Emerging Concerns on Air Pollutants from Chemistry Laboratories of University: Ozone Formation Potential, Emission Characteristics, and Emission Inventory in Beijing, China

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Research Article

1 **Emerging Concerns on Air Pollutants from Chemistry Laboratories of University: Ozone Formation**

2 **Potential, Emission Characteristics, and Emission Inventory in Beijing, China**

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10 **Abstract**: Chemical laboratories of Universities are an important source of air pollutant emissions in urban area,

11 but their detailed emission factors have rarely been investigated. This study determined the concentration level

12 and chemical composition spectrum of air pollutants from 21 typical chemical laboratories of universities in

13 Beijing. Based on quantitative analysis using a GC-MS/FTIR/FID system, the emission intensity of each

14 laboratory area was estimated, the ozone formation potential (OFP) was calculated, and the emission inventory of

15 atmospheric pollutants in chemical laboratories of universities in Beijing was estimated. According to the results,

16 the atmospheric pollutants discharged by the laboratories could be characterized by wide species distribution and

17 low concentrations of single components. The average concentrations of atmospheric pollutants from the three

18 outlets were 20.6±8.9 μmol/mol (mean ± S.D.), 26.5±4.8 μmol/mol, and 14.7±5.8 μmol/mol. VOC emission was

19 significantly affected using organic solvents. Pollutant emissions from the laboratories exhibited strong periodicity,

20 and the raw materials used in the experiments were the main factor affecting the final pollutant concentration. The

21 emission intensities of atmospheric pollutants from the three outlets were 35.06±38.08 g/(m^2·d), 22.83±18.88

22 g/(m^2·d) and 24.03±28.78 g/(m^2·d), and their TOFP were 27.8±39.1 μmol/mol, 22.0±21.2 μmol/mol, and

23 14.5±28.9 μmol/mol. The total emission of atmospheric pollutants from university chemical laboratories in

24 Beijing in 2019 was estimated at approximately 2630.8±2710.3 t, including 675.8±610.6 t of inorganic gaseous

25 pollutants and 1932.0±2081.2 t of VOCs, with Haidian District as the largest contributor.

26 **Keywords**: urban environment; chemical laboratory; atmospheric pollutants; emission characteristics; emission

27 inventory; ozone formation potential

28 **1. Introduction**

29   Laboratories are an indispensable workplace for teaching and scientific research in academic institutions.

30 However, they also pose threats to the atmospheric environment due to their emissions. A large number of volatile

31   chemical reagents and multi-component compressed gases are used in the working process of chemical

32   laboratories. Moreover, thermophysical experiments such as high-temperature pyrolysis and combustion are

33   performed in some laboratories. During experiments, a large number of harmful gases are generated, which poses

34   great safety hazards. In order to ensure safety, laboratories are equipped with gas collectors, such as fume hood

35   and gas collection hood, to gather toxic and harmful gases and exhaust them into the atmosphere through

36   ventilation ducts.

37   In recent years, with the rapid development of science and technology in China, multi category and cross-

38   disciplinary laboratories have been established. According to the Beijing Statistical Yearbook 2020, there are 175

39   colleges and universities in Beijing, 112 of which are involved in the use of laboratories. Such 45 colleges and

40   universities are mainly distributed in the center area in Beijing that contained Haidian, Xicheng, Dongcheng,

41   Chaoyang, Fengtai, Shijingshan what the local people called "the six districts in city". With such a large number

42   and wide variety, laboratories, especially chemical laboratories, will inevitably release pollutants to the urban

43   atmospheric environment. Gas emissions from laboratories have brought a series of environmental problems. The

44   most obvious issue is the odor of the emitted gases, which is a major complaint of residents and households around

45   the laboratory (Xue et al., 2020). After preliminary test, the main components of these exhaust gases are volatile

46   organic compounds (VOCs), including esters, aromatic compounds, polycyclic aromatic hydrocarbons, aldehydes,

47   alcohols, and ketones, which are resistant to degradation. Some VOCs, such as benzene, polycyclic aromatic

48   hydrocarbons (PAHs), and heterocyclic aromatic amine (HCAs), are even carcinogenic to humans (Kabir, 2010;

49   Vicente, 2018). Moreover, some VOCs in laboratory exhaust, such as alkane, toluene, and xylene, react

50   photochemically with nitrogen oxides (NO_X) to produce ozone in the atmosphere, and these VOCs are thus called

51   ozone potential bodies. The increase in ozone level due to emissions of these VOCs (Kim and Lee, 2018; Shin et

52   al., 2013; Wang, 2018) will contribute to the formation of photochemical smog and secondary organic aerosols,

53   which are hazardous to human health and the environment (Jiaru, 2020; Qu, 2020). Different VOCs exhibit

54   different reactivities to ozone generation, and the main approach toward analyzing the impact of VOCs on the

55   atmospheric environment is to evaluate VOC reactivity (Robert and Avery, 2006). Therefore, it is crucial to

56   monitor and analyze gas emissions from chemical laboratories.

57   Although more than 20 industrial air pollutant emission standards have been issued by Ministry of Ecology

58   and Environment of the People's Republic of China (MEE), none of them was limited the pollutant emissions

59   from chemical laboratories. And on May 24, 2019, MEE issued the VOC Unorganized Emission Control Standard

60   (GB37822-2019) to solve the problem of VOC pollution. However, this standard did not clearly define chemical

61 laboratories as VOC emission sites for supervision as well. The Regulations of Beijing Municipality on the

62 Prevention and Control of Atmospheric Pollution requires institutions discharging toxic and harmful gases into

63 the atmosphere to install purification devices or take other measures to prevent pollution of the surrounding

64 environment. However, the control and supervision of atmospheric pollution from chemical laboratories are still

65 very weak, and analyses on the composition and emission law of waste gas from chemical laboratories are lacking.

66   In recent years, some scholars have analyzed characteristic pollutant emissions according to the type of

67 solvent used (Tong et al., 2019; Tian et al., 2017; Fang et al., 2019). Guo et al. (2019) investigated indoor air

68 quality related to chemical lab activities and evaluated the effect of reagent volatilization of indoor air pollutants

69 on the human body. Some scholar attempted to reveal the emission conditions of part of the pollutants in chemical

70 laboratories through various methods, such as the analysis of chemical laboratory exhaust emissions and the

71 introduction of two methods of processing chemical laboratory waste gas (Zhao et al., 2020). Xue et al. (2020)

72 calculated the VOC production and emissions of a chemical laboratory in Beijing using the material balance

73 algorithm; a photoionization ionization detector (PID) was used to detect the concentration of VOC pollutants

74 inside some of the laboratory fume hood, and the VOC emission level of the laboratory was preliminarily

75 identified. Florent et al. (2020) studied the influence of indoor ventilation efficiency on the release of VOCs by

76 substances, and concluded that the ventilation effect would significantly affect the release of individual VOCs.

77 However, the systematic and comprehensive description of the emission characteristics of atmospheric pollutants

78 produced by chemical laboratories have rarely been reported, and specific analyses on the impact of atmospheric

79 pollutants discharged by chemical laboratories on atmospheric environmental quality are lacking.

80   In order to solve the abovementioned problems, based on long-term and periodic field monitoring, this study

81 determined the emission concentration level and chemical composition spectrum of air pollutants from three

82 typical chemical laboratories in Beijing. The emission factor method was used to calculate the emission inventory

83 of atmospheric pollutants from chemical laboratories of universities in Beijing. Moreover, the impacts of chemical

84 laboratory emissions on the environment were explored. The findings of this study provide scientific basis and

85 technical support for the prevention and control of air pollutants from chemical laboratories of academic

86 institutions.

87 **2. Materials and methods**

88 2.1 Monitoring object

89   Chemical laboratories with a centralized discharge device were taken as the research object. Samples were

90   collected from Monday to Friday every week in 21 typical laboratories from 3 universities in Beijing. University

91   A and C are in Haidian District, while University B is in Fangshan District, as marked in Figure 1.
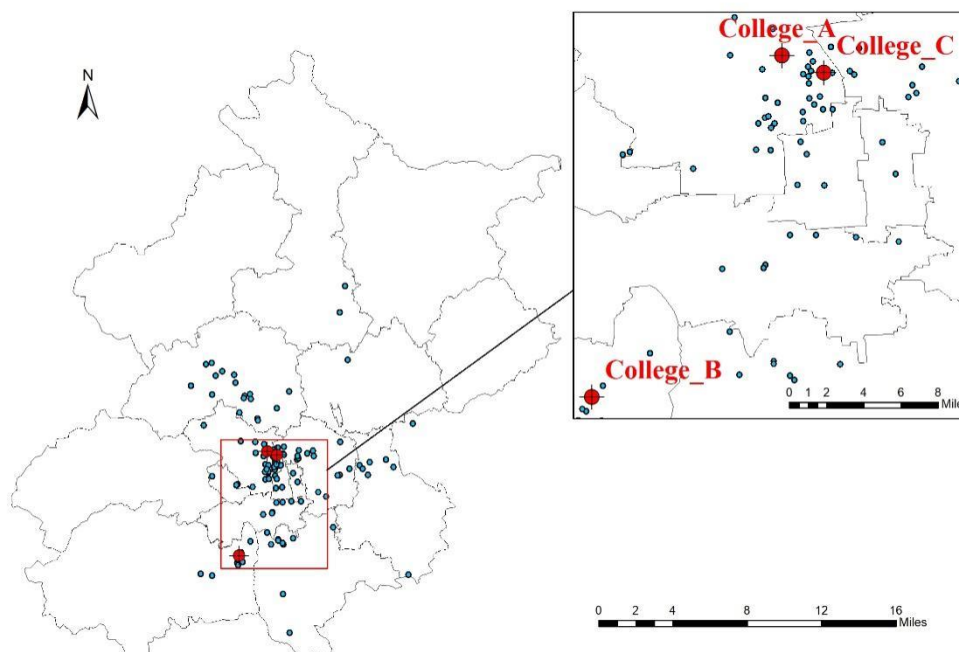

92

93   Figure 1 Geographic location of universities in Beijing and the surveyed universities

94   The laboratory of University A was set with an independent outlet, as the monitoring object, which just

95   connect with a single organic chemistry laboratory. The laboratories of University B and C had comprehensive

96   exhaust outlets, which were connected by an air duct to the exhaust system of several laboratories and sent to the

97   roof for discharge. As the comprehensive outlets are all in series, check valves were installed at the access ports

98   of each laboratory to prevent back-flow. Therefore, there was no air back-flow at the interface, and the sample at

99   the outlet reflects the real emission of each laboratory. The comprehensive outlets of 8 laboratories in the 2–9th

100   floors of University B and 12 laboratories in the 1–12th floors of University C were selected. Basic information

101   of corresponding laboratories for each outlet is shown in Table 1.

102   2.2 Sample collection and analysis

103   2.2.1 Analysis of inorganic gaseous pollutants

104   The sources of inorganic gaseous pollutants in chemical laboratories mainly include volatilization of volatile

105   reagents such as strong acid and alkali, leakage and emission of inorganic gases such as standard gas and carrier

106   gas, and exhaust gas generated during combustion. In this study, some standard methods, such as HJ688, HJ549,

107   HJ1040, HJ544, and HJ1076, were referred. A gas collector (Laoying[TM] 3072, Tsingdao, China), which was

108 connected with an acid/alkaline-base absorption liquid, was employed for inorganic gas sampling. All collected

109 samples were tightly sealed and properly stored before further analysis in the laboratory.

110 　　　The inorganic components in the absorption liquid were preliminarily analyzed using the ICS-1000 ion

111 chromatograph (DIONEX^{TM}, United States). Subsequently, the DX4000 Fourier Transform Infrared spectrometer

112 (FTIR) (Gasmet^{TM}, Finland) was used to conduct periodic continuous monitoring of the preliminarily screened

113 substances. All samples were collected on a pipe connected to a flue-gas concentrated fan.

114 2.2.2 Analysis of volatile organic compounds

115 　　　VOCs were produced by the volatilization of organic chemical reagents and chemical reactions in the process

116 of reagent mixing. It was collected using a 3.2 L stainless steel Summa tank with external Teflon pipe (Entech^{TM},

117 USA). The gas collecting head of the pipe was inserted into the center of the flue gas duct for 45 min, and 5

118 samples were collected every day. Then, the chemical components of VOCs were analyzed by gas

119 chromatography-mass spectrometry (Trace 1300/ISO QD, Thermo^{TM}, USA) with reference to EPA TO15. The

120 components were monitored periodically via FTIR spectroscopy (DX4000, Gasmet^{TM}, Finland) and non-methane

121 hydrocarbons (NMHC), which is the comprehensive index was monitored periodically via a portable flame

122 ionization detector (FID) (Huayi^{TM}, Tianjin). Similar to the continuous monitoring of inorganic gaseous pollutants,

123 VOCs were collected on the pipe of the flue gas outlet.

124 2.2.3 Sampling time and quality-checks of the data

125 　　　Periodic monitoring of pollutant emissions from the chemical laboratories of 3 universities were conducted

126 from June to October, 2019. Each outlet was monitored for at least 5 days, which from Monday to Friday, and the

127 monitoring time was from 9:00 am to 17:00 pm every day. By removal of outliers such as the data less than the

128 check-out limit, trim the data of unstable time such as before power-on stabilization, N_2 gas cleaning time. 4233

129 values which averaged by minute from FTIR analysis system were obtained.

130 2.3 Ozone formation potential (OFP)

131 　　　Currently, there are many indicators for evaluating the reactivity of VOCs, and different scholars adopt

132 different methods according to different situations (Chen and Luo, 2012; Zhang et al., 2012; Zeinali et al., 2011;

133 Martien et al., 2003; Carter, 1996). In this study, the maximum incremental reactivity (MIR) method was adopted

134 to characterize the reactivity of VOCs discharged by chemical laboratories and the OFP of the surface boundary

135 layer (Carter, 2010). The MIR coefficient was based on the latest research results of Cater Laboratory in 2013

136 (Cater, 2013). Equations (1) and (2) were used to analyze the OFP of VOCs.

137 $$C_j^{MIR} = MIR \times C_j \times \frac{\mu_j}{\mu_{ozone}} \tag{1}$$

138     $OFP_{MIR} = \sum_j C_j^{MIR}$ (2)

139 where, C_j^{MIR} is the maximum ozone concentration that a certain VOC can produce, mol/mol; MIR is the

140 maximum reactivity factor of some VOCs, gO₃/g VOCs; C_j is the volume fraction of some VOCs, mol/mol; μ_j

141 is the molecular weight of VOCs, g/mol;

142 μ_{ozone} is the relative molecular weight of ozone, 48 g/mol; OFP_{MIR} is the maximum ozone concentration

143 produced by total VOCs, mol/mol; and j is the category of VOCs.

144 2.4 Emission inventory

145   The main equipment for discharging atmospheric pollutants in the laboratories are fume hoods and gas hoods.

146 According to various design specifications, the ventilation system should be installed in direct proportion to the

147 area of the laboratory. In other words, the exhaust flow of air pollutants in the laboratory should be proportional

148 to the usable area of the laboratory. Therefore, the usage area of the laboratory can be used to measure the emission

149 intensity of the laboratory. To evaluate the emission intensity of air pollutants in the chemical laboratory, a

150 pollutant Emission Factor based on the usage area of the chemical laboratory was established as Equation (3).

151    $EM_i = (\frac{C_i \times M_i}{V_m} \times Q \times t)/S \times 10^{-3}$ （3）

152 where, EM_i is the emission intensity of a single pollutant, g/(m²·d); C_i is the measured volume fraction of a

153 pollutant, mol/mol; M_i is the molar mass of a pollutant molecule, g/mol; and V_m is the molar volume of the gas,

154 L/mol; Q is the measured fan exhaust air volume, m³/h; t is the operating time of the laboratory day, h/d; and

155 S is the total usable area of the test laboratory, m². During the test period, the average temperature and air pressure

156 in Beijing were 25℃ and 101, 000 Pa（measured by Testo 480 Detector）, V_m = 24.5 L/mol, respectively.

157   The emission intensity method was used to measure the emission of atmospheric pollutants from laboratories

158 in Beijing. By obtaining the activity level information of university laboratories in Beijing and combining with

159 the relevant emission intensity coefficient, the emission amount of pollutants can be obtained. This method is

160 suitable for regional scale research (Huang et al., 2014; Yan et al., 2017), and the calculation method is shown in

161 Equation (4).

162    $E_i = \sum EM_i \times A_t \times S_t$ （4）

163 where, E_i is the total discharge of a certain pollutant, t/a; EM_i is the emission intensity of a single pollutant,

164 g/(m²·d); A_t is the average operation days of laboratories of the study area in a year, (d/a); S_t is the total area

165 of the chemical laboratories in the study area, m².

166 **3. Results and discussion**

167   3.1 Emission characteristics of air pollutants from laboratories

168   The analyses revealed 47 types of atmospheric pollutants from the chemical laboratories of the three

169   universities that were stable above the detection limit. These included 8 types of inorganic pollutants, 12 types of

170   alkanes, 1 type of olefins, 8 types of the benzene series (BTEX), 8 types of halogenated hydrocarbons, 8 types of

171   oxygen-containing organic compounds (OVOCs), and 2 types of nitrogenous organic compounds (NVOCs), as

172   shown in Table 2.

173   Take the sum of the mixing ratios of all measured species, the average concentration of atmospheric pollutant

174   of the three tested units showed a relatively low difference, ranging from 14.65 to 26.47 μmol/mol. Among them,

175   University B exhibited the highest overall emission concentration, and its dominant component was nitrogen oxide

176   (12.85 μmol/mol, 48.5%), followed by University A (6.33 μmol/mol, 30.7%). The possible reason is that

177   concentrated nitric acid was used in one laboratory for sample digestion during the test process in University A;

178   in University B, combustion experiments were being conducted in two laboratories and nitric acid was used for

179   digestion in one laboratory, leading to the emission of high concentrations of nitrogen oxides. In terms of VOC

180   emission, the following order was observed: University A (12.32 μmol/mol) > University B (11.11 μmol/mol) >

181   University C (10.24 μmol/mol). Halogenated hydrocarbons (A: 30.5%) and alkanes (B: 40.8%, C: 37.7%) were

182   the dominant components in VOCs. In University A, a large amount of carbon tetrachloride and vinyl chloride

183   were used as experimental solvents, which led to the obvious increase of chlorinated hydrocarbons in exhaust gas.

184   A large amount of petroleum ether was used as solvent in the pharmaceutical engineering laboratory of University

185   B and the organic chemistry laboratory of University C. The test results showed that the content of n-hexane in

186   the exhaust gas VOCs from the laboratories of University B and C accounted for 12.9% and 14.0%, respectively.

187   These results show that various chemical experiments performed in the laboratories can produce pollutants, which

188   may be emitted to the atmospheric environment.   Furthermore, due to of University C, the proportion of

189   halogenated hydrocarbon emissions was high (29.6%) in University C because of the use of carbon tetrachloride

190   as an organic solvent in its material testing laboratory.

191   Through the periodic monitoring of air pollutants from the chemical laboratories of three universities, a

192   strong consistency was observed in the time series of the pollutant emissions, which can be divided into three

193   periods: 9:00–12:30 a.m., 12:30–13:30 p.m., and 13:30–17:00 p.m. These periods were determined by the unified

194   work and rest timing of colleges and universities.

195   In order to study temporal changes of atmospheric pollutant emissions, NMHC, the comprehensive emission

196   index, was selected for time series analysis. All 13 days sampling data of the 3 universities were sorted according

197   to the period 9:00–17:00 every day, and fitting statistics were conducted at the same time point of each day, as

198   shown in Figure 2. The graph corresponding to each time point is composed of the normal distribution of the 13-

199   day data, the blue solid line represents the average of the 13-day data, and the shaded part represents the 95%

200   confidence interval of the corresponding data at each time point. NMHC emission was characterized by

201   intermittent low peak and low mean value, with 3–6 emission peaks appearing in a day. The maximum emission

202   concentration during the sampling period was 11.98 mg C/m^3, but the peak occurred only for a short time, and the

203   concentration tended to be flat after approximately 10 min. This characteristic was closely related to a large

204   number of teaching experiments in universities. As we all know, a great feature of teaching experiment is

205   unsustainable for a long time. In general, the discharge of laboratory pollutants was significantly influenced by

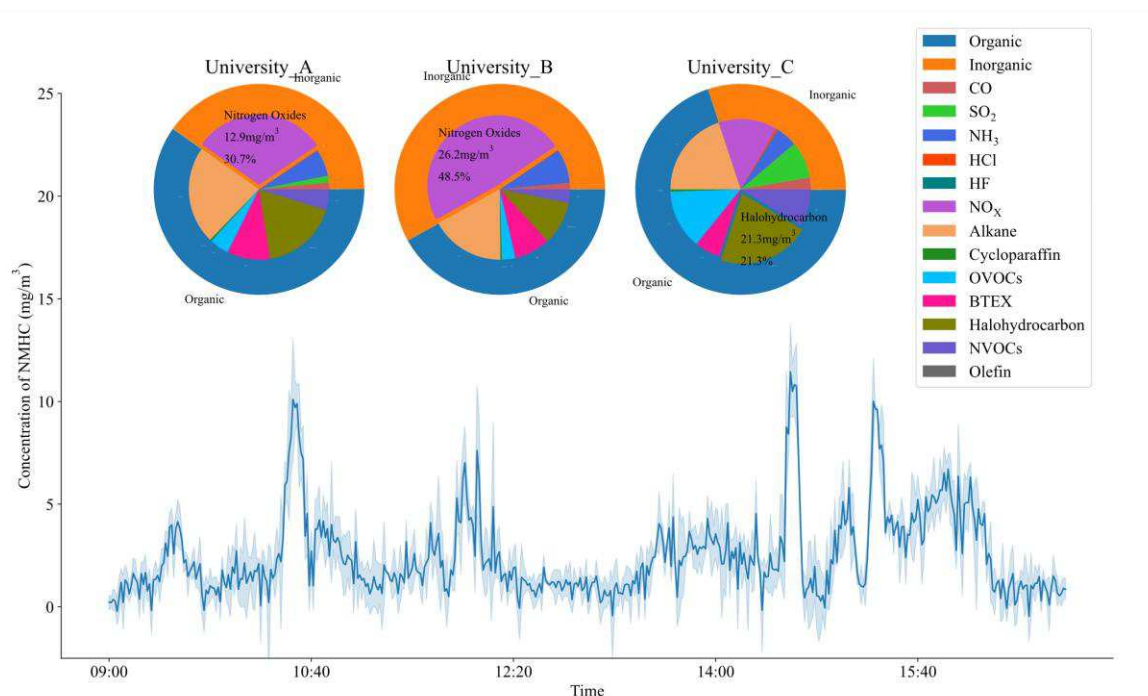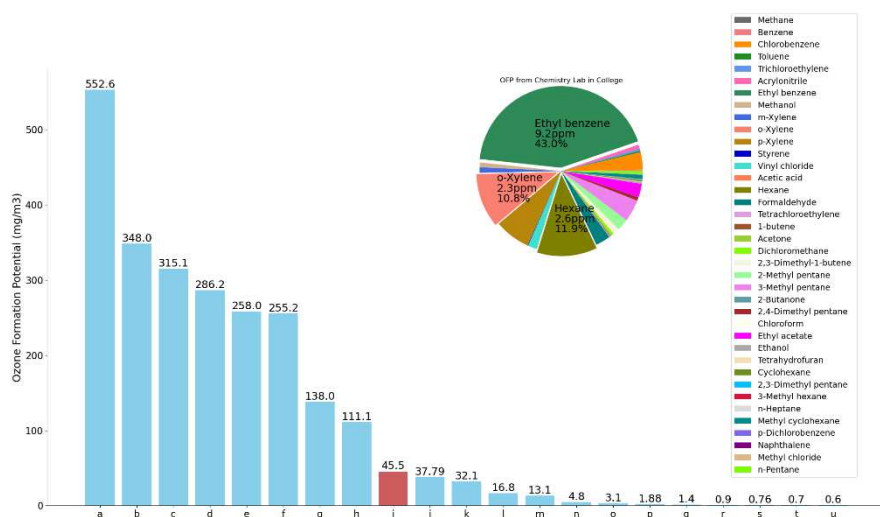206   the working conditions of the laboratory, and was highly instantaneous.

208   Figure 2 Emission concentration and distribution of atmospheric pollutants in 3 laboratories

209   3.2 Ozone formation potential

210   According to Equations (2) and (3), the C_j^{MIR} values of dominant VOC species and the OFP_{MIR} values of

211   the VOCs discharged from different units of the laboratories are shown in Table 3.

212   Ethylbenzene, o-xylene, n-hexane, and formaldehyde were the largest contributors to OFP, accounting for

213   52.0%–79.7% of the total OFP (TOFP). For VOC species with low reactivity, even if their concentration is high,

214   they will not significantly contribute to ozone formation. On the contrary, even low concentrations of highly

215   reactive VOCs species may contribute significantly to ozone production (Tang et al., 2016). Combined with Figure

2, although alkanes accounted for a relatively high proportion of emitted VOCs, benzene series and halogenated

hydrocarbons have a greater impact on the atmospheric environment owing to their high MIR values. Therefore,

the control of low concentration and highly active substances is a key aspect of laboratory pollutant control.

*a: Coke oven flue (Zhang et al., 2020), b: furniture (Zhang et al., 2019), c: medical (Li et al., 2014), d: furniture

(Zhang et al., 2019), e: furniture (Zhang et al., 2019), f: medical (Li et al., 2014), g: furniture (Zhang et al., 2019),

h: medical (Li et al., 2014), i: chemistry lab, j: medical (Li et al., 2014), k: medical (Li et al., 2014), l: coking plant

(Zhang et al., 2020), m: coking plant (Zhang et al., 2020), n: coking plant (Zhang et al., 2020), o: medical (Li et

al., 2014), p: printing (Liu et al., 2019), q: plywood (Lv et al., 2020), r: printing (Liu et al., 2019), s: iron and

steel(Zhang et al., 2020), t: plywood (Lv et al., 2020), u: plywood (Lv et al., 2020)

Figure 3 OFP in different studies (Li et al., 2014; Liu et al., 2019; Lu et al., 2020; Xu et al., 2020; Zhang et al.,

2019; Zhang et al., 2020)

The ozone generating potential of VOCs emitted by the chemical laboratory in this study was compared with

that of other typical VOC emission sources, as shown in Figure 3. It was found that compared with other research,

the influences of different industries and different solvent processes on TOFP were significantly different. (Li et

al. 2014) conducted a study on the chemical synthetic pharmaceutical industry, and found that the TOFP values

of VOCs emitted from the exhaust were significantly different, ranging from 3.1 to 315.1 mg/m^3, which could be

attributed to differences in the raw materials and excipients used by various enterprises and the emission

concentration. (Lu et al. 2020) studied a typical plywood manufacturing enterprise and found that the contribution

of VOCs to TOFP and each component of VOCs to OFP was different in different process stages (hot pressing

process, gluing process and exhaust outlet), but the overall TOFP was low, ranging from 0.5 to 1.3mg/m^3. In this

study, the OFP of emissions from the laboratories was lower than that of coking plants, pharmaceutical industries,

238 and furniture enterprises, but much higher than that of steel works, plywood manufacturing enterprises, packaging

239 printing and publication printing industries. Therefore, the control of atmospheric pollutant emissions, especially

240 VOCs, from chemical laboratories of academic institutions should be strengthened.

241 3.3 Emission inventory of air pollutants from chemical laboratories of universities in Beijing

242 3.3.1 Emission factor by testing

243 According to Equation (3), the emission intensity of air pollutants in each chemistry laboratory was

244 calculated, and the results are shown in Table 4.

245 The overall emission intensity of University A was higher than those of the other two universities, with

246 benzene series, halogenated hydrocarbons, and alkanes accounting for a large proportion. The emission intensity

247 of University A was relatively high because the detection point was an organic chemistry laboratory, and the

248 experiments mainly involve organic chemical reagents. The average emission intensity of air pollutants in the

249 three universities was 27.3 ± 28.6 g /(m$^2 \cdot$d).

250 3.3.2 Emission inventory

251 According to the National Institution of Higher Education statistics (Wu and Gao, 2014), in 2012/2013, the

252 area of university laboratories in Beijing was1.8 million m^2, with an average annual growth rate of 8.83%. Among

253 them, engineering and science laboratories accounted for 62.59% of the total number of laboratories. The

254 allocation of laboratory area and emissions was carried out with the number of students in each university as the

255 weight. Combining these statistics with the emissions intensity obtained in this study, an air pollutant emission

256 inventory of chemical laboratories of universities in Beijing in 2019 was established. In 2019, the total emission

257 of atmospheric pollutants from chemical laboratories of universities in Beijing was 2630 tons, including 698 tons

258 of inorganic gaseous pollutants and 1932 tons of VOCs. The corresponding pollutant emissions of chemical

259 laboratories of universities in various districts and counties of Beijing are shown in Table 5.

260 Haidian district was the main source of atmospheric pollutants emitted by chemical laboratories of

261 universities in Beijing, with the highest total emission of pollutants (2630.8 ± 2710.3 tons/year) among all the

262 districts of Beijing. This can be explained by Haidian district having the largest number of universities, with a

263 total of 33, accounting for 28.2% of the total number of universities in Beijing. According to the development

264 needs of Beijing, colleges and universities gradually set up new sites in the outer suburbs. Combined with Figure

265 1, With the increasing number of branch campuses in Changping (20 colleges) and Fangshan (10 colleges), the

266 pollutant emissions of chemical laboratories in these two areas have also reached 335.7 tons/year and 225.9

267 tons/year, ranking the third and fourth among all districts.

268   Figure 4 shows the spatial distribution of air pollutants from chemical laboratories of universities in Beijing

269   in 2019. In this study, the emission inventory was developed at a 3 km×3 km spatial resolution based on the

270   Emission Factor Method. The spatial resolution was set according to the actual area occupied by universities in

271   Beijing City and the emission range what calculated by the Gauss expand equation.
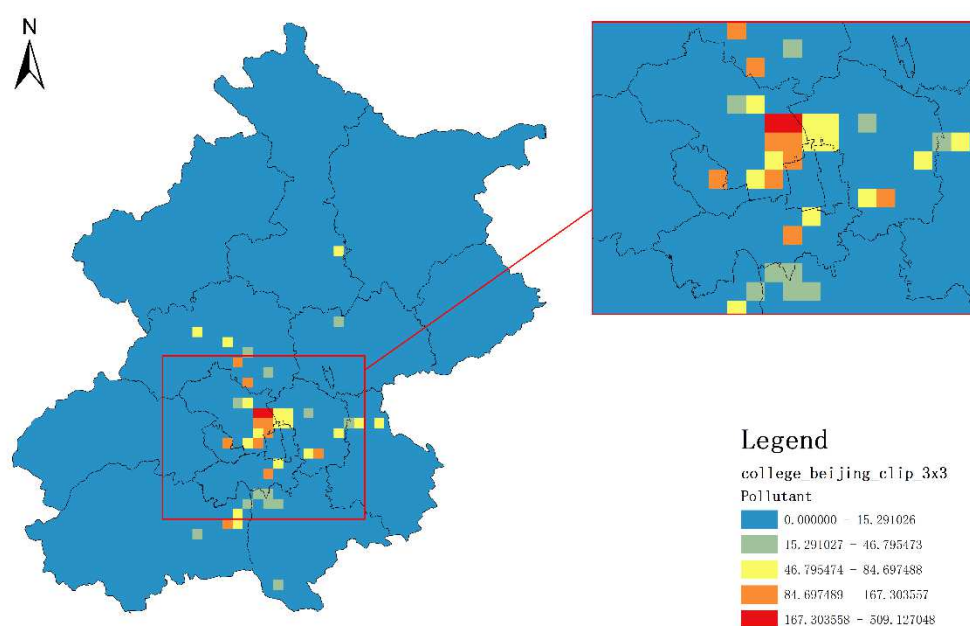

272

273   Figure 4 Pollutant emission grid of chemical laboratories of universities in Beijing

274   As shown in Figure 4, the emission of atmospheric pollutants from chemical laboratories of universities in

275   Beijing was concentrated in the central urban area of Beijing, and the highest pollutant emission was from the

276   southeast of Haidian District, where located lots of universities such as Tsinghua University and Peking University.

277   The distribution was closely related to the development of economy and science and technology in Beijing. The

278   total emission of atmospheric pollutants was within the range of 81–309 tons/grid.

279   In the figure, the area with high pollutant emission corresponds to the science and technology innovation and

280   development center of Beijing, where universities are more densely distributed and more well-known universities

281   are located. Universities in this area have more abundant means for scientific research than other universities.

282   These universities also use the largest amounts of chemical reagents and emit the largest amount of waste liquid

283   among all the universities in Beijing.

284   Meanwhile, the density of permanent residents in Haidian District is 7,796 people/square kilometers, ranking

285   the 4th among the 17 districts in the city. VOCs emitted by chemical laboratories of universities significantly

286   affect the surrounding residents.

287   3.3.3 Uncertainty analysis

288   In the estimation of any emission inventory, uncertainties are inevitable because of inadequate or incomplete

289   information and data. These uncertainties might affect the estimation of emission inventories to some extent

290   (Zhong et al., 2007; Wei et al., 2011). In this study, the number of college students was used to allocate the area

291   proportion of chemical laboratories in each university, and measured data from the three universities were used to

292   represent the emission factors of chemical laboratories in all universities, which would lead to certain uncertainty.

293   To assess the uncertainties in the emission inventory, a quantitative approach was applied to estimate the

294   uncertainty range for each class of pollutant using Monte Carlo simulations at 90% confidence interval. The

295   activity level information was obtained from the survey and annual statistical report, and the uncertainty of activity

296   level information was set as ±80% with reference to the empirical value of the TRACE-P list (Streets et al., 2003).

297   The uncertainty of the pollutant discharge inventory of chemical laboratories of universities is shown in Table 6.

298   **4. Conclusion**

299   According to the analysis results of this study, 8 types of inorganic substances such as acid inorganic gas and

300   alkaline inorganic gas, and 39 types of organic pollutants such as alkanes, alkenes, benzene series, halogenated

301   hydrocarbons, oxygen-containing organic compounds and nitrogen-containing organic compounds were

302   identified, which were stable above the detection limit of the equipment. Among the three universities, University

303   B showed the highest overall emission concentration of 31.16 μmol/mol, with nitrogen oxides as the main

304   component. University A showed the highest VOC concentration (12.3 μmol/mol). In addition, pollutant

305   emissions from the chemical laboratories exhibited strong periodicity, and the periodicity of the same type of

306   laboratory was relatively consistent, which is closely related to the working status and rest time. Pollutant

307   emissions from the laboratories were characterized by intermittent low peak and low mean value, but the peaks

308   existed only for a short time, and the concentration tended to be flat after approximately 10 min. The raw materials

309   used in the laboratory experiments were the main factor determining the final pollutant emission concentration.

310   The emission intensities of air pollutants from the chemical laboratories of the three universities were $35.06 \pm$

311   38.08 g/(m^2·d), 22.83 ± 18.88 g/(m^2·d) and 24.03 ± 28.78 g/(m^2·d), and the OFPs were 27.8 ± 39.1, 22.0 ± 21.2

312   and 14.5 ± 28.9, which are higher than those of plywood manufacturing enterprises, and packaging and printing

313   industries. In 2019, the total emission of atmospheric pollutants from chemical laboratories of universities in

314　Beijing was 2630 t, including 698 t of inorganic gaseous pollutants and 1932 t of VOCs. Haidian District was the

315　largest contributor to the emissions among all districts of Beijing. The control of low concentration and high

316　activity substances is a key aspect of air pollutant control for chemical laboratories.

317　**Declarations**

318　**Ethics approval and consent to participate**

319　Not applicable

320　**Consent for publication**

321　Not applicable

322　**Availability of data and materials**

323　All data generated or analysed during this study are included in this published article [and its supplementary

324　information files].

325　**Competing interests**

326　The authors declare that they have no competing interests

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330　**Authors' contributions**

331　CW performed the analysis of testing data, and was a major contributor in writing the manuscript.

332　XZ has contributed a lot to the on-site sampling work.

333　KW calculated the emissions inventory of universities in Beijing.

334　PZ provided ideas for data analysis.

335　JG and YZ translation the manuscript to English language.

336　YT offered suggestions for revision of this manuscript.

337　QL and LT spent a lot of time on site sampling work.

338　YH sorted out and counted the sampling data of the site.

339　TY provided the overall framework of the manuscript.

340　All authors read and approved the final manuscript.

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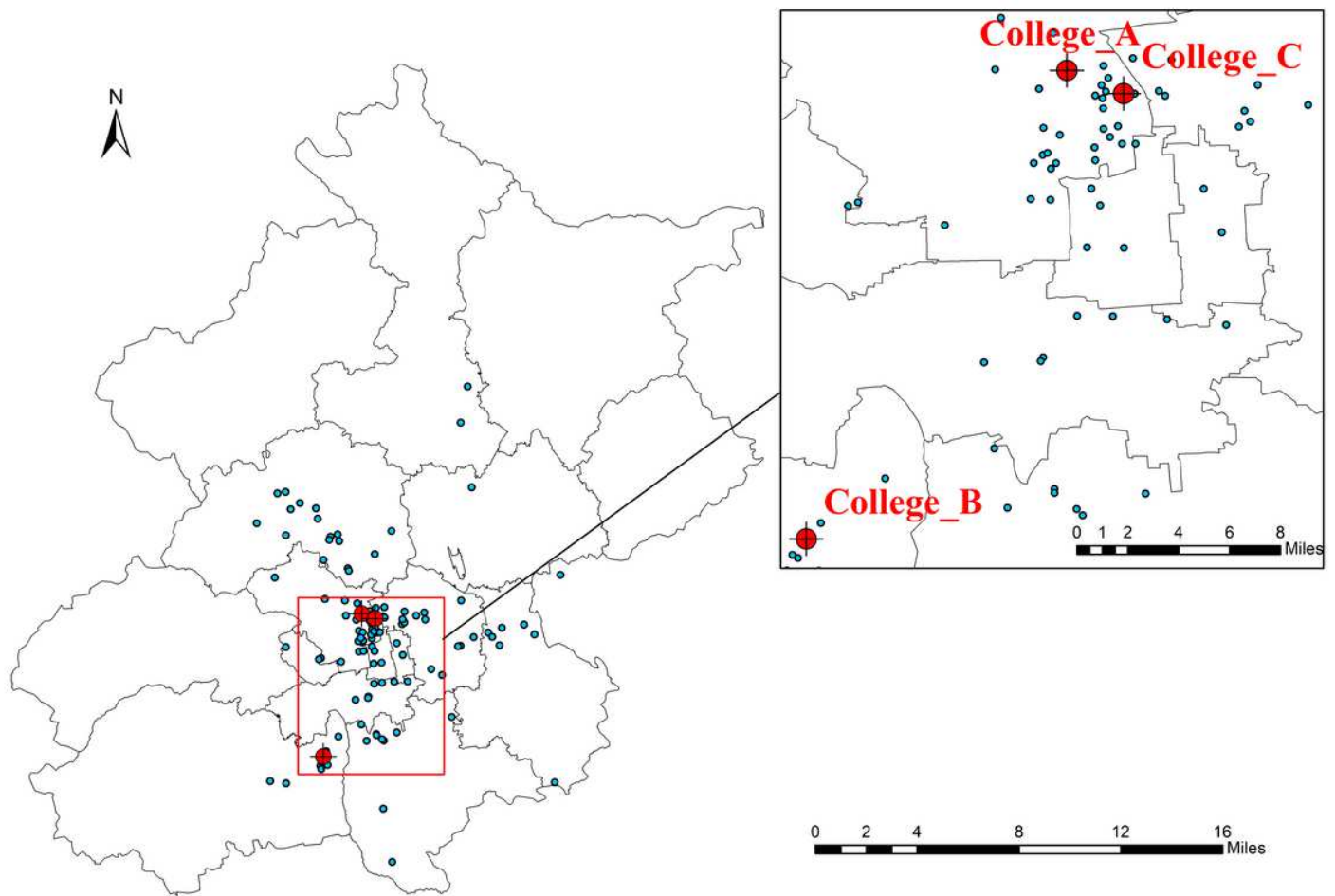
Figures

Figure 1

Geographic location of universities in Beijing and the surveyed universities Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
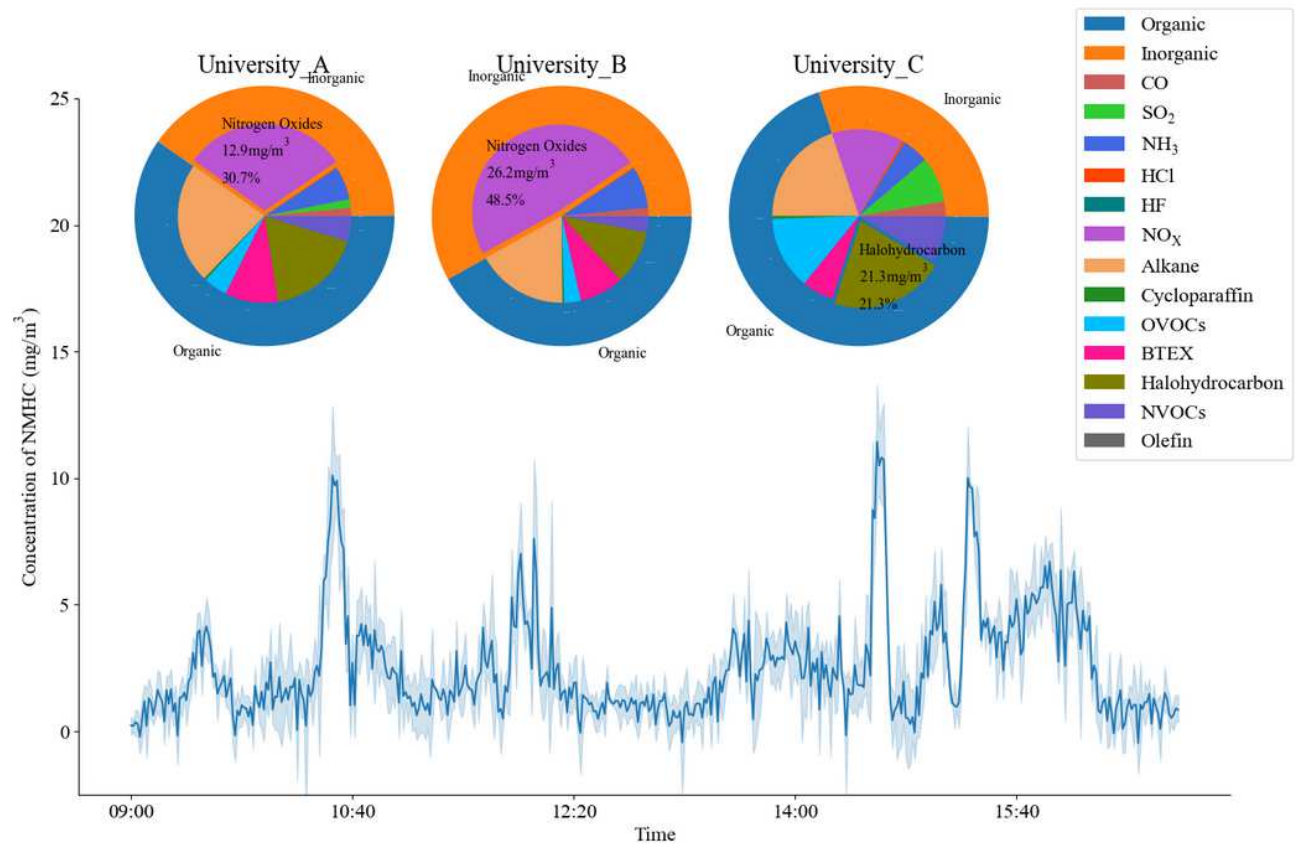
Figure 2

Emission concentration and distribution of atmospheric pollutants in 3 laboratories
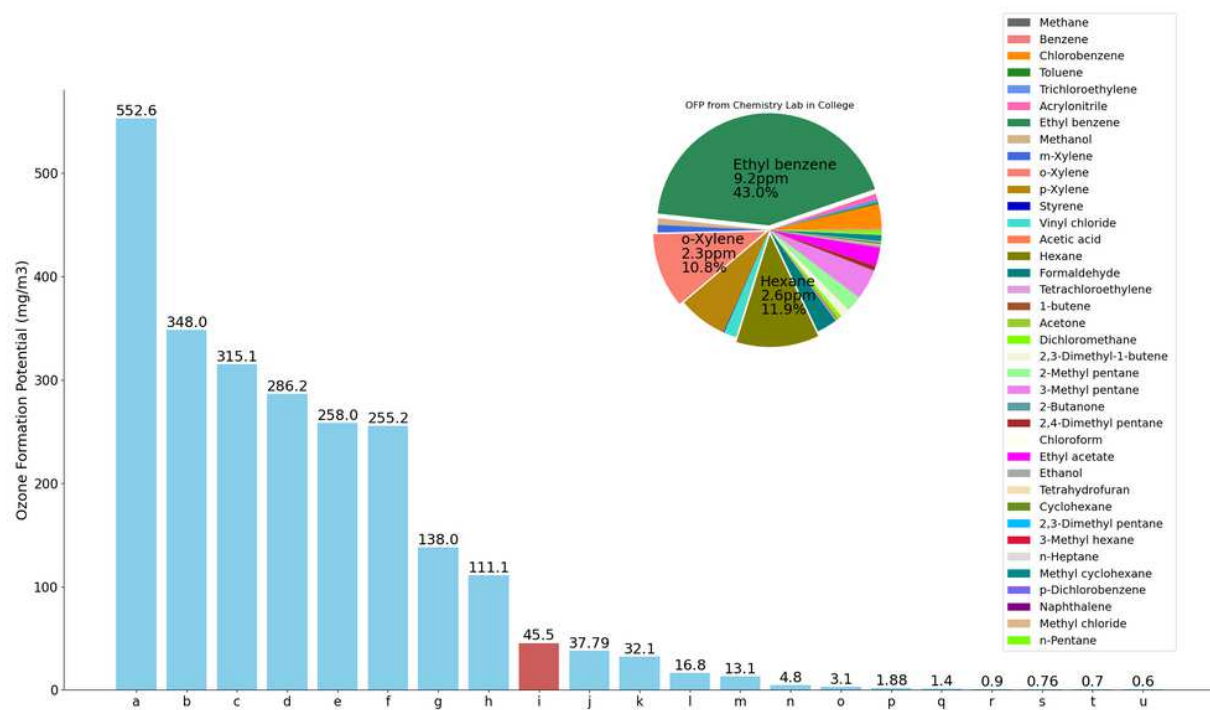
Figure 3

OFP in different studies (Li et al., 2014; Liu et al., 2019; Lu et al., 2020; Xu et al., 2020; Zhang et al., 2019; Zhang et al., 2020) *a: Coke oven flue (Zhang et al., 2020), b: furniture (Zhang et al., 2019), c: medical (Li et al., 2014), d: furniture (Zhang et al., 2019), e: furniture (Zhang et al., 2019), f: medical (Li et al., 2014), g: furniture (Zhang et al., 2019), h: medical (Li et al., 2014), i: chemistry lab, j: medical (Li et al., 2014), k: medical (Li et al., 2014), l: coking plant (Zhang et al., 2020), m: coking plant (Zhang et al., 2020), n: coking plant (Zhang et al., 2020), o: medical (Li et al., 2014), p: printing (Liu et al., 2019), q: plywood (Lv et al., 2020), r: printing (Liu et al., 2019), s: iron and steel(Zhang et al., 2020), t: plywood (Lv et al., 2020), u: plywood (Lv et al., 2020)
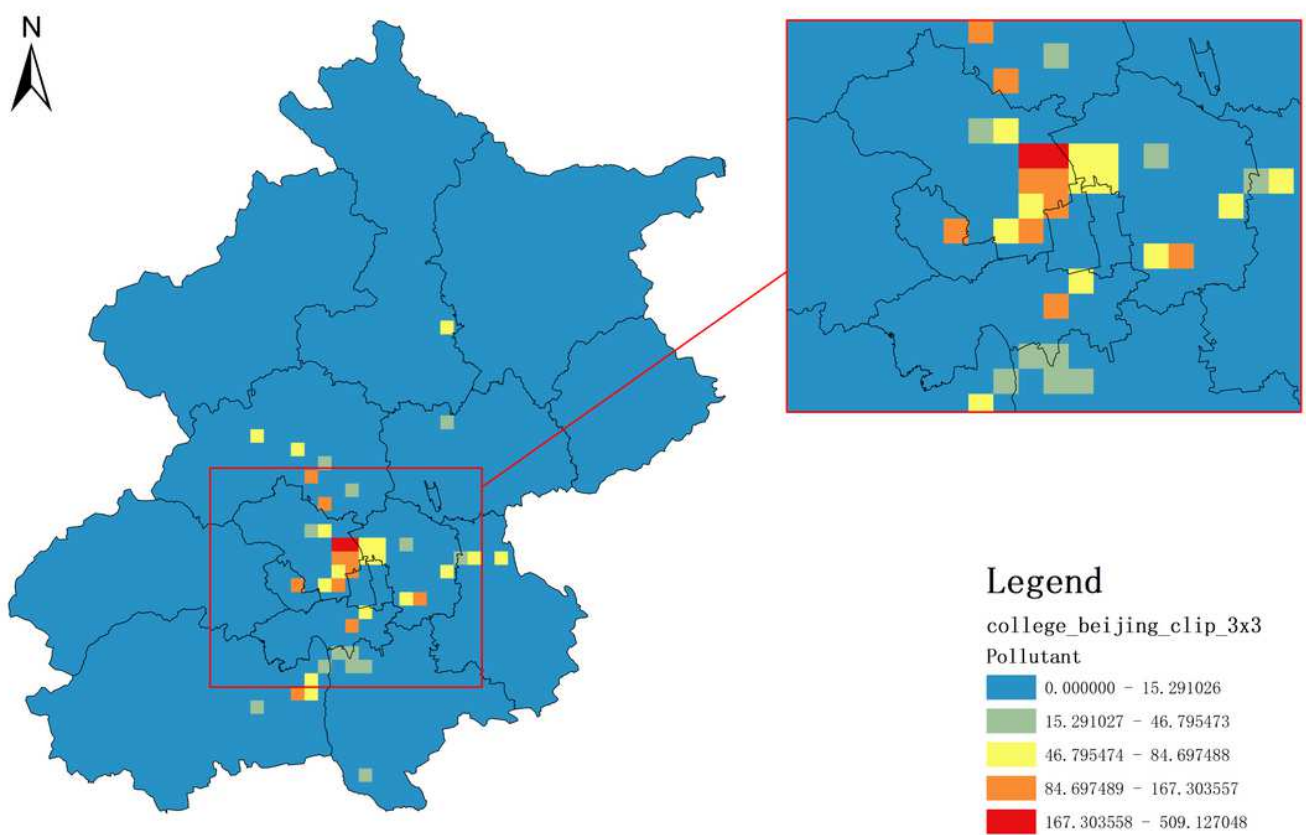

Figure 4

Pollutant emission grid of chemical laboratories of universities in Beijing Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.