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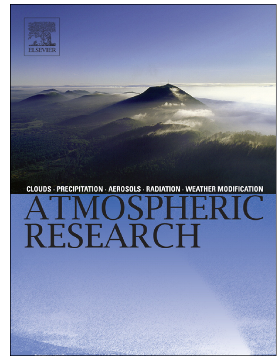

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Air quality during and after festivals: Aerosol concentrations, composition and health effects

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Highlights

- Fireworks and bonfires are sources of atmospheric pollutants and typically affect short-term air quality.
- This review article presents a summary of the impacts of fireworks and bonfires on air quality, visibility, and human health.
- Typically, concentrations of air pollutants can be 2-8 times higher than average during fireworks events. Additionally, concentrations of elements including Ba, Cu, Pb, Cr and Sr are reported to be several times higher during fireworks events.
- Limited studies have shown an impact on respiratory health, but significant gaps in knowledge remain.

Abstract

Ambient particulate matter (PM) continues to be among the top environmental health concerns globally; in 2017, nearly 3 million deaths were attributed to exposure to $PM_{2.5}$ around the world (HEI, 2019). While much attention is paid towards point and mobile sources of PM (e.g., power plants, vehicles), episodic/periodic events such as dust storms, use of fireworks etc. can also increase ambient PM levels and lead to adverse effects on air quality, visibility, and human health, albeit in the short-term. Fireworks and bonfires are commonly used during religious and cultural festivals including Diwali (India), Lunar New Year (China), Bastille Day (France), Guy Fawkes Night (UK), Australia Day (Australia), Fourth of July/Independence Day (USA), New Year's Eve (worldwide) as well as large sporting and other events. During these events, use of fireworks results in smoke plumes which can raise the PM concentration levels for short periods of time. This review article summarizes the current body of literature on the role of fireworks use (and bonfires) on air quality, visibility, and human health. A summary of distinct type of fireworks and existing legislations/laws in different countries is also presented. Overall, there is clear evidence that such events produce exceptionally high level of pollutants, and as a result there can be intense exposures to a multipollutant mixture. In particular, the sharpest spikes are found in pollutant concentrations (such as $PM_{2.5}$, PM_{10}, and NO_x) during and immediately after the firework event, followed by a decrease in the concentrations back to background levels within 24 hours. Peak concentrations of pollutants during firework events can exceed ambient levels by 2-8 times. As a result, overall visibility also decreases significantly, and in some cases, by as much as 92% during fireworks events. Moreover, significant health risks due to fireworks activities are also reported, although limited research has been conducted on this type of rapid air pollution exposure. The review concludes with a list of suggested future research priorities required to better understand the impacts of fireworks and bonfires on human and environmental health.

Keywords: Particulate Matter, Fireworks, Air Quality, Trace Metals, Visibility

1.0 Introduction

Over the past few years, concern over short and long-term effects of exposure to air pollution has increased dramatically. Several studies have linked exposure to particulate matter (PM) with a range of respiratory and cardiovascular diseases (Dockery and Pope, 1994; Dominici et al., 2006; Goldberg et al., 2006; Hoek et al., 2013; Peters et al., 1997; Thurston et al., 2016). Major sources of air pollution include transportation, residential energy use, industries, power plants, dust and waste burning (Amato et al., 2016; Karagulian et al., 2015; Thurston et al., 2011; Viana et al., 2008).

Numerous festivals and events around the world involve the use of fireworks/bonfires including Diwali (India), Lunar New Year (China), Bastille Day (France), Guy Fawkes Night (UK), Australia Day (Australia), Fourth of July/Independence Day (USA), New Year's Eve (worldwide) and large sporting events (***Table 1***). Use of fireworks and bonfires to mark cultural or national celebrations can be an important short-term anthropogenic source of air pollutants with significant impacts on local air quality (Galea and Powles, 2010; Pathak et al., 2013). Firework and bonfire events have previously been connected to poor visibility and air quality around the globe, with corresponding health concerns (Becker et al., 2000; Kong et al., 2015a; Kulshrestha et al., 2004; Nasir and Brahmaiah, 2015; Pathak et al., 2013; Pope et al., 2016; Singh et al., 2015; Singh et al., 2005; Van Kamp et al., 2006; Witsaman et al., 2006; Yerramsetti et al., 2013). Use of fireworks or bonfires can release a range of air pollutants including particulate matter and gases (e.g., sulphur dioxide [SO_2], nitrogen oxides [NO_x], carbon dioxide [CO_2], carbon monoxide [CO]); these pollutants can have direct impacts on human health (Hamad et al., 2016; Kulshrestha et al., 2004; Ravindra et al., 2003; Seidel and Birnbaum, 2015). PM and gaseous pollutants emitted during such events can scatter and absorb light radiation and contribute to light extinction, thus influencing visibility (Appel et al., 1985; Singh et al., 2017; Singh and Dey, 2012). A recent analysis in Mexico also linked use of fireworks with enhanced production of nitrous acid (HONO) (Retama et al., 2019). The sudden spike in pollutant concentrations during fireworks and bonfire events can trigger a variety of adverse health effects including asthmatic attacks, lung infection, eye allergies, cough, fever and cardiovascular disease (Barman et al., 2008; Becker et al., 2000; Beig et al., 2013; Hirai et al., 2000). Finally, use of fireworks is also associated with high levels of noise which can impact wildlife (Shamoun-Baranes et al., 2011), and chemicals released from fireworks (e.g., perchlorates) have been reported to affect surface water quality (Wilkin et al., 2007) and contaminate snow (Steinhauser et al., 2008).

Despite being an important short-term source for air pollution, there are still significant gaps in our understanding of the characteristics of pollutants emitted during firework events, and related impacts. This review summarizes the existing literature on fireworks and bonfires and their impact on air quality and visibility. Knowledge gaps in the field are highlighted and will aid in shaping future research efforts. For the purposes of this review, relevant literature was collected via searches on PubMed, Web of Knowledge, Google Scholar and Science Direct using keywords such as "fireworks", "bonfire", "air pollution", "air quality", "visibility", "particulate matter", "particle", "gas", "health impact", "meteorology", "relative humidity, "temperature", "wind" , "urban/city" and "festivals/celebration".

2.0 Types of fireworks and regulatory frameworks

Fireworks can be divided into four specific categories based on their use; (1) indoor fireworks, (2) outdoor fireworks, (3) display fireworks, and (4) professional fireworks. In general, professional and display fireworks are used during large events and generate large amounts of smoke and pollution while consumer fireworks (e.g., sparklers, bottle rockets, fountains and smoke bombs) are low-scale fireworks and typically generate relatively less smoke, sparks and flames (Martín-Alberca and García-Ruiz, 2014; Shimizu, 1996). Each type of firework typically has four major components- fuel (e.g., charcoal or sulphur, aluminium and magnesium), oxidizing component, which are typically chlorates, perchlorates or nitrates (e.g., potassium chlorate, barium or strontium nitrates etc.), metal-containing colorants (e.g., aluminium, iron, zinc, barium, lead etc.) which add colour and a combustible binder (e.g., nitrocellulose, shellac, resins etc.) (Betha and Balasubramanian, 2013; Kulshrestha et al., 2004; Li et al., 2017; Liu et al., 1997; Wang et al., 2012) . A number of metallic compounds are used for adding colour to the fireworks. Greens are usually associated with barium compounds (e.g., $BaCl_2$), while blues are usually associated with copper compounds (e.g., CuCl). In terms of emission rates (for particle concentration), among handheld firecrackers (sparklers), whistling sparklers are reported to have the highest PM emission rates (3.24 x 10^{10} particles per gram of sparkler burnt compared to 1.68 × 10^9 particles per gram of sparkler burnt for low-smoke sparklers), and together with coloured sparklers, have higher respiratory deposition efficiency compared to low smoke sparklers (Betha and Balasubramanian, 2013). The burning rate, and hence efficiency, have also been reported to contribute to air pollution emission rates.

For public safety, many countries have legislation and specific regulatory guidance on the storage, manufacture, import, export, purchase and use of all type of fireworks (***Table 2***).

Table 1: List of festivals and celebrations involving fireworks and bonfires

Festival/Event	Country	Time of year	Description
Diwali	Predominantly India	October/ November	Also referred to as the festival of lights, Diwali is celebrated using lights and fireworks. The festival is widely celebrated in India by the Hindu community, and celebrations also take place in other countries including Indonesia, Malaysia, Myanmar, Fiji, Nepal, Sri Lanka, Thailand, Mauritius, Australia, USA, Britain, South Africa, Canada, Singapore, and Trinidad and Tobago.
Lunar New Year	Predominantly China	January/ February	Chinese New Year or the Spring Festival is the biggest holiday in China. The Spring Festival is also celebrated in other Asian countries such as Vietnam, Taiwan, Singapore, Indonesia, Malaysia, Thailand, Australia, Philippines, USA and Britain. Celebrations typically last for a fortnight, with firework displays on New Year's Eve the largest.
Guy Fawkes Night	United Kingdom	November	Guy Fawkes Night or Bonfire Night is the biggest traditional event in the UK involving fireworks displays and bonfires, and is celebrated every year on and around 5th November. It is celebrated in remembrance of the event of that day in 1605, when Guy Fawkes failed to blow up the House of Parliament in the Gunpowder Plot.
Australia Day	Australia	January	Australia Day or National Day is the official event of Australia, which is celebrated on every 26th January. This special Day marks the anniversary of the arrival of the first fleet of convict ships from Great Britain to the British colony at New South Wales in 1788 and raising the Union Jack at Sydney port cover by Captain Phillip. However, in contemporary times, the day is used to celebrate the unity of a diverse society, national pride and prodigious

			achievements. People celebrate this day especially displaying of fireworks, spare time with their family and friends, attending barbecue party and official events such as parade and concerts.
Fourth of July	USA	July	Independence Day of USA is celebrated on 4th of July to commemorate the Independence from British Empire after the Revolutionary war in 1777. The Day is commonly celebrated with using of firecrackers/firework display associated with parades, concerts, family gathering and fairs.
New Year's Eve	Worldwide	December/ January	New Year's Eve, the last day of the year (31st Dec Eve) in the Gregorian Calendar is celebrated by millions of people with intensive and wide spread use of firecrackers, fireworks display and bonfires across the world.

Table 2: Regulations associated with fireworks use in select countries

Country	Firework type(s)	Regulation(s)	Temporal regulation
United Kingdom	• Indoor fireworks • Garden fireworks • Display fireworks • Professional fireworks (to be handled only for trained individuals)	Under the *UK Fireworks Act 2003*, specific regulations are listed for control and handling of fireworks, and additional regulations were introduced in 2004 under *Fireworks Regulations 2004* (HMSO, 2004). Normally, UK imports fireworks mainly from Asian countries, where the UK has set safety standards for its import (British Standard 7114) under the Fireworks Act 2003, Regulation 3 (Galea and Powles, 2010). In the UK, fireworks can be bought from any licenced shop all year round, and during special events (e.g., Guy Fawkes Night, New Year's Eve, Diwali and Chinese New Year), fireworks can be bought from any registered seller (HMSO, 2004). Any illegal fireworks activities can result in a fine and jail time, and there are significant restrictions towards purchase and use of fireworks for a person below the age of 18 (HMSO, 2004).	Use of fireworks is restricted between 11:00 pm GMT to 07:00 am GMT, with the exception of special events such as Guy Fawkes Night, New Year's Eve, Diwali and Chinese New Year when fireworks' use is permitted until 01:00 AM (HMSO, 2004).
USA	• Display/professional fireworks • Consumer fireworks • Articles pyrotechnic ("Pyrotechnic devices for professional use similar to consumer fireworks in chemical composition and construction but not intended for consumer use"- (BATF, 2009))	In USA, Code of Federal Regulations (CFR) controls the fireworks activity legislation (https://www.ecfr.gov/). Under title 16 (parts 1500 and 1507) and 27 (part 555), CFR define specific regulations for explosives and consumer product safety (BATF, 2009; Martín-Alberca and García-Ruiz, 2014; U.S. Code, 2017a; U.S. Code, 2017b) while the Department of Transportation (DOT) categorises and regulates its transportation (U.S. Code, 2017c). A federal explosive license from the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), a federal law enforcement agency, must be required under CFR title 27 (part 555) for any type of manufacturing, storage, and dealing with transportation of fireworks or activity under display fireworks category (with restrictions on who can obtain the license), while no ATF licence is required for transportation, purchase, storage and use of consumer and articles pyrotechnic fireworks (BATF, 2009). In addition, states in USA have their own regulations for professional/display or consumer fireworks use and purchase, with some states including Indiana, South Carolina and Tennessee with very liberal regulations for fireworks activities, and others (e.g., Delaware, Massachusetts) with complete ban on storage, purchase and use of consumer fireworks (Canner et al., 2014).	
India	• Sound emitting fireworks Colour/light emitting fireworks • Display fireworks • Fireworks for export purpose	In India, the Petroleum and Explosive Safety Organisation (PESO), Ministry of Commerce and Industry regulates all aspects of explosives (such as fireworks - low hazardous explosive) under the Explosive Act 1984 (PESO, 2017). Specific centres (Explosives and Fireworks Research and Development Centre-Sivakasi, Tamil Nadu and Departmental Testing Station- Nagpur, Maharashtra) have been established under PESO for explosives' and fireworks' quality control, testing and research. In 2017, the Supreme Court of India completely banned the use of five toxic chemicals and heavy metals- lithium (Li), antimony (Sb), mercury (Hg), arsenic (As) and lead (Pb) in firecracker manufacturing and also directed the national government to stop import of these firecrackers (Lokur, 2017). Following this, in 2018, the Supreme Court of India banned the sales of any traditional fireworks and the use of firecrackers was restricted to a two-hour window in the evening (Gupta, 2018). A licence (depending on firework type) is required to manufacture, transport, sell and store any explosives listed under Part 1 of Schedule IV (The Gazette of India, 2008). However, during major festivals/occasions (such as Dussehra, Diwali,	Use of fireworks is completely restricted between 10 OM and 6 AM IST on normal days under Environmental Protection Act (1986) and The Noise Pollution (Regulation and Control) Rules (2000-2010). During major festivals or events, use of fireworks is permitted until 12 am IST (The Gazette of India, 1986; The Gazette of India, 2010).

		New Year's Eve and Eid), a temporary licence can be issued from District Magistrate for sale and transport of fireworks.	
Australia	• Type 1 (indoor domestic fireworks which has very small amount of pyrotechnic) • Type 2 (consumer fireworks for outdoor use) • Type 3 (professional or display fireworks for large events) and Theatrical fireworks (for concert purpose) (WorkSafe Tasmania, 2016). [only applicable in Tasmania]	Australia has very strong but specific laws on fireworks manufacturing, sale, purchase and use in different parts of the country. Use of consumer fireworks is completely banned in Western Australia and New South Wales (under Explosives Regulation 1963), Queensland (under Explosives Regulation 1999 and 2003), Victoria (under Explosives Regulation 2005) and South Australia (under Explosives Regulation 1936, 2001), while display fireworks can be conducted during special occasions or purposes in these territories by pyrotechnicians and licenced operators (ACT, 2009). Few territories allow sale, purchase and use of consumer fireworks only on specific days such as 1st July (Northern territory), and Queen's Birthday Public Holiday weekend (Australia Capital territory) (ACT, 2009). In Tasmania, Type 1 fireworks are exempt but Types 2 and 3 and theatrical fireworks are allowed in Tasmania with a licence under Explosive Regulations 2012.	
China		Given the harmful effects of fireworks, China has introduced several laws on its use, handling and storage since the 1990s. However, fireworks' laws and regulations in China are usually controlled by public safety management at local level (such as district and township level). Most of the cities in china have adopted specific regulations for fireworks use during different occasions (Lai and Brimblecombe, 2017). For example, in Beijing, use of fireworks on New Year's Eve is allowed only within 5th ring road until the midnight while in Shenzhen the use of fireworks is completely restricted in all main areas of the city(Lai and Brimblecombe, 2017). Like Beijing and Shenzhen, other megacities such as Chongqing, Tianjin, Chengdu, Shanghai, Guangzhou, and Nanjing too, have very strict regulations of fireworks use during Chinese New Year, but some cities like Xi'an, Taipei and Kaohsiung have no strict law rules for fireworks. In particular, after introduced many rules and regulations, air quality trends have improved during fireworks Chinese New Year (Lai and Brimblecombe, 2017).	

3.0 Air quality during fireworks events

Air pollutants from fireworks typically consist of PM, black carbon (BC), SO_2, CO and NO_x. Most studies on fireworks typically make measurements before, during and after the event, in order to quantify the impact of fireworks emissions on air quality. These studies have reported several-fold increase in concentrations of pollutants including PM_{10} (PM with aerodynamic diameter < 10 µm), $PM_{2.5}$ (PM with aerodynamic diameter < 2.5 µm), and NO_x during fireworks events across the world (Barman et al., 2008; Kong et al., 2015a; Seidel and Birnbaum, 2015). On average, studies have reported concentrations between 2–8 times higher than normal days during fireworks events (***Figure 1***). The sharpest spikes in concentration are typically reported during and immediately after the event, followed by a decrease in the concentrations back to background levels within 24 hours (Drewnick et al., 2006; Kulshrestha et al., 2004). Fireworks are typically used after sunset to maximize the visual effect of bright light against a dark background, and as a result, highest concentrations of pollutants are reported during evening hours. In the case of Diwali, for example, highest concentrations have been reported during extended evening hours (20:00-01:00 hours) (Kumar et al., 2016a), while during New Year fireworks events, highest concentrations have been reported around midnight to coincide with the new year festivities (Drewnick et al., 2006). Across cities, average concentrations during fireworks' events range between a few µg/m^3 to as high as 2 mg/m^3 for short periods of time (***Table 3, Figure 1***).

In USA, short-term increases in PM concentrations as well as its constituents have been reported during the Independence Day (July 4th) fireworks (Wang et al., 2012), and in one analysis, several stations were found to exceed the 24h National Ambient Air Quality Standard [NAAQS] for $PM_{2.5}$ (35 µg/m^3) during the event (Seidel and Birnbaum, 2015). Similarly, in China, a number of studies have reported significant elevation in pollutant concentrations during Chinese New Year activities (Carranza et al., 2001; Han et al., 2014; Lai and Brimblecombe, 2017; Li et al., 2017; Li et al., 2013; Shi et al., 2014; Song et al., 2017). Wang et al. (2007) also reported increases up to 150% for PM_{10} during Lantern Day celebrations. In India, a number of studies have assessed levels of air pollutants before, during and after Diwali, one of the largest Hindu festivals (Ambade, 2018; Barman et al., 2008; Gautam et al., 2018; Kumar et al., 2016a; Rao et al., 2012; Yerramsetti et al., 2013). Additionally, Nishanth et al.

(2012) reported increases up to 100% in concentrations of PM_{10} during a local festival (Vishu) where fireworks are used. In Italy, Masiol et al. (2014) reported high contribution for both PM_{10} (peak concentration of 700 µg/m^3) and trace gases during folk fires burnt on the eve of Epiphany (January), with average increase of between 65 and 200 µg/m^3 for PM_{10} and 90-235 µg/m^3 for $PM_{2.5}$. Finally, in Iran, higher than average PM concentrations have been reported during the fireworks related to the Chahar-Shanbe Suri festival (Oroji et al., 2019). A summary of results in presented in ***Table 3***.

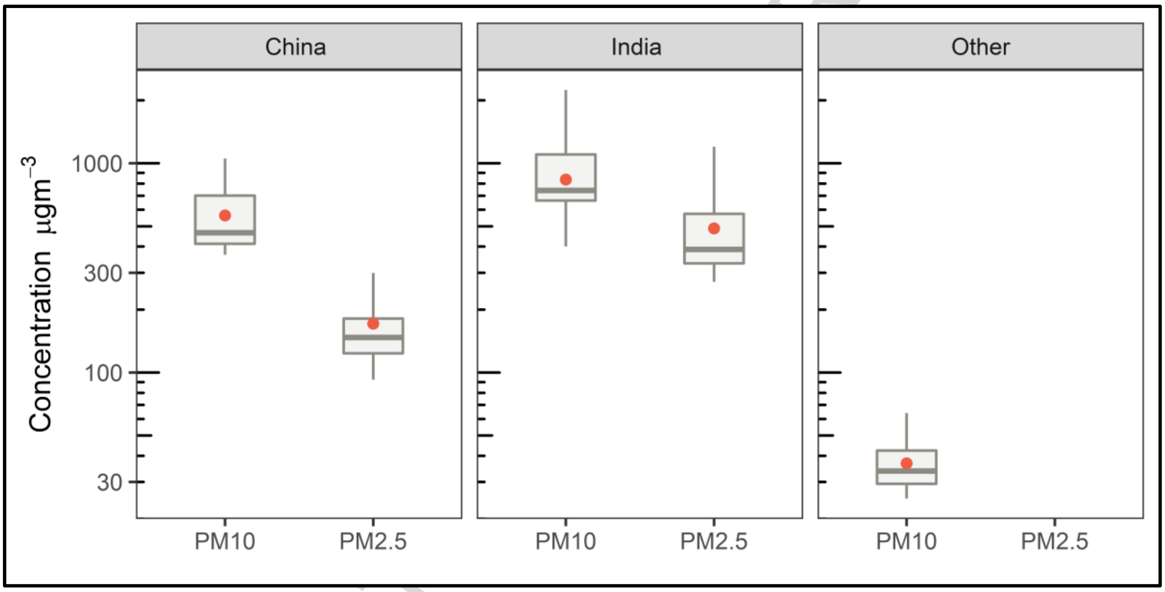

Figure 1: Summary of PM_{10} and $PM_{2.5}$ concentrations in India (Diwali) and China (Lunar New Year) and fireworks events elsewhere *(all values in µg/m^3)*

A few studies have also attempted to quantify the contribution of firework emissions to total PM concentrations through source apportionment analyses. For example, during a fireworks event in Milan (Italy), Vecchi et al. (2008) estimated that nearly half of observed PM_{10} was attributable to fireworks; in India, Sarkar et al. (2010) attributed between 20-30% of the total PM_{10} to fireworks emissions in Delhi (India) and between 21-27% of the total ambient PM_{10} in Jamshedpur (Ambade, 2018). In China, Wang et al. (2007) attributed significant fractions (> 30% of observed concentration) of various elements (e.g., Zn and Pb) to fireworks emissions during the Lantern

Festival and Ji et al. (2018) found fireworks to contribute to 36% of ambient $PM_{2.5}$ during the Spring Festival in Beijing.

3.1 PM composition associated with fireworks and bonfires

A number of marker species have been proposed for firework emissions. Potassium (K) is identified as one of the key components of fireworks emissions (Drewnick et al., 2006; Wang et al., 2007). The high concentrations of K in fireworks related particles are attributed to the use of black (gun) powder, which is rich in potassium nitrates, chlorates and perchlorates (Drewnick et al., 2006; Moreno et al., 2007). Given the use of heavy metals as colorants for fireworks, it is unsurprising that emissions from fireworks are rich in heavy metals. Results from a combustion chamber analysis revealed abundance of magnesium (Mg), K, aluminium (Al), lead (Pb), iron (Fe), barium (Ba), chromium (Cr) in coarse and fine fractions of PM emitted from fireworks (Tsai et al., 2012). Firework associated PM has been found to be rich in metal elements including Pb, Ba and manganese (Mn), as well as organic compounds including polycyclic aromatic hydrocarbons (PAHs) (Dutcher et al., 1999; Gaeggeler et al., 2008). Several elements have been proposed as tracer species for fireworks, including strontium (Sr) (Vecchi et al., 2008) and Ba, Sr and copper (Cu) (Moreno et al., 2007). Barium compounds are used for a variety of purposes- as oxidizers, stabilizers and colouring agents (Moreno et al., 2007) and can be reliably used as markers for fireworks emissions. In Taiwan, Tsai et al. (2012) reported high concentrations of Mg, K, Pb and Sr as well as changes in the Cl^-/Na^+ and OC/EC ratios while in China, Feng et al. (2016) reported increase in concentrations of K, Fe, Mg, Al and K^+ and Cl^- during the Spring and Lantern Festival. During a Chinese Spring Festival in Tianjin, a study by Liu et al. (2016) also found a clear changes in the concentrations of OC and EC as well as their ratios. Barman et al. (2008) reported increases in Cu, nickel (Ni), Cr, zinc (Zn) and cadmium (Cd) in Lucknow, India during Diwali. Kulshrestha et al. (2004) reported significant increases in concentrations of Ba (1091× more than the day before Diwali), K, Al, arsenic (As), Sr, Cu, Mg, Ni, vanadium (V) with the most significant increases in barium, potassium, aluminium and strontium (concentration of K was reported to be 58 $\mu g/m^3$ during Diwali event for particles with aerodynamic diameter of 25 µm and lower). Vecchi et al. (2008) reported increases in concentration of Mg, Sr, Ba, K and Cu. In China, multiple studies have reported predominance of metallic particles rich in Sr, Ba, Pb, Al and Cu, with some K-containing particles (Shi et al.,2011; Li et al., 2017), while in USA, firework related particles were reported to be rich in K, sulphate and elements including Mg, Pb, Ba and Al (Liu et al., 1997). Similarly, in Thailand, Pongpiachan et al. (2018) reported elevated concentrations of Ba and Pb during Bonfire night (see ***Figure 2***). In Spain, Moreno et al. (2007) reported elevated concentration of Ba, Sr, Pb, and antimony (Sb) with modest increases in concentration of Cu, Mg, Al, and titanium (Ti). Using a Time of Flight- Aerosol Mass Spectrometer (TOF-MS), Drewnick et al. (2006) reported high concentrations of K^+, SO_4^{2-}, total organics and chloride within the non-refractory PM fraction in Germany and the chemical composition of PM was found to be significantly different compared to regular background aerosol composition. Some studies have also reported elevated concentrations of PAHs although the consensus seems to be that fireworks are not a significant source of PAH emissions (Drewnick et al., 2006; Li et al., 2017; Shi et al., 2014). Interestingly, one study from India (Kumar et al., 2016a) reported a decline in BC emissions during Diwali due to a reduction in traffic emissions. Recently, Liu et al. (2019) reported the use of Ba, Cu, Pb and Cr as tracers for firework activity in a model for source attribution. Considering the body of literature on composition of PM emitted from fireworks, several elements including Ba, Cu, Sr, K and Mg emerge as good candidates as tracers for source apportionment studies.

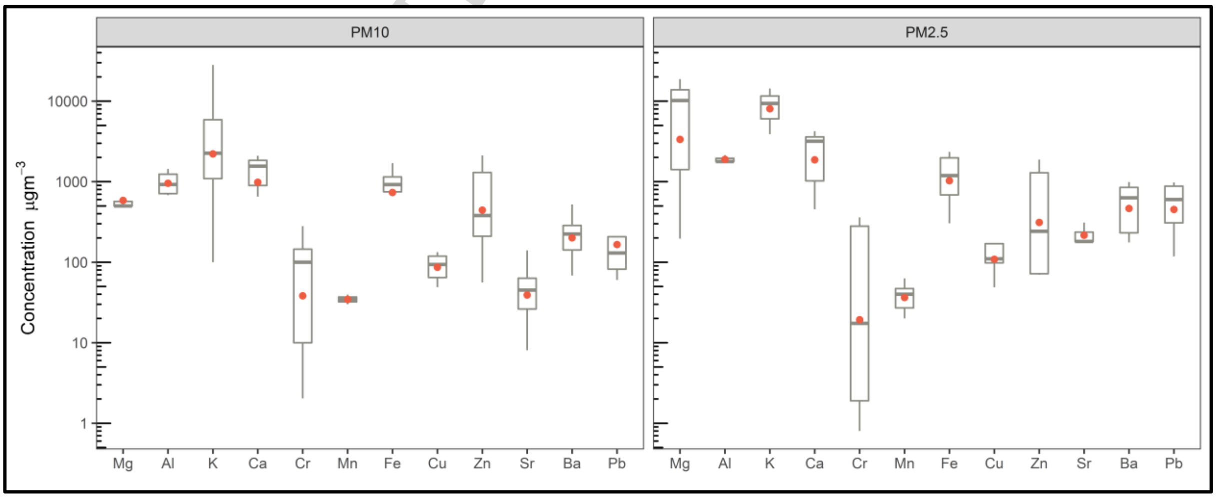

Figure 2: Reported concentrations for various elements during fireworks events in different countries for coarse ($PM_{2.5\text{-}10}$ and PM_{10}) (Moreno et al., 2007; Pongpiachan et al., 2018; Tsai et al., 2012; Vecchi et al., 2008) and fine ($PM_{2.5}$) PM *(Kong et al., 2015b; Liu et al., 2019; Tsai et al., 2012) (all values in ng/m^3). Please note that the studies represented here used various methodologies for element speciation.*

Table 3: Summary of pollutant concentrations and visibility during fireworks' (values in brackets represent the standard deviation)

Country/City	Year	Visibility			Ambient pollutant concentrations (µg/m^3)					Reference
		Normal day (mean, km)	During event (km)	% reduction	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_x	
Diwali; all reported studies from India										
Lucknow	2005				807.5–1632.4 (D)			176.9-283.3 (d)	126.7–190.8 (D)	Barman et al. (2008)
Lucknow	2005					352 (D)				Barman et al. (2009)
New Delhi	Nov 2010	~2.0 (0.5)	0.5	75 (5.0)	1216 (D)					Kumar et al. (2016b)
Kolkata	Nov 2012	~3.0 (0.5)	2	33.3 (9.5)	1000 (D); 1100 (AF)		35 (D)		95 (NO_2) (D)	Saha et al. (2014)
Kolkata	Oct 2013	~3.0 (0.5)	1.5	50.0 (7.1)	875 (D); 1660 (AF)		41 (D)	125 (D)	190 (NO_2) (D)	Saha et al. (2014)
Kolkata	Nov 2010				153 ± 34 (night); 122 ± 24 (day) 711 (night, D); 397 (BF); 507 (AF) 125 (day, BF); 338 (D); 468 (AF)					Chatterjee et al. (2013)
Rajnandgoan	Oct 2011				431.43 ± 41 (D); 110.23 ± 12 (BF); 321.65 ± 10 (AF); 105.00 ± 19 (ND)					Ambade and Ghosh (2013)
Hyderabad	2009-2011						~6-12		15-20 ppbv	Yerramsetti et al. (2013)
New Delhi	Nov 2007				1200-1400 (D)	1200-1400 (D)				Tiwari et al. (2012a)
Delhi	Nov 2010				>2500 (D)	>2000 (D)				Beig et al. (2013)

Delhi	2006, 2007 and 2008				~ 400 in 2006 ~ 1300 in 2007 ~ 730 in 2008 (D)			~ 27 in 2006 ~ 72 in 2007 ~ 8 in 2008 (D)	~ 42 in 2006 ~ 65 in 2007 ~ 34 in 2008 (D) (NO_2)	Mandal et al. (2012)
Delhi	2007 and 2008				610-1294 (D) in 2007; 578-931 (D) in 2008					Tiwari et al. (2012b)
Dibrugarh	Nov 2012						11.03 – 11.3 (D)		13.5-15.3 ppb (D)	Pathak et al. (2013)
Vadodara City	2009-2011	4.2 in 2009; 3.7 in 2010; 3.5 in 2011			99.9-699.5 (D) in 2009; 68-173 (D) in 2010; 106-320 (D) in 2011			38.75-87.62 (D) in 2009; 5.79-29.57 (D) in 2010; 4.11-16.6 (D) in 2011	16.5-38.7 (D) in 2009; 10-27.7 (D) in 2010; 4.5-28.9 (D) in 2011	Nasir and Brahmaiah (2015)
Delhi	2002-2007	~1.8	0.135 – 0.293	84-92	237 ± 55.2 - 368± 28.3 (D)			29 ± 8.5 - 75± 14.1 (D)	41.5 ± 4.9 - 90± 11.3 (D)	(Singh and Dey, 2012; Singh et al., 2010)
Kolkata	2008				2237.25 (D)	1199.74 (D)		12.30(D)	97.54 (D)	Thakur et al. (2010)
Delhi	2008-2009				767 in 2008 (D); 620 in 2009 (D)	448 in 2008 (D); 365 in 2009 (D)				Perrino et al. (2011)
Delhi	2009				317.2-616.8 (D)					Sarkar et al. (2010)
Tejpur University, India (rural area)	2009				40.88 ± 19					Deka and Hoque (2014)

Nagpur					930 (D);	271 (D);				Rao et al. (2012)
Bhilai	Nov 2012					1501.19 (D)				Pervez et al. (2016)
India	Oct 2015				2220 (Ahmedabad); 726 (Delhi); 741 (Lucknow); 432 (Varanasi)	412 (Delhi); 280 (Varanasi)	11. 4±1.7 (regular); 8.8 (BF); 10.2 (D); 7.3 (AF)			(Kumar et al., 2016a)
Jamshedpur					500.5			8.6 µg/m^3	73.32 µg/m^3	Ambade (2018)
Palwal						131-145 with a maximum of 296				Gautam et al. (2018)
Guwahati	2015				311					Garaga et al. (2018)
Chinese Spring Festival/New Year Festival/Lantern Festival; China unless otherwise listed										
Nanjing	Jan-Feb 2014	>10	4.3 ± 3.2	52 ± 16		113 ± 69				Kong et al. (2015a)
Jinan	Feb 2008					134.5 ± 97.4				(Yang et al., 2014)
Beijing	Feb 2007					58-224; 130 (BF Festival Eve); 132 (AF Festival Eve)				Xingru et al. (2009)
Yellow River Delta (YRD), Shandong Province	Jan-Feb 2011		<10			117-217 (D festival); 25 (BF and AF the festival)	4-8 (D festival); 2 (BF and AF festival)			Li et al. (2013)
Tianjin	Fen 2013				148.74(D, light fireworks); 249.08 (D, heavy fireworks); 133.30 (during non-fireworks days)	96.80 (D, light fireworks); 140.59 (D, heavy fireworks); 83.98 (during non-fireworks days)				Tian et al. (2014)

Xinxiang	Feb 2015		<10			112 ±78				Feng et al. (2016)
Zhengzhou	Jan-Feb 2014				365 ±264	173 ±125				Liu et al. (2014)
Shanghai	Jan-Feb 2009					91 (mean during whole festival period)				Feng et al. (2012)
Shanghai	2009				1054 ±322 (D)					Zhang et al. (2010)
Beijing	2015	22	7.8	64.5		248.9		57.8		Zhang et al. (2017)
Shanghai	Jan-Feb 2009	~17	4.9	71.2	>900 (D)	>900 (D)	>8.5(D)	438 (D)	286 (D)	Huang et al. (2012)
Beijing	Feb-March 2013					775 (LNY); 650 (LFD); 320(LF)				Jiang et al. (2015)
Beijing	Feb 2006	7.58	1.81	77	466.2 (D); 85.6 (ND)	184.3 (D); 26.1 (ND)		>150	>80 (NO_2)	Wang et al. (2007)
Kaohsiung City, Taiwan	Feb 2009					112.61 (D)				Tsai et al. (2012)
Xi'an	Feb 2007	13.1	11.8	10		298.8±26.7 (D); 130±63.9 (ND)				Shen et al. (2009)
Beijing	Feb 2013				103.5 (D)					Jing et al. (2014)
Beijing						148 (2016) 92.4 (2018)				Liu et al. (2019)
Other										
Nottingham, UK	2000-2012	~14.5 (3.0)	5.1	64	37.4 (D); 23.1 ± 3.1 (ND)	31.25-38.75 (D); 11.5 ± 4.0 (ND)	6.0 (D); 2.0±0.7 (ND)			Singh et al. (2015); Guy Fawkes Night
USA (315 sites across the country)	July (1999-2013)					17 (national average during Fireworks); 5 (ND)				Seidel and Birnbaum (2015); US Independence Day

Milan, Italy	July 2006				63.9 (D) *53% form fireworks*					Vecchi et al. (2008); FIFA World Cup Celebration#
Montréal, Canada	June-July 2007					>1000 (during display)				Joly et al. (2010); 2007 Montréal International Fireworks Competition
Girona, Spain	June 2008					25.3-30.8 (D) 16.3-22.1 (BF) 20.1-22.1 (AF)				Moreno et al. (2010); *Sant Joan* fireworks event
Malta	July-October 2005				25.1-58* (D)					Camilleri and Vella (2010); Religious festivals (*festas*)

*Weekly mean concentration, this study did not estimate the impact for a single day but over several months during which fireworks are used ; #Fireworks display
D= during festival/fireworks event; ND= Normal days; AF= after fireworks; BF= before fireworks; LNY=Chinese Lunar New Year; LFD=Lunar Fifth Day; LF=Lantern Festival
Haze is defined as visibility of less than 10 kilometres.

3.2 Particle number concentration

A limited number of studies have looked at changes in particle number concentration (PNC) during fireworks events, and similar to PM mass, PNC also increases dramatically during such events (Drewnick et al., 2006; Wehner et al., 2000). Similar to other combustion processes, firework emissions are typically associated with particles in the accumulation mode; one study in USA reported particle size to vary between 0.3 and 1.9 µm (Liu et al., 1997). Betha and Balasubramanian (2013) reported that between 60 to 85% of the particles from fireworks were in the ultrafine size range (i.e., particles with aerodynamic diameter <100 nm) while a Yang et al. (2014) reported Aitken and accumulation mode to account for 57% and 42% of the total PNC in China. In Beijing (China), total PNC of 7.7 x 10^4 /cm^3 was reported during Spring festival fireworks, and the average particle diameter was observed to be 150 nm (Jing et al., 2014) while in Jinan (China), an average PNC of 24783 cm^{-3} was reported during firework use, together with an increase in particles in the accumulation mode during the activity (Yang et al., 2014). In Germany, Wehner et al. (2000) also reported a dramatic increase in PNC in the accumulation range (> 100 nm) during a fireworks event.

3.3 Ozone formation during fireworks use

Coloured fireworks are reported to also generate ozone [O_3] at the ground level (Attri et al., 2001; Ravindra et al., 2003; Xu et al., 2018). These coloured fireworks contain a mixture of rich substances such as sulphur, barium nitrate, potassium, perchlorate, manganese, and aluminium which generate colour/light. Usually, in the atmosphere ozone is produced by chemical reactions of NO_x, CO and VOCs in the presence of sunlight via photochemical oxidation process. However, Attri et al. (2001) suggest ozone can be also formed without sunlight; burning a significant number of coloured fireworks generates significant amount of radiative energy which is enough to isolate atmospheric molecular oxygen into atomic oxygen and is able to cause ozone formation without sunlight. However, there has been very limited research on this topic, and further investigation is warranted.

3.4 Visibility

Fireworks emissions can lead to significant deteriorations in visibility. A large number of studies have evaluated the long-term impacts of aerosols and gases on visibility but only a few were focused on the influence of fireworks (Huang et al., 2012; Kong et al., 2015a; Saha et al., 2014; Shen et al., 2009; Singh et al., 2015; Singh et al., 2010; Wang et al., 2007; Zhang et al., 2017). In general, visibility is defined as the maximum visible distance along a horizontal line at the Earth's surface, and is largely dependent upon the scattering and absorption of light by PM. Absorption by gas phase NO_2 can also account for loss of visibility, but this is typically negligible compared to the loss of visibility caused by PM scattering and absorption (Singh et al., 2015).

Visibility loss during fireworks can be more pronounced and significant under certain meteorological conditions (Kong et al., 2015b; Saha et al., 2014; Singh et al., 2015). In particular, high RH conditions can cause water uptake onto hygroscopic particles (Pope et al., 2010) thus changing the extinction coefficient of PM, and therefore the resulting degradation in visibility (Singh et al., 2015). RH is dependent upon air temperature and atmospheric pressure. As RH increases, hygroscopic particles grow in size, volume and weight due to water uptake through absorption and adsorption thus changes in particle physical and chemical properties. Enhanced water content can also alter the particle composition by enabling particle phase chemistry to occur (Gallimore et al., 2011). High PM loading in addition to high RH conditions can encourage fog formation and thus lower the visibility.

Table 3 summarises the available literature on the effect of firework events on visibility. The high loading of atmospheric PM generated by combustion of fireworks can lead to impairment of visibility up to 10 - 92%. Typically, visibility loss due to fireworks is short-lived. Typically, it can take between 2-7 days for visibility to return to normal background conditions, depending upon atmospheric, meteorological and topographical conditions.

Satellite measured Aerosol Optical Depth (AOD), a measure of PM quantity distributed within a column of air from the Earth's surface to the top of the atmosphere, can also be used to understand and investigate the effect of fireworks on visibility and air quality (Kessner et al., 2013; Khor et al., 2014; Pope et al., 2016; Wu et al., 2014;

Zheng et al., 2017). Devara et al. (2015) reported an approximately four-fold increase in AOD values during the Diwali festival in India. These results are similar to the observations in the UK where a significant increase (2-4 fold) in the aerosol loading during Guy Fawkes Night was reported (Pope et al., 2016). Both PM (PM_{10} and $PM_{2.5}$) as well as AOD values were observed to be much higher compared to background levels during a fireworks event in the UK (Pope et al., 2016) and higher (10-90%) than normal AOD levels have also been reported during fireworks events in China (Yu et al., 2013; Zheng et al., 2017). One notable exception was a study in Delhi, which reported a lack of association between AOD and the fireworks events during Diwali in India; this discrepancy was attributed to the temporality of the satellite measurement, which is restricted to the overpass time (Kumar et al., 2016a).

4. Health Impacts

Exposure to air pollution in the short-term has been linked to several health effects (Brunekreef and Holgate, 2002; Nhung et al., 2017; Shah et al., 2015; Shang et al., 2013; Wu et al., 2016). In case of fireworks, there are several types of health effects possible including the effects related to air pollution exposure, but also physical injuries such as burn injuries or damage to the eyes. In fact, in the literature, much of the focus around the health effects of fireworks has been on burn injuries and ocular damage. There is limited evidence on the health effects of exposure to air pollution related to fireworks (Greven et al., 2019). Careless handling of fireworks during storage, transport and handling can have serious implications including skin burns, eye damage, and hearing loss (Billock et al., 2017; Canner et al., 2014; Maglieri and Henderson, 1973; Moore et al., 2014; Vernon, 1988). Typically, children and young adults, especially men, have been found to suffer the most injuries. Over the past two decades, however, overall injury rates have been reported to be declining (Billock et al., 2017; Chaparro-Narváez et al., 2017; Moore et al., 2014; Puri et al., 2009). Fireworks events are also associated with an increase in noise levels, and this can trigger psychological stress (Ising et al., 1980; Tanaka et al., 2016; Verma and Deshmukh, 2014); affect hearing function (Björkman and Rylander, 1997; Gjaevenes et al., 1974) and possibly increase the chances of cardiovascular disease (Babisch, 2000). One study linked poor visibility due to short-lived fireworks-related pollution with disturbance in public safety (Rose, 2014).

Exposure to air pollutants including PM and gases has been found to trigger specific health effects including respiratory and cardiovascular diseases (Brook, 2008; Brook et al., 2010; Franklin et al., 2015; Laumbach and Kipen, 2012). In particular, children and the elderly as well as people with pre-existing health conditions are vulnerable to health effects associated with exposure to firework related emissions. In the US, specific studies have reported exacerbation of asthma in individuals exposed to firework related emissions (Becker et al., 2000), and exposure to fireworks-related PM has also been associated with a decline in lung function (Smith and Dinh, 1975); in Oahu (Hawaii), a statistically significant increment of 113% in treated respiratory illnesses during fireworks events was reported (Bach et al., 1975). Other studies since have reported similar associations between fireworks' events and respiratory health (Gouder and Montefort, 2014) although a recent analysis in the Netherlands reported mixed results for the relationship between PM_{10} concentrations and daily mortality during periods of firework activity (Greven et al., 2019). In India, Sarkar et al. (2010) estimated at least 2% increase in the health effects associated with exposure to a set of elements associated with fireworks emissions (Al, Mn, Ba) during Diwali while in Bangkok, there was no significant difference in risk level for metals such as Pb, Zn and Cr during fireworks episodes (Pongpiachan et al., 2018). In a study of inhalation exposures, carcinogenic risk were found to be more pronounced in instances where the emissions were more highly concentrated (Betha and Balasubramanian, 2013). In Shanghai (China), exposure to fireworks-related emissions was found to contribute between 1.4 and 3.8% of the total daily mortality in the city (Yao et al., 2019).

The health impact of firework emissions is largely relevant in the context of acute exposures with exposure window of a few hours to days. It is unclear, at present, if there are long-term health effects associated with these acute exposures. The usage pattern of fireworks (e.g., fireworks display vs individual fireworks use) and the prevailing meteorological conditions can also influence the extent of exposure for the population. Notably, many firework related festivals/events take place during autumn/winter (e.g., Diwali (India), New Year's Eve (worldwide), Guy Fawkes Night (UK) and the Spring Festival (China)) when temperatures and wind speeds are typically low, which will likely encourage the build-up of pollution through low boundary layer heights and low horizontal dispersion. When used at ground level, people can get directly exposed to metallic fumes released from handheld firecrackers (e.g., sparklers). Several elements associated with fireworks emissions, especially transition elements including Cu have been associated with increase in exogenous reactive oxygen species (ROS) in the lung cells, through Fenton-type reactions (Lippmann and Chen, 2009). A study in London reported significantly higher *in vitro* PM oxidative potential per unit mass for firework associated PM_{10} compared to PM_{10} associated with traffic emissions (Godri et al., 2010).

5. Impact of restrictions on use of fireworks on air quality

In some regions in China, stringent regulations on firework use has led to a decline in overall emissions' contribution from this source (Lai and Brimblecombe, 2017), and there is a strong public health argument for restricted use. In Beijing, Liu et al. (2019) reported a decline in the use of fireworks after the introduction of a stringent prohibition policy which has in turn led to a 72.9% decline in the contribution of firework activity to ambient $PM_{2.5}$ concentrations during periods of fireworks' use. Similarly, in Shanghai, $PM_{2.5}$ levels reduced from 79 to 32 μg/m^3 between 2013 and 2017 at the rate of −13.8 μg/m^3/yr after restrictions on the use of fireworks (Yao et al., 2019). In India, sale and purchase of fireworks were restricted in 2018 (Trivedi, 2018), but no air quality benefits have been reported as yet.

6. Conclusions

Despite the potential impacts of short-term anthropogenic pollution events from the use of fireworks use, there are a limited number of studies focused on the impact of fireworks-related emissions on air quality and public health. The highest number of studies are from India and China. The current body of literature, including data from different countries around the world, provides clear evidence of the impact of fireworks events' on air quality and visibility, albeit for short periods of time. Additionally, data on chemical composition of PM reveals higher levels of specific elements including Ba, Pb, K and Sr during such events. Based on the available literature, it is reasonable to assume that elements including Ba, Sr, Mg, K and Cu can be considered relevant tracers for fireworks-related PM. While some of these elements also serve as tracers for other sources (for example Ba and Cu are also markers for brake-wear emissions), the saliency of the fireworks events allows for estimation of specific impacts associated with such events. There are some early results on the role of fireworks-related emissions in formation of ozone, nitrous acid, and associated atmospheric chemistry, but more research is needed.

Furthermore, there are only a few studies that report on the health effects associated with exposure to fireworks-related air pollution. However, it is clear that in the short-term, exposure to fireworks-related PM can lead to exacerbation of respiratory illnesses including asthma.

It must be noted that it is difficult to rigorously compare the reported effects of fireworks upon air quality, largely due to the transient nature of the fireworks' events (often lasting only a few hours to days). Due to the limited time periods where the fireworks source is relevant, most studies tend to include a limited number of samples. Study designs are often vastly different, between different studies, rendering it difficult to compare and synthesise results. Additionally, fireworks events are held at different times of the year (i.e. different seasons), and due to the prevalent meteorological conditions, it can be difficult to make generalizations regarding underlying atmospheric processes that cause visibility reduction.

After a careful review of the literature, it is reasonable to conclude that:

1. Field measurements of firework events should aim for consistency in measurement approach. In particular, measurements before, during and after the event should be attempted. Detailed meteorological data should also be collected over the same timeframe, and where possible, PM data should be speciated to understand the chemical composition of particles. Studies could be designed specifically to measure fireworks' related emission loads through comparison of sampling at field and background locations.
2. Most studies, so far, have assessed concentrations and composition of PM_{10} and $PM_{2.5}$, but very limited data are available for particle mass and number size distributions. Current evidence indicates that use of fireworks can lead to a significant increase in PNC, and future studies should focus on improving the understanding on this topic.

3. Chamber studies such as Betha and Balasubramanian (2013) can help to generate evidence on detailed emissions profiles and tracers for firework events. Such profiles can then be used in the receptor modelling framework to estimate the contribution of fireworks emissions to ambient $PM_{2.5}$. Such data can also be useful for estimation of health risks associated with exposure to fireworks emissions.
4. Global satellite measurements can be further utilized during firework events to understand spatial and temporal variations in pollutant concentrations related to firework events. Ancillary data such as fireworks sales can also be useful to generalise the results.
5. Future studies should focus on characterization of health effects associated with acute exposure to air pollutants during fireworks' events. For example, daily hospital visit and mortality data can be analysed to understand the short-term health effects related to fireworks' emissions. Given the very high concentrations of specific elements in fireworks emissions, similar to Godri et al. (2010), further analysis on the toxicity of fireworks-related particles may also help to improve our understanding of the health impacts.
6. In areas where specific interventions are introduced, either legal or through government policy, studies could be undertaken to understand the impact of the policy on air quality during fireworks events. This will create a rich evidence base for control of fireworks-related emissions.
7. Finally, given the evidence that PM concentrations often return to 'normal' air quality levels within 24 hours of such events, air quality alerts might be deployed strategically to ensure that exposure is minimized, especially for the vulnerable sections of the population.

In conclusion, wider regulations on the use of fireworks will help in reducing exposure to fireworks-related air pollution, but significant socio-cultural beliefs and practices are often associated with religious/cultural events, making it difficult to introduce strict regulations. It is important to recognize that celebrations associated with use of fireworks can act as a force to bring people together and have deep cultural and social significance and can lead to positive psychological impact on individuals and communities. In addition, alternate modes of celebrations including light shows, use of lanterns and candles, LED-based fireworks replicas etc. can be promoted in order to reduce direct exposures related to fireworks emissions. In terms of public health, awareness regarding the health impacts is key and gradual behavioural shifts, spurred through public health alerts and advisories before and during fireworks events could help in minimizing the health burden.

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Highlights

- Fireworks and bonfires are sources of atmospheric pollutants and typically affect short-term air quality.
- This review article presents a summary of the impacts of fireworks and bonfires on air quality, visibility, and human health.
- Typically, concentrations of air pollutants can be 2-8 times higher than average during fireworks events. Additionally, concentrations of elements including Ba, Cu, Pb, Cr and Sr are reported to be several times higher during fireworks events.
- Limited studies have shown an impact on respiratory health, but significant gaps in knowledge remain.

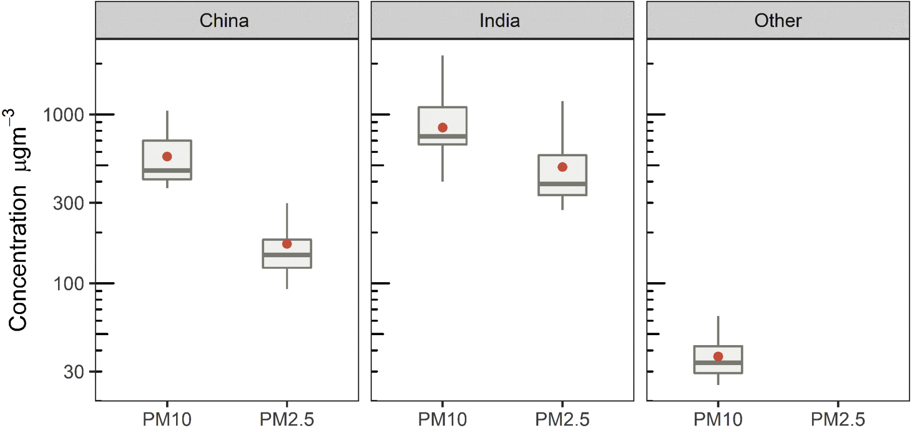
China
India
Other
Concentration µgm^{-3}
1000
300
100
30
PM10
PM2.5
PM10
PM2.5
PM10
PM2.5

Figure 1

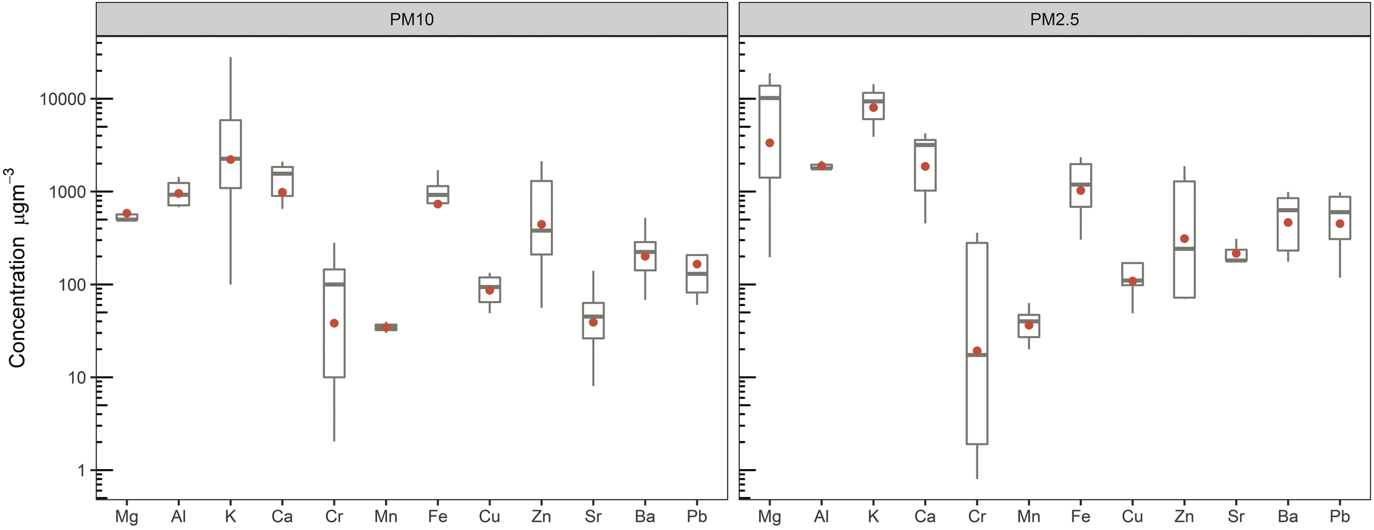
PM10
PM2.5
Concentration μgm⁻³
10000
1000
100
10
1
Mg
Al
K
Ca
Cr
Mn
Fe
Cu
Zn
Sr
Ba
Pb

Figure 2