Review

Research Progress of HP Characteristics, Hazards, Control Technologies, and Measures in China after 2013

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Abstract: In recent years, hazy weather (hazy weather (HW) has frequently invaded peoples’ lives in China, resulting in the disturbance of social operation, so it is urgent to resolve the haze pollution (HP) problem. A comprehensive understanding of HP is essential to further effectively alleviate or even eliminate it. In this study, HP characteristics in China, after 2013, were presented. It was found that the situation of HP is getting better year by year while it has been a pattern of high levels in the north and low levels in the south. In most regions of China, the contribution of a secondary source for HP is relatively large, and that of traffic is greater in the regions with rapid economic development. Hazards of HP were then summarized. Not only does HP cause harm to human health, but it also has effects on human production and quality of life, furthermore, property and atmospheric environment cannot be ignored. Next, the source and non-source control technologies of HP were first reviewed to recognize the weakness of HP control in China. This review provides more systematic information about HP problems and the future development directions of HP research were proposed to further effectively control HP in China.

Keywords: HP; distribution characteristic; hazard; control technology

1. Introduction

According to the definition given by China Meteorological Administration [1], fog is a common weather phenomenon, and haze refers to a turbidity phenomenon caused by unexplained large amounts of particulates in suspension such as smoke and dust, whose core material is suspended PM in the atmosphere, besides, the formation of hazy weather (HW) is closely linked to the relative humidity in the atmosphere. The deterioration of atmospheric visibility is mainly caused by the haze when the relative humidity is less than 80%, and the mixture of haze and fog also results in poor visibility when the relative humidity is between 80% and 90%. In recent years, throughout the world there has been trouble with haze pollution (HP) to varying degrees [2–7]. Long-term HW can not only break the situation of human harmonious life, but also seriously threaten the natural changes of global climate. Therefore, how to lessen the occurrence of HW and improve air quality has become a hot topic in the world [8–11].

Of course, China is no exception. Since heavy HW occurred in 2013, Chinese governments at all levels have started to intensify efforts to control air pollution and to resolutely win the battle of defending the blue sky [12,13]. For instance, in January 2013, the most serious HP event of this century appeared in Beijing, which lasted a long time, covered a wide range, and affected a large number of people. The highest instantaneous concentration of PM$_{2.5}$ was up to 1000 µg/m$^3$ in some heavily polluted areas, subsequently, the Beijing municipal government formulated the relevant clean air action
Depending on the latest data provided by China Statistical Yearbook [16–20], on the one hand, if the annual mean concentration (AMC) of respirable PM (PM with aerodynamic equivalent diameter equal to or less than 10 µm, known as PM$_{10}$) in the atmosphere is taken as a statistical index, the air quality changes of key environmental protection cities in China from 2013 to 2017 is shown in Figure 1, where the abscissa represents the number of surveyed cities. It can be seen that the percentage of cities meeting the secondary China ambient air quality standards (AAQS, 70 µg/m$^3$ for annual mean of PM$_{10}$) [21] show the increasing trend, from 14.2% in 2014 to 33.6% in 2017, with growth rates of 136.6%, correspondingly, the percentage of cities with unsatisfactory air quality tended to decrease (Figure 1 (bar chart)). However, it is noteworthy that the number of cities that are up to the AAQS in 2017 is less than 1/2 of the total survey, and the city quantity meeting the air quality standards (20 µg/m$^3$ for annual mean of PM$_{10}$) recommended by World Health Organization (WHO) is 0 (Figure 1 (line chart)). On the other hand, if the concentration of fine PM (PM with aerodynamic equivalent diameter equal to or less than 2.5 µm, known as PM$_{2.5}$) in the atmosphere is taken as a statistical index, as we can see in the Figure 2, the percentage of cities meeting the AAQS (35 µg/m$^3$ for annual mean of PM$_{2.5}$) increase year by year, and the proportion of cities meeting the AAQS in 2017 ascended to about 2.5 times than that in 2013 (Figure 2 (bar chart)). Similarly, the number of cities up to the AAQS in 2017 is less than a quarter of the total survey, and the city quantity up to the air quality standards (10 µg/m$^3$ for annual mean of PM$_{2.5}$) recommended by WHO is 0 (Figure 2 (line chart). The above data demonstrate that the treatment of HP in China has begun to bear fruit, but it still lags far behind the goals given by WHO. Therefore, it is required to further strengthen efforts to control the atmospheric HP in China, without any slack.

Many developed countries, including the United States, Britain, Germany, Japan, etc. have gained some successful experience in tackling HP [22–25]. Selecting Los Angeles in the United States as an example, since the heavy HP events of the 1940s, the City of Los Angeles efforts to deal with HP were roughly divided into two steps: firstly, a special organization was set up to find out the main causes of HW and determine the sources of haze pollutants, and then, aiming at the causes and sources of HP, Los Angeles implemented a policy of crushing them one by one. For example, in 1958, Los Angeles parliament passed a resolution banning the sale of cars without smoke control devices in California after 1961.
Thereafter, following in order and advancing step by step, Los Angeles had basically overcome the HP problem by the beginning of the 21st century, after half a century of bitterness [26]. Despite the pressure of atmospheric HP in these developed countries having declined recently, relevant studies are still continuing [27–31]. Hence, effective control of HP cannot be completed overnight. Furthermore, along with the social and economic development, causes and roots of HP, control technologies on HP, relevant laws and regulations are all constantly updated and changed, and finally a sustainable and dynamic treatment mechanism can be established. From the experience of developed countries settling HP, it is not difficult to find that if China wants to effectively resolve HP, it is necessary to improve the function of each link in an all-round way and make up for the shortcomings as far as possible. However, at present, there are many troublesome issues in coping with HP in most areas of China, such as an unclear understanding of the sources and causes of haze, unreasonable control measures, technical defects, insufficient public awareness of the haze hazard and environmental protection, inadequate implementation of laws and regulations, etc. [32–34].

Thus, in this study, relevant literatures published after 2013 are searched to sort out and review, the following four aspects mainly: (1) summarizing the basic situation of atmosphere HP in China; (2) describing threats and hazards of haze pollutants to human beings and the environment; (3) reviewing the main prevention, control technologies, and measures of HP in China at present; and (4) discussing the development direction of HP related research. In this way, it can provide a scientific basis for further solving HP and related research in China.

2. Overview of the Basic Situation of Haze

2.1. Main Causes of HW Formation

The formation of HW needs to satisfy two basic conditions: the first is the source that can continuously transport sufficient PM to the atmosphere; the second is the meteorological conditions that are unfavorable to the diffusion and dilution of these PM and make them suspended at low altitude and near the ground, which can provide favorable conditions for the formation of secondary pollution sources and the interaction between chemical species with meteorology [35–37]. These two factors work together to bring about the concentration of these PM in the atmosphere reaches or exceeds the limit of the atmosphere self-purification capacity, thereby forming HW [38,39].
Sources of producing PM, generally come from human and natural factors. Human factors mainly consist of industrial production, vehicle exhaust, combustion source, construction dust, mineral mining, etc. and natural factors comprise sandstorm, volcanic eruptions, forest fire, resuspension of road or soil dust, etc. [40,41]. With regard to meteorological conditions, one consideration is the phenomenon of static wind in the horizontal direction of the atmosphere increases, and there is basically no power source for PM diffusion, which results in more and more suspended PM accumulation. For another, there is an inversion layer in the vertical direction of the atmosphere, i.e., the temperature in the upper air is higher than that in the lower air, which greatly limits the free diffusion passage of PM in the atmosphere to the high altitude and makes them build-up by degrees in the space near the ground and low altitude. Moreover, air temperature and relative humidity are also important factors that contribute to the formation and evolution of HW [42,43]. Under these conditions, this offers enough time and space for the chemical reaction of pollutants discharged into the atmosphere, such as an oxidation reaction, hydration reaction, photochemical oxidation reaction, etc., which will generate many new PM and increase the concentration of PM in the atmosphere. In addition, they can generate the interactions between aerosols with planetary boundary layer (PBL) or cloud and further impact on regional weather and climate. For example, black carbon (BC) aerosols can induce heating in the PBL, particularly in the upper PBL, which can depress the development of PBL as the resulting decreased surface heat flux substantially, thus, the occurrences of extreme haze pollution episodes were consequently enhanced [44,45].

2.2. Temporal and Spatial Distribution Characteristics of HP

Since the formation of HW is susceptible to the meteorological factors, therefore, in China with complicated topographic conditions, observing the change of HP on time and space scales has a certain reference significance for further overall understanding of the distribution characteristics of HP.

HW exhibits strong seasonality [46]. Winter is the high incidence period of HW, and summer is the lowest, while spring and autumn are transitional periods. During the transition from spring to summer, the quantity of HW descend steadily and the air quality takes a turn for the better gradually. During the transition from autumn to winter, the days of HW surge and the air quality grows worse [47,48]. This is because the surface radiation cooling is evident at night in winter, and the atmospheric temperature near the ground is lower than that at the upper level, forming an inversion phenomenon. Meanwhile, precipitation in winter is insufficient and the wind force in the horizontal direction of the atmosphere is relatively feeble, which leads to haze pollutants inability to spread [49–51]. In winter, because of the low temperature, residents in northern China often keep warm with coal burning, and incomplete combustion of mixed gases in motor vehicle engines, etc., exhaust gases from these causes are discharged directly into the atmosphere, thus, the concentration of PM in the atmosphere soars [52]. By contrast, the temperature is relatively high and the rainfall is sufficient in summer, consequently, the air quality is better.

Similarly, during the continuous haze period, the haze PM concentration in different time periods of the day also has obvious changes [53,54]. Generally speaking, about 06:00–07:00 (Beijing time, the same below) and 13:00–17:00 in a day, the haze PM concentration is at a lower level, while about 21:00–23:00 is a period of high concentration of haze PM. At about 06:00–07:00, the relative humidity in the atmosphere is higher, and the haze PM can be absorbed and wrapped by the droplets, moreover, the emission of haze pollutants at night is significantly reduced, thus, the concentration of haze PM in this period is relatively low. At about 13:00–17:00, the turbulent exchange is gradually strengthened, which provided favorable conditions for the diffusion of haze PM, resulting in the lower concentration of haze PM in this period. For about 21:00–23:00, the atmospheric structure is relatively stable and the thermal inversion is obvious, which makes the concentration of haze PM close to the ground accumulate, resulting in a higher level of haze PM concentration.

From the perspective of time sequence, using the primary PM$_{2.5}$ in haze pollutants as an example, the AMC distribution of PM$_{2.5}$ in China from 2013 to 2017 is shown in Figure 3. In 2013, AMC of
PM$_{2.5}$ in most regions (blue and black) failed to meet AAQS, and only a few regions (green) were up to scratch. With the growth of the year, the area of the green region extended little by little, while the area of the blue-black region shrunk gradually. By 2017, a large area of the black region had vanished basically, and the green region tended to dominate. This means that the air quality has been greatly improved. In terms of the relationship between pollutant emission trend and emission concentration, for example, in Beijing, the emission of PM$_{2.5}$ in 2012–2017 was 82,344, 73,389, 67,939, 57,370, 44,879, and 38,987 tons, respectively [55], showing a decreasing trend year by year, which was consistent with the change of AMC of PM$_{2.5}$, with a positive correlation. The reason for this is that high-efficiency mitigation measures have been increasingly implemented in all emission source sectors according to the Clean Air Action [56].

China is divided into seven regions: Northwest, North, Northeast, East, South, Southwest, and Central, as shown in Figure 3a. Spatially, AMC of PM$_{2.5}$ varies significantly across different regions. Taking the case of 2015 (Figure 3d), the region with the highest AMC of PM$_{2.5}$ (higher than 70 $\mu$g/m$^3$) was principally concentrated in the central and northern, especially in Beijing, Tianjin, Hebei, and their peripheral regions. AMC of PM$_{2.5}$ in northwest, northeast, and east regions was chiefly in the range of 40 to 70 $\mu$g/m$^3$, and the distribution was relatively uniform. The lowest AMC of PM$_{2.5}$ was discovered in the southwest, south and southeast (Fujian Province and its adjoint regions), and was equal to or less than 35 $\mu$g/m$^3$. From these, the regions with better air quality are mainly located in the southern part of China, while the northern part has demonstrated the opposite, that is, the AMC of PM$_{2.5}$ presents a tendency of “higher in the north and lower in the south”. In fact, the southern part of China is close to the equator, mostly with tropical monsoon climate, and the increase of static
wind in horizontal direction provides favorable conditions for the diffusion of haze PM. The annual average temperature is relatively high, which greatly reduces the occurrence of inversion phenomenon, moreover, the humidity is also relatively high. Thus, this greatly limits the occurrence of HW.

2.3. Major Source of Haze PM in Different Regions

According to the analysis of the spatial distribution characteristics in previous sections, AMC of PM$_{2.5}$ manifests distinct regional differences, therefore, making clear the major sources of haze pollutants in different regions is the basis and prerequisite for targeted control HP. Although many literatures have introduced the sources of PM in the past, most of them are general descriptions or specific analysis within a certain city, and fewer observe and analyze the spatial distribution of HP sources from a macro-overall perspective.

Source apportionment of PM is an effective means to clearly understand the types and contribution rates of HP sources. At present, there are three commonly used methods for source apportionment of PM in China: (1) based on receptors, the characteristic information of emission sources and environmental samples of PM is analyzed and extracted, then, the types of pollution sources are determined, and the contribution rates of various pollution sources to receptors are calculated, i.e., receptor model, which contains principal component analysis (PCA), chemical mass balance (CMB), UNMIX model and factor analysis (FA), etc.; (2) According to the emission factors and activity levels, the emissions of various pollutants is estimated, and the type and contribution rates of HP sources are determined, i.e., source inventory method; (3) Taking the physical and chemical changes of haze pollutants at spatial scale as foundation, the contribution ratio of different pollution sources is assessed, i.e., source model method. Among them, receptor model is the most commonly used method for source apportionment of PM in China [57–60].

Since 2013 is the year of the starting of the “China Action Plan for the Prevention and Control of Atmospheric Pollution”, this section took 2013 as the node, then, 71 articles on the source apportionment of PM published between 2017 and 2019 (as of 27 September) were searched from the China National Knowledge Infrastructure and Web of Science, and combined with literature data published before 2017, which came from the work of Zhu et al. [61]. Even though Zhu et al. undertook relevant research, literature data after 2013 were not enough. Therefore, in order to observe the contribution rate of various pollution sources in different regions with the change of years, in this work, according to the seven geographical regions in Section 2.2, the percentage of different PM sources in 2007–2012 and after 2013 were calculated. For the contribution of various types of pollution sources in diverse regions, only seven kinds of pollution sources are exhibited here, and the relatively smaller ones were belonged to other categories, as shown in Figure 4.

In Northwest China, before 2013, secondary source, coal burning, and traffic were three largest pollution sources, and their contribution rates added up to 63%, which exceeded half of the total. The proportion for industrial factors and dust was the same, about 14%. Furthermore, the ratio of biomass burning and other sources was 5% and 4%, respectively. Statistical results of literature data from 2017 to 2019 [62–68] and Zhu et al. revealed that secondary source and traffic were still the two most considerable contributors to PM, accounting for 21% and 20%, respectively. Besides, industrial factors (16%) and dust (25%) turned into two other substantial pollution sources. There is a larger area of desert in Northwest China, which can readily lead to windy sand weather or even sandstorms. Therefore, the dust source has always accounted for a large proportion. In addition, the average sunshine time in Northwest China is relatively long, which may provide good light conditions for the chemical reaction of air pollutants, thus forming secondary pollution sources. In addition, for traffic source, taking Xinjiang as an example, by the end of 2017, the number of civil vehicles had reached 3.6556 million, showing an increase of 10.8% over the end of last year, of which the number of private vehicles was 3.0174 million, which were up 12.6% year-on-year [69]. The proportion of coal burning (13%) was gradually diminished while that of biomass burning (5%) stayed the same.
Figure 4. Major sources of PM in different regions of China from 2007 to 2012 and 2013 to 2019.

In the Northern region, the top four sources were dust (24%), coal burning (16%), secondary source (14%), and traffic (14%) in 2007–2012. Except for the contribution of construction dust, there is also a high incidence of dust weather in the vast area of Inner Mongolia, which can have a great contribution to the dust source. Industrial factors, biomass burning, and other sources individually contributed 13%, 4%, and 15%. After 2013, the percentage of dust dropped to 16%, while the contribution of coal burning, traffic, and secondary source separately risen to 19%, 15%, and 24% [61,70–88], and they were the top four sources as before. This shows that the treatment project of sandstorm sources of Beijing and Tianjin has achieved preliminary success in recent years. However, the control effect of traffic emission was not pronounced, which was also related to the increase in vehicle ownership year by year. As far as Beijing is concerned, in 2017, the rise of vehicle ownership was 192,000, and it was 175,000 in 2018, with a total of 6.084 million. In addition, the contribution from biomass burning, external source and other sources were 5%, 1%, and 8%, respectively.

In Northeast China, from 2007 to 2012, similar to Northern China, coal burning, traffic, secondary source, and dust were the four most important pollution sources, contributing to 19%, 18% 14%, and 14% of total PM. The percentage from other sources (25%) was more than twice as much as industrial factors. In 2013–2019, the industrial factor was the top pollution source, accounting for 21%, whose contribution to PM was triple that of biomass burning (7%), and sevenfold external source (3%) [61,89–91]. The ratio of dust increased to 19%, while that of coal burning, traffic and secondary sources decreased to 15%, 11% and 8%, respectively, followed by other sources (16%). This may be related to the heavy industrial
center of China. Other sources principally consisted of some unsolved sources, such as sea salt, oil burning, etc. in this region.

In East China, in 2007–2012, secondary source (29%) and dust (21%) were the two most significantly pollution sources, and their contribution rates accounted for a half of the total. The proportion of coal burning, traffic, and industrial factors was the same, accounting for 13%. Biomass burning (4%) and other sources (7%) were next. Between 2013 and 2017, the sum of proportion of traffic and secondary source was the same as before, occupying 42% [61,92–113]. Meanwhile, the sum of the contribution of industrial factors (12%) and dust (15%) was equal to that of coal burning (16%) and other sources (11%), and was about seven times as much as biomass burning. As a region with rapid economic development in China, the number of vehicle ownerships increased sharply, which resulted in a larger contribution of the traffic source to HP.

Like the Eastern regions, in the Central region, the top two sources were secondary source (24%), and dust (32%) during 2007–2012, and their contribution rates added up to exceed half of the total. The proportion of traffic (16%) was equal to the sum of coal burning (15%) and industrial factors (1%), and was double other sources (8%) and quadruple biomass burning (4%). After 2013, not only the contribution rates of secondary source (18%) and dust (18%) occupied an important position, but also that of traffic and industrial factors climbed to 18% and 21%, changing into another two important pollution sources [61,114–122]. The percentage of coal burning dropped to 10%, while that of biomass burning (8%) was twice as much as before, equal to other sources and the largest in the same category in China. As a plain region in China, the central region possesses flat terrain, which can provide good terrain conditions for the diffusion of haze pollutants. However, HW is still frequent, which is likely due to excessive emission of HP sources. In addition, the central part of China is a locus of agricultural production, so the contribution of biomass burning cannot be ignored.

In the Southern region, from 2007 to 2012, secondary source and traffic were the two most important pollution sources, accounting for 21% and 31%, and industrial factors (13%), dust (12%), and other sources (13%) were next. Biomass burning, coal burning, and external source were the three least important sources, accounting for 4%, 4%, and 3%. After 2013, secondary source (22%) and traffic (20%) were still the two foremost pollution sources [61,123–129]. The proportion of industrial factors (13%) was the same as coal burning, and remained constant. Similarly, the percentage of dust (12%) also stayed the same, followed by biomass burning (7%). The key enterprises of HP in Southern China are less distributed, so the contribution of industrial factors to PM stays the same for long. Because of its unique climate, it can provide adverse conditions for the formation of HP, and coal combustion cannot be used for heating in winter in this region, which minimizes the source emissions of HP. However, the contribution of traffic sources has not been effectively controlled.

In the Southwest region, whether before or after 2013, dust and secondary source were the two most significant pollution sources, accounting for 29% and 28% in 2007–2012 and 27% and 24% in 2013–2017 [61,130–133], respectively. The complex topography of Southwest China, with many mountains and basins, limits the diffusion of haze pollutants, and the humidity in the atmosphere is relatively high, which may provide favorable conditions for the formation of secondary sources. In addition, Southwest China has abundant mineral resources, and has a large amount of mining, which will cause a lot of dust in the process, so this factor is also very important. Between 2007 and 2012, the contribution from coal burning was identical to the sum of traffic and biomass burning, occupying 15%, followed by industrial factors (7%) and other sources (6%). Coal burning, industrial factors, traffic and biomass burning accounted for 14%, 11%, 8%, and 5% in 2013–2017.

Overall, it can be seen that the proportion of HP sources in different regions is diverse, which is caused by many factors, not only depended on the local terrain and climate conditions, but also closely related to the level of economic development, industrialization process and social background, etc. Secondary source is the most important pollution source of PM in most regions of China. The NOx and volatile organic compounds from combustion, industry and traffic sources are used as catalysts and combine with the corresponding climatic conditions to promote the formation of secondary
pollution sources. However, at present, research on the specific formation mechanism of secondary pollution sources is not deep enough, and the accurate prediction and effective control of secondary pollution sources are an urgent problem to be solved. In addition, the traffic is also a more significant pollution source, which may be closely related to the current car ownership in China. In recent years, with the rapid economic development, people’s living conditions are improving rapidly, so people’s demand for vehicles is also increasing, which results in a large number of vehicle ownerships.

3. Hazards of HP

In the past, researchers mainly focused on the impact of HP on human health, but paid less attention to other aspects. On this basis, this section not only sorts out the harm mechanism and possible results of haze pollution to human health, but also summarizes the three aspects of human production and life, economic loss, and atmospheric environment, so as to further understand hazards of HP.

3.1. Effects of HP on Human Health, Production, and Life

3.1.1. Effects of HP on Human Health

Some results indicate that the composition of PM is very complex, including not only some heavy metals, organic compounds (such as particulate organic compounds), inorganic salts (including sulfates, ammonium salts, nitrates, etc.), pollen and allergic substances containing carbon particles, but also a variety of pathogenic microorganisms such as bacteria, fungi, and viruses. What is more, the particle size of PM is small, while the surface area is large and the activity is strong, which is easy to carry a large number of toxic and harmful substances in the atmosphere for a long time [134–136]. Therefore, PM can have a serious impact on human health.

Human respiratory system bears the brunt [137]. The human body mainly inhales PM through the respiratory system and directly contacts them. These inhaled haze PM can give rise to various degrees of damage to the respiratory system through a series of complex functions, such as immune damage, oxidative stress, inflammatory reaction, and carcinogenic effect [138–140]. The number of people hospitalized for respiratory system diseases caused by HP is quite large every year. Only in Beijing, on 10–15 January 2013, the number of people hospitalized for respiratory system diseases, acute bronchitis, and asthma were about 1056 (95% CI: 0–1805), 10,132 (95% CI: 6116–11,375) and 7643 (95% CI: 5820–9114), respectively [141]. In medicine, the respiratory system is often divided into upper and lower respiratory tract, in which the upper respiratory tract includes nose, pharynx, larynx, and other organs and the gas channel (including the bronchi in the lung) below the trachea is belonged to the lower respiratory tract. The inhaled PM can affect the upper and lower respiratory tract of the respiratory system. Firstly, for the upper respiratory tract, PM can gradually deposit on the surface of the upper respiratory tract mucosa through the nasal cavity, then, harmful substances carried by PM will have a greater contribution to the epithelial cell damage and inflammatory response, in this way, which can result in some diseases such as nasal cavity and throat inflammation [142,143]. Wu et al. [144] revealed that the PM concentration in the atmosphere was positively correlated with the number of visits to upper respiratory tract diseases. Secondly, For lower respiratory tract, the PM with smaller particle size, such as PM$_{10}$, PM$_{2.5}$, etc., can enter the gas channel below the trachea and deposit on the surface of bronchi at all levels and alveoli, and further induce asthma [145], chronic obstructive pulmonary disease [146], bronchitis [147], and lung cancer [148] and other lower respiratory tract diseases in different degrees.

The human cardiovascular and cerebrovascular system can also be hit. The inhaled PM has negative effects on the human cardiovascular and cerebrovascular system through direct and indirect effects [149].The direct effect mainly comprises two ways: (1) some harmful components carried by the PM enter the human body circulatory system through the alveolar epithelial cells and directly act on the cardiac myocytes and (2) the exposure of the PM causes the rise of red blood cells and hemoglobin, which leads to the rise of blood viscosity and promotes thrombosis [150]. There are two ways of
indirect action: (1) PM may indirectly affect the cardiovascular and cerebrovascular system by inducing the dysfunction of autonomic nervous system and (2) harmful components carried by PM entering the lung interact with macrophages in the lung tissue, which will produce inflammatory mediators, chemokines and activated oxygen, and trigger inflammatory reaction and oxidative stress, thus, it can indirectly affect the heart vascular system [151]. Furthermore, PM with various particle sizes have unequal effects on the human cardiovascular and cerebrovascular system. For PM$_{10}$, the excess risk (the difference between the risk of an outcome in the exposed group and the unexposed group) of cardiovascular disease and cerebrovascular disease was 0.63% (95% CI: −0.02%−1.28%) and 0.33% (95% CI: −0.26%−0.92%) for every 10 µg/m$^3$ increase in concentration; for PM$_{2.5}$, that was 0.85% (95% CI: −0.28%−1.99%) and 0.75% (95% CI: −0.17%−1.68%) for every 10 µg/m$^3$ rise in concentration [152].

As far as Beijing is concerned, during heavy haze, On the basis of 75 µg/m$^3$ for the daily average PM$_{2.5}$ concentration mean (the second standard limit of AAQS), for every 10 µg/m$^3$ increase in concentration, 21 cases of cardiovascular diseases were hospitalized [141].

HP has some other health threats to human body. According to Fu et al. [153], in 2014, the number of people who died prematurely due to PM$_{2.5}$ in Hebei Province was 108,640; on 10–15 January 2013, about 201 cases died prematurely due to HP in Beijing [141]. HP can also do harm to human skin tissues. Based on the survey results in Nanchang, Jiangxi Province, the prevalence rate of skin and mucous membrane diseases in HP area was greater than that in clean area by 10.75% [154]; Wang et al. [155] pointed out that for each 1 µg/m$^3$ increase of PM$_{2.5}$ and PM$_{10}$ concentration in single pollutant model, the relative risk (the ratio of the probability of an outcome in an exposed group to the probability of an outcome in an unexposed group) of the increase of daily visits of urticaria was 1.0001 (95% CI: 0.9997~1.0004) and 1.0002 (95% CI: 0.9999~1.0004), respectively. This means that urticaria is closely related to the concentration of PM. Moreover, HP also has a greater impact on people’s mood, on the basis of the survey results of 27 provincial capitals and four municipalities directly under the central government in 2013–2015, PM$_{2.5}$ concentration in each region was positively related to people’s depression index, with a correlation coefficient of 0.33 [156], which had a negative impact on people’s well-being [157].

3.1.2. Effects of HP on Human Production and Life

HP not only poses a threat to human health, but also affects other aspects of human activities. For instance, when the haze occurs, people have to lessen their travel, and especially those who like outdoor sports have to reduce or even not carry out outdoor activities, so as to avoid exposure to haze environment as much as possible. During heavy haze, the visibility is seriously reduced, resulting in paralyzed traffic or even frequent traffic accidents, flight delays or cancellations and other problems, which seriously affects the normal transportation. In addition, it is possible to promote the spread of some infectious diseases [158].

HP has a huge effect on the production and circulation of crops. First of all, during the period of haze, the growth environment of crops is mainly affected by the following three aspects: (1) poor photosynthesis of crops, because the PM in the air absorb a portion of the solar radiation, the light intensity in crops growth environment and the lack of light time were declined [159–161]; (2) for the greenhouse crops, they are easy to grow in the environment with low temperature and high humidity, giving rise to diseases such as freeze damage, crops diseases, and insect pests; and (3) the settlement of PM brings about pollution on the crops and the growing soil or water resources environment, such as heavy metal pollution. Next, HP has an effect on the quality and yield of agricultural products. This is not difficult to understand, because in the case of the condition of poor growth environment, it can inevitably influence the normal development of crops, thus affecting the yield, nutritional value and appearance quality of agricultural products. Relevant research showed that the HP could also affect the normal circulation of agricultural products, which are mainly due to the HP affecting traffic and indirectly leading to the circulation difficulties of agricultural products [162].
In the same way, HP also affects other industries. For example, in terms of the livestock industry, HP can aggravate the deterioration of livestock living environment, provide favorable conditions for the reproduction and transmission of pathogenic microorganisms, and render livestock diseases. And some studies manifested that HP can also cause ecosystem degradation and reduce biodiversity to a certain extent [163]. Besides, PM fall on the surface of some utensils or materials, bringing out some physical and chemical effects, which result in damage or shortened life. Of course, HP can also play a positive role in promoting some industries, such as air purification equipment, air pollution monitoring equipment, and seedlings, which are conducive to the treatment of HP.

3.2. Effects of HP on Economic Losses

HP takes a great toll on human health as well as economy, especially direct health economic loss. Firstly, in the region with severe HP, in terms of Beijing, on 10–15 January 2013, during the haze in Beijing, the economic loss related health reached 489 million Chinese Yuan (95% CI: 2.04–7.49), of which the most chief economic loss came from premature death, acute bronchitis, and asthma, accounting for more than 90% of the total. Furthermore, the economic loss of hospitalization due to HP in Hebei Province in 2015 was calculated to reach 77.049 billion Chinese Yuan, contributing to 2.59% of the province’s GDP [153]. In the region with relatively mild HP, for instance, in Shanghai, the average health economic loss caused by HP during 2006–2015 was about 9.464 billion Chinese Yuan, about 5.42% of GDP [164]. From a nationwide point of view, the direct economic losses owing to HP in 20 provinces and cities in January 2013 were conservatively estimated to be about 23 billion Chinese Yuan, of which the economic losses of emergency/outpatient health terminals alone was nearly double that of all health terminal losses caused by PM pollution in the case of non-haze events in the existing literature [165].

HP can also bring about relevant indirect economic losses. Likewise, taking Beijing as an example, during the haze period in January 2013, the total indirect loss of industrial linkage touched off by the direct economic loss of the transportation sector on account of HP was 21.0355 million Chinese Yuan, which was more than three times the direct economic loss of the transportation industry [166]. In addition, in 2012, it was estimated that the total indirect economic losses in Beijing were 13,139,204,04 million Chinese Yuan from the perspective of demand, accounting for 0.735% of GDP. From the perspective of supply, the indirect economic losses caused by the total indirect sector related economic loss were about 25,172,726,988 million Chinese Yuan, contributing to 1.408% of GDP in that year [167]. It is not difficult to find that the indirect economic losses aroused by HP should not be underestimated.

3.3. Effects of HP on Atmospheric Environment

HP has an impact on the atmospheric environment. Most visibly, when the haze occurs, the visibility of the atmosphere is seriously abated, and the general horizontal visibility is less than 10,000 m. PM can scatter and absorb light, which is the major factor to lessen atmospheric visibility, accounting for about 80% of the total extinction [168]. Wei et al. [169] revealed that sulfate and organic matter in PM were the main components that affect the atmospheric extinction. As the PM contains sulfates, nitrates and complex anion and cation, in case of rainfall, PM can affect the pH value of rainwater as well as the size and quantity of raindrops [170]. The harm of PM falling to the ground with rainwater to soil and water quality cannot be ignored, such as water eutrophication [171]. Interestingly, recent studies pointed out that haze can improve the ocean’s ability to absorb greenhouse gases, which may have an influence on the content of greenhouse gases in the atmosphere [172].

In a word, HP not only causes serious harm to human health, but also the unfavorable effects on the development of related industries, plant growth, property loss (especially indirect economic loss), and atmospheric environment cannot be ignored. Therefore, we need to understand the harm of HP more comprehensively, which is essential to prevent and deal with HP in advance.
4. Prevention and Control Technologies and Measures of HP

HP has brought serious harm to human beings and the environment. Therefore, how to effectively control HP has become an urgent problem. For the causes and conditions of haze formation, meteorological factors are uncontrollable for human beings, while the contribution of human factors to HP is controllable. From the perspective of source control and non-source control technologies of HP, this section summarized the progress made in the treatment of HP in recent years to provide a reference and basis for further comprehensive treatment of HP.

4.1. Source Control Technologies and Measures

Controlling HP from the source is to control the amount of pollutants imported into the atmosphere, so that it is unable to form HP. According to the above analysis results of PM source apportionment in different regions, the sources of HP can be divided into four sources: fixed source, mobile source, open source, and scattered source.

Firstly, fixed sources mainly cover coal combustion, metal smelting, cement production, chemical industry, and other industrial process related pollution sources. This kind of industrial process has the characteristics of high energy consumption and high pollution, therefore, the prevention and control of the transport of PM from them to the atmosphere can be started from the macro, meso, and micro levels. At the macro level, the state is required to upgrade, adjust and optimize the energy structure dominated by coal and the irrational industrial structure, and formulate the emission standards of relevant industries [12]. At the meso level, for all large, medium, and small enterprises, they must select the appropriate and effective air purification equipment. At present, the purification methods for PM in tail gas primarily refer to mechanical precipitators [173–176], wet scrubbers [177–180], bag filters [181,182], electrostatic precipitators [183,184], some mixed type scrubbers [185–188], etc., from these it can realize all-round clean production. At the micro level, the movement behavior of PM in different types of air purification equipment needs to be deeply understood, which can provide a theoretical basis for more cost-effective air purification equipment technology research and development. In this way, the input of PM from fixed sources in the atmosphere can be controlled.

Secondly, mobile sources mainly come from vehicle exhaust emissions. There are internal and external reasons for this kind of pollution. For one thing, the internal reasons can be mainly divided into two general aspects: (1) the quality of motor vehicle fuel is not up to standard [189] and (2) the fuel is not fully burned in the motor vehicle engine [190]. For another, there are two external reasons: (1) the number of motor vehicles has increased rapidly in recent years [191] and (2) The motor vehicle is not equipped with exhaust gas purification device or the efficiency of the exhaust gas purification device installed is not high enough [192]. Therefore, for the pollution caused by internal reasons, first of all, it is necessary to start with improving the quality of motor vehicle fuel, accelerating the further development and promotion of fuel quality improvement technology, upgrading and transforming oil refining enterprises [12]. Secondly, the engine internal purification technology should be vigorously developed, which currently mainly relates to optimizing the structure of the engine combustion chamber, improving the ignition system, improving the fuel supply and air intake system, etc. [193,194]. Furthermore, the emission of gaseous and particulate pollutants can be declined by improving and replacing the conventional fuel, such as change the composition of the fuel and substitution of the traditional fuel with clean fuel [195]. For the pollution caused by external factors, firstly, the number of motor vehicles should be strictly controlled in the country, and the old motor vehicles ought to be gradually eliminated, then public transportation is vigorously developed [196]. After that, the external purification technology of motor vehicle engines can be developed and promoted, which requires that motor vehicles must be equipped with appropriate and efficient exhaust purification devices [197,198]. Furthermore, a series of policies and regulations need to be formulated, such as fuel consumption standard, oil product standard, heating measurement standard, etc. [12].
Thirdly, in terms of open sources, they mainly refer to some pollution sources such as construction dust and road dust which are directly exposed to the atmosphere. According to different types of open sources, pollution control measures should be implemented depending on local conditions. For the construction dust, above all, a certain height of baffle must be applied to close the construction site to separate from the outside and prevent the dust diffusion everywhere. In the construction site, the entrances, exits, and the major roads have to be hardened, and the rest of the bare ground should be afforested or solidified, meanwhile, slag soil, construction waste, and bulk materials must be classified, stacked, and covered. It is necessary to formulate emission standards, real-time monitor, spray dust removal treatment, and strengthen supervision and management for the construction dust. The construction of transport vehicles are obliged to be exploited closed hopper, and clean the dirt and dust for outside the vehicle, so that vehicles cannot carry mud on the road [199–201]. For road dust, first of all, strengthen the management of road greening, such as greening or hardening all the exposed ground in the road, regularly clean the road, spray water and mechanical dust to avoid creating dust conditions on the road itself. The transportation department must strengthen traffic control, restrict or prohibit all kinds of vehicles with poor sealing effect, involving omissions and spills, and impose a fine according to law [202,203].

Finally, scattered sources deal with residential raw coal combustion and crop residue burning, etc. For this, firstly, people’s awareness of environmental protection should be improved to spontaneously put an end to the use or manufacture of scattered pollution sources [12]. Secondly, these scattered pollution sources can be intensively treated, for instance, the pollution caused by residential raw coal combustion for heating, can be centralized treatment by the project of “coal to electricity”. In addition, the government can implement ultra-low emissions, eliminate coal-fired boilers that do not meet the standards, or employ clean energy such as “coal to gas” to replace scattered coal combustion [204,205]. For pollution from crop residue burning can be recycled in a centralized way and used in biogas, agriculture, pasture, and biomass power plants. From another point of view, starting from the level of scattered sources themselves, it needs to improve the quality of raw coal and prohibit the circulation of inferior coal [206] and, it can utilize modern mechanical technology with smashing straw back to the field, or prohibit burning crop residue [207].

4.2. Non-Source Control Technologies and Measures

From the perspective of non-source to control HP, that is, it is necessary to cut down on the concentration of the particles that have been discharged into the atmosphere to ensure the purification capacity of the atmosphere itself. Therefore, from two aspects of green plant absorption and artificial control, this section elaborates the non-source control technologies and measures of HP.

Green plants absorption, that is, through green plants to absorb the PM discharged into the atmosphere. Studies have shown that green plants possess distinct effects of blocking and adsorption on atmospheric PM, therefore, the planting area of green plants can be expanded to augment the coverage rate of green plants, while the exposed ground is lessened as much as possible. The greening construction of three-dimensional space can also be promoted, such as implementing roof greening and wall greening for related buildings [208]. Gao et al. [209] pointed out that various plant leaves have different adsorption effects on PM, and the percentage of 10–100, 2.5–10 and 0.2–2.5 µm PM adsorbed by different plant leaves is about 75.4%, 15.8%, and 8.9%, respectively. Therefore, it is very important to select the plant species which have remarkable adsorption effect on PM in the local atmosphere in different regions.

Artificial control, that is, through the development of effective atmospheric dust control technology to directionally collect PM in the atmosphere. Firstly, the effect of laser gradient force, relevant research showed that the laser gradient force can be used to act on PM during the occurrence of haze, which can accelerate the deposition rate of haze PM, and the larger the PM size, the more obvious the deposition effect [210,211]. Secondly, the effect of modified lightning rod, according to the principle of electrostatic precipitator, during the HW, the modified lightning rod could release negative electricity through the tip of the lightning arrester, so that the respirable particles in the atmosphere were charged with negative
electricity, and then were absorbed by the ground through electrostatic induction. For Shenyang, when \( PM_{2.5} \) is 200 \( \mu g/m^3 \), about 245 t of respirable particles were collected in an hour [212]. In addition, the “particle-sink” effect can also be applied to remove haze PM. Based on the concentration gradient force, haze PM can change from irregular Brownian motion to strong directional migration to purification device, forming a “particle-sink” relative to the “particle-source” [213,214].

While the source control technologies and measures of HP tasks are to be well performed, non-source control technologies should not be ignored. For non-source control technologies, if a concentration monitor is configured and the corresponding standard is set, when the haze pollutant index in the atmosphere is lower than this standard, the haze removal device developed according to these technologies can be automatically started. In this way, the source and non-source control technologies cooperate with each other, and the removal effect of haze pollutants in the atmosphere will be further improved.

5. Conclusions and Prospects

To more comprehensively understand the haze situation and latest research progress in China, the basic situation, hazards, control technologies, and measures of HP in China were reviewed, and the conclusions are as follows:

(1) The situation of HP in China is getting better year by year, which is closely related to the national policy and vigorous supervision, while it has been a pattern of high levels in the north and low levels in the south.

(2) In most regions of China, the contribution of secondary source for HP is relatively large, and that of traffic is greater in the regions with rapid economic development.

(3) HP not only causes serious harm to human health, including the mental mood, but also the effects on the human production and life, plant growth, property, and atmospheric environment cannot be ignored.

(4) The source and non-source control technologies and measures of HP were the first surveyed, and from which we found that the current research on non-source control technology of HP is not in-depth and it has not been widely applied at present.

Based on this, aiming at the HP in China, the following research should be focused in the future:

(5) The source apportionment of PM in the atmosphere is the premise of accurate and effective control of HP. At present, the research on source apportionment of PM is mainly concentrated in the developed regions such as municipalities and provincial capitals, while that on small- and medium-sized cities or underdeveloped regions is relatively scarce, and the conclusions of different source apportionment technologies are not consistent. Therefore, in the next step, we should further promote the sources apportionment of PM, and then establish a dynamic database of the sources of haze pollutants in different regions.

(6) In most regions of China, the proportion of secondary sources is relatively larger. Therefore, it is necessary to have a deeper understanding of the formation mechanism of secondary pollution sources, so as to provide a substantial theoretical basis for further control HP.

(7) At present, China relies on the government to lead and constantly improve relevant laws and regulations, but individual or public participation is very limited. Therefore, while studies on the legal countermeasures of HP were strengthened, we should further enhance people’s awareness of environmental protection and improve the social health security system, so as to ensure the unity of efforts from the top to the bottom.

(8) In studies on the technologies and measures to control HP, the key point is on the source control technology and measures, but the research on the non-source control technology and measures is not deep enough. Thus, at the same time as reducing the emission of PM to the atmosphere, we should also pay attention to reducing the concentration of existing PM in the atmosphere, and then, build a twin-track strategy to ensure the purification capacity of the atmosphere itself.
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