million tons (13%). Specially, the EFs of each pollutant in raw coal combustion are higher than those in briquette coal combustion, and areas with large raw coal consumption may lead to more pollutant emissions. This has been proved in many studies (Liu et al., 2018a; Tian et al., 2018; Peng et al., 2019). The rural areas with dense population and low temperature in BTH region have a large demand for heating in winter, resulting in relatively high emission intensity of air pollutants in some areas (Chen et al., 2018). Pollutant emissions exhibit a clear consistency with spatial patterns in residential coal consumption (Zhao et al., 2018).

Overall, the regional distribution of pollutant emission in BTH region was obvious, and the intensity of pollutant

emission was related to factors such as coal consumption and population density (Liu et al., 2017b). The region may produce compound air pollution under adverse weather conditions, thus affecting the ambient air quality of the region and its surrounding areas (Zhong et al., 2018b). As an important input data for the air quality model, high-resolution pollutant emission inventory helps to better understand the real situation of regional air pollution, so as to study the complex pollutant formation mechanism under different meteorological conditions, and formulate accurate pollution prevention and control measures and policies for regional pollution.

Conclusions

In this study, we developed the emission inventory of RCC at the county level in BTH region in 2020. Pollutants including PM_{10} , $PM_{2.5}$, BC, OC, CO, NO_x , SO_2 , and VOCs were considered in the emission inventory. The pollutant emissions of each county were distributed into 1-km \times 1-km grids. The annual emissions of different cities were allocated according to the temporal resolution of monthly, daily, and hourly, based on the time distribution factor obtained from long-term follow-up survey data of RCC of households in BTH region.

The results showed that the emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs in BTH region were 19.58, 15.67, 2.98, 8.33, 296.96, 3.51, 36.67, and 5.87 million tons in BTH region, respectively. Chengde contributed the most PM_{2.5}, BC, OC, and VOCs in BTH region, which accounted for 11.48%, 13.71%, 11.52%, and 12.72%, respectively, while Shijiazhuang contributed the most PM₁₀, CO, NO_x, and SO₂ in BTH region, which accounted for 11.55%, 11.60%, 11.55%, and 12.10%, respectively. The spatial distribution characteristics of pollutants indicated that the higher pollutant emission from RCC concentrated in the northern, eastern, and southern areas of BTH region, such as Chengde, Beijing, Tianjin, Tangshan, Cangzhou, Shijiazhuang, and Handan.

The temporal distribution of emissions in BTH region showed that the higher emissions occurred in mid-November to mid-March. The highest emissions appeared in January, and the emissions of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs reached 61,122.76t, 48,851.56t, 9219.32t, 25,980.34t, 927,188.56t, 10,952.88t, 114,686.96t, and 18,217.24t, respectively. Conversely, low emissions occurred from May to October in each city, which accounted for less than 14%. The emission characteristics of daily showed that emission peaks occurred in mid-December, early January, and mid-February, and the hourly emission characteristics indicated that the peak emission of pollutants appeared at 8:00, 11:00, 18:00, and 21:00.

The uncertainties of the air pollutants from RCC in BTH region were analyzed by the Monte Carlo method. The uncertainty range of PM₁₀, PM_{2.5}, BC, OC, CO, NO_x, SO₂, and VOCs under 95% confidence intervals was −35.55 to 45.96%, −50.22 to 55.65%, −48.18 to 51.84%, −58.44 to 73.13%, −35.25 to 40.03%, −41.40 to 47.50%, −32.48 to 33.07%, and −51.43 to 59.92%, respectively.

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Author contribution Ruting Zhang: conceptualization, formal analysis, writing—original draft preparation, writing—review and editing. Chuanmin Chen: investigation, validation, supervision, project administration, funding acquisition. Songtao Liu: investigation, resources, methodology. Huacheng Wu: funding acquisition, formal analysis. Weiqing Zhou: resources funding acquisition, formal analysis. Peng Li: validation, methodology, data curation.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to participate Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Consent to publication All authors have read and approved this manuscript and take responsibility for its contents. The participant has consented to the submission of the manuscript to the journal.

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References

- Bai L, Lu X, Yin SS et al (2020) Recent emission inventory of multiple air pollutant, PM_{2.5} chemical species and its spatial-temporal characteristics in central China. *J Clean Prod* 269:122114
- Beijing Ecology and Environment Statement 2020, Beijing (in Chinese). <http://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/sthjlyzgw/1718880/1718881/1718882/10985106/2021110818014254063.pdf>
- Cai SY, Li Q, Wang SX et al (2018) Pollutant emissions from residential combustion and reduction strategies estimated via a village-based emission inventory in Beijing. *Environ Pollut* 238:230–237
- Cao GL, Zhang XY, Gong SL et al (2011) Emission inventories of primary particles and pollutant gases for China. *Chin Sci Bull* 56(8):781–788
- Carter EM, Shan M, Yang XD et al (2014) Pollutant emissions and energy efficiency of Chinese gasifier cooking stoves and implications for future intervention studies. *Environ Sci Technol* 48(11):6461–6468
- CESY (2020) China Energy Statistical Yearbook. China Statistics Press, Beijing, China
- CESY (2021) China Energy Statistical Yearbook. China Statistics Press, Beijing, China
- Chen YJ, Tian CG, Feng YL et al (2015) Measurements of emission factors of PM_{2.5}, OC, EC, and BC for household stoves of coal combustion in China. *Atmos Environ* 109:190–196
- Chen WW, Zhang SC, Tong QS et al (2018) Regional Characteristics and Causes of Haze Events in Northeast China. *Chin Geogr Sci* 28(5):836–850
- Cheng MM, Zhi GR, Tang W et al (2017) Air pollutant emission from the underestimated households' coal consumption source in China. *Sci Total Environ* 580:641–650
- China's Environmental Bulletin (CEB) in 2020, Beijing (in Chinese). <https://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/202105/P020210526572756184785.pdf>
- EPA, U.S. (1997) Guiding Principles for Monte Carlo Analysis. Report. EPA/630/R-97/001
- Fu X, Wang SX, Zhao B et al (2013) Emission inventory of primary pollutants and chemical speciation in 2010 for the Yangtze River Delta region, China. *Atmos Environ* 70:39–50
- Hebei Province Ecology and Environment Condition Statement, Hebei (in Chinese) 2020. <http://hbepb.hebei.gov.cn/res/hbhjt/upload/file/20210527/52beab3193614b0bb940966ba682527e.pdf>
- Hua SB, Tian HZ, Wang K et al (2016) Atmospheric emission inventory of hazardous air pollutants from China's cement plants: temporal trends, spatial variation characteristics and scenario projections. *Atmos Environ* 128:1–9
- Li X, Wu JR, Elser M et al (2018) Contributions of residential coal combustion to the air quality in Beijing-Tianjin-Hebei (BTH), China: a case study. *Atmos Chem Phys* 18(14):10675–10691
- Li P, Wu HC, Zhou WQ et al (2021) Emission inventory of atmospheric pollutants replaced by “coal-to-electricity” policy in Beijing-Tianjin-Hebei region. *China Environ Sci* 41(4):1489–1497

- Liang B, Song H, Bai HL et al (2017) Prevention and control of air pollution from the household coal combustion part I: a comparative experimental on combustion characteristics of household coal stoves of different designs. *Clean Coal Technology* 23(4):89–94
- Liu J, Mauzerall DL, Chen Q et al (2016) Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proc Natl Acad Sci U S A* 113(28):7756–7761
- Liu PF, Zhang CL, Xue CY et al (2017a) The contribution of residential coal combustion to atmospheric PM_{2.5} in northern China during winter. *Atmos Chem Phys* 17(18):11503–11520
- Liu SH, Hua SB, Wang K et al (2017b) Spatial-temporal variation characteristics of air pollution in Henan of China: Localized emission inventory, WRF/Chem simulations and potential source contribution analysis. *Sci Total Environ* 624:396–406
- Liu HJ, Wu BB, Liu SH et al (2018a) A regional high-resolution emission inventory of primary air pollutants in 2012 for Beijing and the surrounding five provinces of North China. *Atmos Environ* 181:20–33
- Liu YF, Zhang Y, Li C et al (2018b) Air pollutant emissions and mitigation potential through the adoption of semi-coke coals and improved heating stoves: field evaluation of a pilot intervention program in rural China. *Environ Pollut* 240:661–669
- Meng WJ, Zhong QR, Chen YL et al (2019) Energy and air pollution benefits of household fuel policies in northern China. *Proc Natl Acad Sci U S A* 116(34):16773–16780
- National Bureau of Statistics of China (NBSC) (2021) Beijing Statistical Yearbook 2021. China Statistics Press, Beijing
- Pan T, Xue YF, Zhong LH et al (2016) The methodology for air pollutants emission inventory from residential coal combustion and its application. *Environ Prot* 44(6):20–24
- Peng LQ, Zhang Q, Yao ZL et al (2019) Underreported coal in statistics: a survey-based solid fuel consumption and emission inventory for the rural residential sector in China. *Appl Energy* 235:1169–1182
- Qi J, Zheng B, Li M et al (2017) A high-resolution air pollutants emission inventory in 2013 for the Beijing-Tianjin-Hebei Region, China. *Atmos Environ* 170:156–168
- Qiu HG, Yan JB, Lei Z et al (2018) Rising wages and energy consumption transition in rural China. *Energy Policy* 119(AUG.):545–553
- Ru MY, Tao S, Smith K et al (2015) Direct energy consumption associated emissions by rural-to-urban migrants in Beijing. *Environ Sci Technol* 49(22):13708–13723
- Shen GF, Wei SY, Wei W et al (2012) Emission factors, size distributions, and emission inventories of carbonaceous particulate matter from residential wood combustion in rural China. *Environ Sci Technol* 46(7):4207–4221
- Shen GF, Chen YC, Xue CY et al (2015) Pollutant emissions from improved coal- and wood-fuelled cookstoves in rural households. *Environ Sci Technol* 49(11):6590–6098
- Shen GF, Ru MY, Du W et al (2019) Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. *Nat Commun* 10:3405
- Shen FZ, Zhang L, Jiang L et al (2020) Temporal variations of six ambient criteria air pollutants from 2015 to 2018, their spatial distributions, health risks and relationships with socioeconomic factors during 2018 in China. *Environ Int* 137:105556
- Silveira C, Ferreira J, Monteiro A et al (2017) Emissions from residential combustion sector: how to build a high spatially resolved inventory. *Air Qual Atmos Health* 11:259–270
- Sun ZR, Wu YP (1988) Study of emission factor of SO₂ due to coal burning in Shanghai. *Shanghai Environ Sci* 7(12):15–18
- Sun Z, Yang WJ, Xie XF et al (2014) Experimental study on the size spectra and emission factor of ultrafine particle from coal combustion. *Environ Sci* 35(12):4495–4501
- Sun X, Luo XS, Xu JB et al (2019) Spatio-temporal variations and factors of a provincial PM_{2.5} pollution in eastern China during 2013–2017 by geostatistics. *Sci Rep* 9:3613
- Tao S, Ru MY, Du W et al (2018) Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey. *Nat Energy* 3:567–573
- Tian J, Ni HY, Han YM et al (2018) Primary PM_{2.5} and trace gas emissions from residential coal combustion: assessing semi-coke briquette for emission reduction in the Beijing-Tianjin-Hebei region, China. *Atmos Environ* 191:378–386
- Tianjin Ecology and Environment Statement 2020, Tianjin (in Chinese). <http://sthj.tj.gov.cn/YWGZ7406/HJZL9827/HJZKG8866/TJSLNHJZKGB6653/202109/W020210902617722026319.pdf>
- Wang R, Jiang ZJ (2017) Energy consumption in China's rural areas: a study based on the village energy survey. *J Clean Prod* 143(FEB.1):452–461
- Wen HX, Nie PY, Liu M et al (2023) Multi-health effects of clean residential heating: Evidences from rural China's coal-to-gas/electricity project. *Energy Sustain Dev* 73:66–75
- Yi A H, Ding F, Hu C J, et al. Analysis of coal burning air pollution control process and impact in China. *Ecol Econ*, 2014, 30(8): 173-176.
- Zhang XL, Tang YX, Xiong YJ et al (2014) Analysis and numerical forecast of a regional for-haze in North China plain. *J Univ Chinese Acad Sci* 31(3):337–344
- Zhang XH, Lu Y, Wang QG et al (2019) A high-resolution inventory of air pollutant emissions from crop residue burning in China. *Atmos Environ* 213:207–214
- Zhang B, Sun J, Jiang N et al (2021a) Emission factors, characteristics, and gas-particle partitioning of polycyclic aromatic hydrocarbons in PM_{2.5} emitted for the typical solid fuel combustions in rural Guanzhong Plain, China. *Environ Pollut* 286:117573
- Zhang MD, Chen WW, Shen XJ et al (2021b) Comprehensive and high-resolution emission inventory of atmospheric pollutants for the northernmost cities agglomeration of Harbin-Changchun, China: implications for local atmospheric environment management. *J Environ Sci* 104:150–168
- Zhang B, Wang C, Sun J et al (2022a) Field measurements of PM_{2.5} emissions from typical solid fuel combustion in rural households in Fenhe Basin, China. *Environ Res* 212(Part C):113361
- Zhang B, Shen ZX, Sun J et al (2022b) County-level of particle and gases emission inventory for animal dung burning in the Qinghai-Tibetan Plateau, China. *J Clean Prod* 367:133051
- Zhao C, Luo KL (2018) Household consumption of coal and related sulfur, arsenic, fluorine and mercury emissions in China. *Energy Policy* 112:221–232
- Zhao Y, Nielsen CP, Lei Y et al (2011) Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. *Atmos Chem Phys* 11(5):2295–2308
- Zhao HM, Yang GY, Xiu AJ et al (2020) A High Resolution Emission Inventory of Domestic Burning in Rural Region of Northeast China Based on Household Consumption. *Chin Geogr Sci* 30(5):921–933
- Zheng B, Cheng J, Geng GN et al (2021) Mapping anthropogenic emissions in China at 1 km spatial resolution and its application in air quality modeling. *Sci Bull* 66(6):612–620
- Zhi GR, Zhang YY, Sun JZ et al (2017) Village energy survey reveals missing rural raw coal in northern China: significance in science and policy. *Environ Pollut* 223:705–712
- Zhong QR, Ma JM, Shen GF et al (2018a) Distinguishing emission-associated ambient air PM_{2.5} concentrations and meteorological factor-induced fluctuations. *Environ Sci Technol* 52(18):10416–10425

- Zhong ZM, Zheng JY, Zhu MN et al (2018b) Recent developments of anthropogenic air pollutant emission inventories in Guangdong province, China. *Sci Total Environ* 627:1080–10912
- Zhou Y, Zi T, Lang JL et al (2020) Impact of rural residential coal combustion on air pollution in Shandong, China. *Chemosphere* 260:127517
- Zhu D, Tao S, Wang R et al (2013) Temporal and spatial trends of residential energy consumption and air pollutant emissions in China. *Appl Energy* 106:17–24
- Zhu MY, Liu L, Yin SS et al (2020) County-level emission inventory for rural residential combustion and emission reduction potential

by technology optimization: A case study of Henan, China. *Atmospheric Environment* 228:117436

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