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Annual air pollution caused by the Hungry Ghost Festival†

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Burning of joss paper and incense is still a very common traditional custom in countries with a majority Chinese population. The Hungry Ghost Festival which is celebrated in the 7 month of the Chinese calendar is one of the events where joss paper and incense are burned as offerings. This study investigates the impact of the Ghost Month Festival (open burning event) on air quality by analysis of the chemical composition of particulate matter (PM) and rainwater samples collected during this event, compared with data collected throughout the year, as well as bottom ash samples from burning the original joss paper and incense. The results showed that the change in the chemical composition of the rainwater and $PM_{2.5}$ (PM $\leq$ 2.5 μm) atmospheric samples could be correlated directly with burning events during this festival, with many elements increasing between 18% and 60% during August and September compared to the yearly mean concentrations. The order of percentage increase in elemental composition (in rain water and $PM_{2.5}$) during the Hungry Ghost Festival is as follows: Zn > Ca > K > Mg > Fe > Al > Na ~ Mn ~ Ti ~ V > Cu > As > Ni > Co > Cd > Cr > Pb. The chemical composition of the original source materials (joss paper and incense for combustion) and their associated bottom ash were analysed to explain the impact of burning on air quality.

Environmental impact

Uncontrolled outdoor burning of paper objects and incense is commonly conducted in countries with Chinese populations as part of religious ceremonies. In this study, we have identified a significant source of atmospheric pollution above normal background levels that occurs in August/September each year, due to the Hungry Ghost Festival. The pollution takes the form of an increase in the metallic composition of particulate matter $\leq$ 2.5 μm ($PM_{2.5}$) released into the atmosphere as well as a measurable contamination of rainwater. The compositions of the $PM_{2.5}$ and rain water were compared with the chemical composition of a range of common materials that are burnt as offerings (Joss paper, incense and papier-mâché) for source apportionment.

1 Introduction

Knowledge of the concentrations of trace elements in particulate matter is an essential primary step in identifying the source characteristics of air pollution for the development of air quality control strategies and evaluating possible implications for public health. Several epidemiological studies have identified a correlation between the exposure to airborne particles and increased health risk such as mortality, respiratory or cardiovascular diseases, and respiratory symptoms.[1]

Rain plays a role in the removal of gases and particulate matter from the atmosphere, therefore, the study of the chemical composition of rainwater can also aid in understanding the contribution of the different sources of atmospheric pollutants.[2] The rainwater composition is often influenced by anthropogenic activities releasing acidic (such as SO_x and NO_x) or basic (such as NH_3) gases into the atmosphere. Acidic rainwater aids the dissolution of many trace metals, which enhances their bioavailability, thus, the study of trace metals in rainwater has increased because of their adverse environmental and human health effects.

An ongoing study was conducted commencing in 2009 to monitor rainwater and airborne particulate matter in a sampling site in western Singapore. One of the interesting features uncovered in this dataset is a local event (common in all countries with a Chinese population), called the Ghost Month, that surprisingly substantially changed the chemical composition of rainwater and particulate matter by increasing the concentrations of a large number of the elements. The Hungry Ghost Month is a traditional festival celebrated by the Chinese in the seventh month of the lunar calendar. They

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believe that the gates of Hell are opened to allow ghosts and spirits access to the world of the living on the first day of the month. The spirits visit their families, feast and look for victims during this month. The fifteenth day of the seventh month in the lunar calendar is called the Hungry Ghost Festival (Ghost Day/Lu Yan). Ghosts are in a heightened state and it is important to hold a large feast to please them and bring luck to the family. In the last day of this month the ghosts and spirits leave the earth and the gates of Hell finally close. These three important days are celebrated and family members pray to God and for their ancestors, make offerings of food and drink and burn a significant amount of joss paper, hell bank notes and incense throughout Singapore (and other countries with a Chinese population). Fig. 1 illustrates the large scale burning of joss paper in the afternoon of the 15th day of the Ghost Month. Fig. S1 (Groups A, B and C) and Video S1 in the ESI† provide more details about Ghost Month celebrations. In recent years, new "luxury goods" made from joss paper, cardboard or papier-mâché have been introduced into the market for burning, with the items ranging from representations of clothing, computers, cars, houses, jewelry, watches, beer cans and even models of servants.

Despite the high number of burning events, relatively few studies have been performed regarding pollutants released from joss paper and incense which are known to generate large quantities of particulates.[3] The burning process has also been shown to release polychlorinated dibenzo-*p*-dioxin/dibenzofuran (PCDD/F), polycyclic aromatic hydrocarbons (PAH)[4] and metals.[5]

Fig. 1 (Upper) Preparing, and (lower) burning of joss paper on the Ghost Day (15th day).

Large scale burning of joss paper and incense often occurs during important outside festivals, although previous studies on joss paper and incense burning have concentrated mainly on assessing the air quality of the indoor/outdoor environments of temples.[4a,e,5c,d,6] To the best of the author's knowledge, only one study has been performed on characterizing the ambient air PAH concentrations emitted during a massive joss paper open-burning event held at a suburban site,[4c] while the elemental compositions emitted from open air burning of joss paper have never been investigated. Consequently, this study was aimed at investigating the impact of outdoor burning of joss paper and incense during the Hungry Ghost Festival on air quality in urban areas. In order to differentiate between the background air pollution of Singapore and the concurrency of the Ghost month with haze events brought about by transboundary air pollution (due to biomass burning in Indonesia), the Ghost Month data were compared with long-term environmental sampling collected over a 5 year period at a site at Nanyang Technological University (NTU). The average PM_{10} value in Singapore is 40 μg m^{-3}. PM_{10} values above 60 μg m^{-3} are typically associated with the transboundary air pollution from biomass burning events ("haze") from nearby Indonesia. In order to remove uncertainty in the pollution originating from the Ghost festival with coincident pollution from transboundary biomass burning, data from days with $PM_{10} > 60$ values were excluded from the comparisons.

The atmospheric PM detected due to the Ghost Month burning events will naturally increase as the sampling device is placed closer to the point of burning. In this study, the sampling site was located away from residential areas so that there was no burning associated with the Hungry Ghost Festival within a 2 km radius (the sampling site location and the closest burning site locations are provided in Fig. S2(b) in the ESI†). We were interested in determining how the Hungry Ghost Festival affected the background pollution levels in airborne particulate matter and rainwater, which required a comparison with data collected from a high volume $PM_{2.5}$ sampler and rain collection system over a long period. Since no long-term background data are available at the sites used for burning, the NTU site provided the best measure of how background levels varied due to the Hungry Ghost Festival. The increase in elements in the $PM_{2.5}$ and rainwater observed over the Hungry Ghost Month indicated that the burnt material was dispersed readily into the atmosphere. The environmental data were compared with data collected from unburnt and burnt (ash) samples of commercial joss paper, incense and papier-mâché offerings.

2 Materials and methods

2.1 Sampling

Rainwater (using an autosampler, New Star Environmental LCC, US) and particulate matter (using Ecotech air sampler HiVol-3000, Australia) samples were collected within the campus of Nanyang Technological University, in Singapore, from August 2009 onward. Airborne particulate matter samples were collected on Emfab filters (Borosilicate glass microfibers reinforced with woven glass cloth and bonded with PTFE, size: 8 × 10 inch, Pallflex, Emfab TX40HI20-WW, Pal, USA). This location encompasses different potential sources of anthropogenic activities as it is located approximately 8 km north of the Tuas and Jurong Island districts which are the most industrialized areas of the country, and also lies within 300 m of the Pan Island Expressway (PIE), a major motorway with heavy truck traffic (Fig. S2(c) in the ESI†). The air pollutants encountered in the region are expected to be of both particulate and gaseous in nature, coming from vehicle emissions and industrial activities. Bottom ash samples from burning joss paper and incense were collected immediately after each event in different residential locations in 2012 and 2013 during the Ghost month.

2.2 Sample preparation

Rainwater samples. Samples were collected immediately after the rain event or in the early morning following night precipitation events. The samples were separated into two aliquots. An unfiltered aliquot was used for pH (using Metrohm 826 pH meter) and electrical conductivity (EC, using IONcheck 30 Conductivity Meter) measurements while the remaining aliquot was filtered through a 0.22 μm cellulose acetate membrane for ion chromatography and inductively coupled plasma (ICP) measurements.

$PM_{2.5}$, joss paper, incense and bottom ash samples. Collected samples were placed in microwave (MW) digestion vessels, and appropriate reagents (Table S1 in the ESI†) were added sequentially. The vessels were capped, placed in the MW system, and digested. After cooling to room temperature, extracts were diluted using ultrapure water, filtered through 0.2 μm syringe filters and carefully transferred to ICP sample vials for elemental analysis. The Emfab filters used to collect $PM_{2.5}$ samples were tested to check for the presence of any impurities. The concentrations of target elements were measured by ICP-MS in solutions of the filter that were digested the same way as the samples. It was found that the filter materials contributed negligible interference to the analysis.

Microwave digestion. Two programmable microwaves (MARS 5, CEM Corp., Matthews, NC, USA and Anton Paar Multiwave PRO, Austria) were used as the closed vessel digestion systems. Effective digestions were achieved by setting the microwave program and power settings and optimizing the nature and amount of acids. Standard reference material 2783 (SRM 2783) of Urban Particulate Matter samples was used to validate the method. The extraction efficiencies (determined by the % recoveries) were >80% for all of the elements present in the reference material. Spiked samples were used to evaluate the MW method for bottom ash samples and original joss paper and incense. The PM and bottom ash samples were digested using the protocols summarized in the ESI document (Table S1 in the ESI†).

2.3 Analysis

Ion chromatography (IC). Cation IC experiments were performed with a Dionex ISC-900 utilizing an Ion Pac CS12A 4 mm × 250 mm analytical column. For cation IC, the eluent consisted of 20 mM methanesulfonic acid and the chemical regenerant consisted of 100 mM tetrabutylammonium hydroxide. Anion IC experiments were performed with a Dionex ICS-1100 utilizing an Ion Pac AS22 4 mm × 250 mm analytical column. For anion IC, the eluent consisted of 4.5 mM sodium carbonate and 1.4 mM sodium bicarbonate and an electrochemical suppressor was used.

Inductively coupled plasma. Both inductively coupled plasma-optical emission spectroscopy (ICP-OES) and inductively coupled plasma-mass spectrometry (ICP-MS) were used to analyze acidified samples for trace elements. In the first two years of this study elemental measurements were performed with a Thermo Scientific iCAP 6500 spectrometer in both axial and radical modes. Since the concentration of some trace elements in samples was not detected by ICP-OES, samples were analyzed using an Agilent 7700 series ICP-MS (Japan) equipped with a 3rd generation He reaction/collision cell (ORS^3) to minimize interference from January 2011. Final optimized instrumental operating parameters for this application are summarized in Table S2 in the ESI.† The analysis of samples using both ICP-MS and ICP-OES helped to test the possibilities of potential interference, since the two techniques suffer from different interference effects.

Data analysis. Data were processed using a Windows based application written in the C# programming language in the .Net platform. All the statistical tests (arithmetic means, maximum and minimum values, standard deviations, percentiles and medians) were run with the same application prior to using the data in graphical plots.

3 Results and discussion

3.1 Phase I

Phase I of this study involved the continuous collection of rainwater and atmospheric $PM_{2.5}$ samples between August 2009 and December 2013 at the NTU sampling site (551 $PM_{2.5}$ and 574 rainwater samples).

Particulate matter. The impact of the Ghost Month on particulate matter was evaluated by measuring the changes of the monthly mean concentrations compared to yearly means for each element. High haze period data (data from days with PM_{10} > 60 values) and special events (such as industrial fires) that were considered as known pollution sources for a short period were excluded from the dataset except for a few days in year 2012 because of coincidence of the ghost month with the haze period. Statistical data (Table S3 in the ESI†) collected from year 2010 to 2013 for $PM_{2.5}$ showed an increase in concentrations for most of the elements during August and September (7th month of Chinese New Year) suggesting a strong contribution of burning events to release particulate matter during the Hungry Ghost Festival. Table 1 lists dates of the Hungry Ghost Festival and Ghost Day that occurred during this study.

For $PM_{2.5}$, the major elements (Na, Ca, Zn, K, Al, and Mg) appeared in concentrations ranging from 5 ng m^{-3} to a maximum of approximately 50 000 ng m^{-3} (50 μg m^{-3}). The concentrations of trace elements were found to vary from values less than the detection limit to a maximum of 1 μg m^{-3}.

Table 1 Ghost Festival and Ghost Day from 2009 to 2013

Year	Hungry Ghost Festival	Ghost Day
2009	20 Aug–18 Sep	2 Sep
2010	10 Aug–7 Sep	24 Aug
2011	31 July–28 Aug	14 Aug
2012	17 Aug–15 Sep	30 Aug
2013	7 Aug–4 Sep	20 Aug

Concentration time series graphs were examined to find out the impact of different industrial and local events on the composition of airborne particulate matter at the NTU sampling site. It was notable that the percentage concentrations of a large number of the elements (listed in Table S3 in the ESI†) increased during August and September and this finding was in agreement with rainwater results (see discussion below).

The $PM_{2.5}$ elemental composition data indicated that the average concentration of many elements during the Ghost Month was higher than their monthly and annual averages. Table S4 in the ESI† contains a comparison of the absolute chemical composition of $PM_{2.5}$ (μg m^{-3}) during August and September (Ghost Month Festival) and the yearly monthly average.

Fig. 2 presents data for 9 metals that are listed among the 188 hazardous air pollutant substances ("HAPS" or "air toxics") defined under the Clean Air Act Amendments of 1990 (ref. 7) (Fig. S3 and Tables S3 and S4 in the ESI† include the full list of the analyzed elements). Fig. 2 shows that there is a significant increase during the Ghost Month from 2010 to 2013 (data for 2009 have not been included since the yearly average is not available). It can be seen in Fig. 2 that the majority of the increase in the elemental composition occurred in August, except for the year 2012 where the commencement of the Ghost month was late. September 2011 experienced the lowest impact since the ghost month ended in August for this year.

In general, the results indicated that Zn, Ca, K, Mg, Fe and Al followed by Zr > Ba > Sn > V > Na ~ Ti ~ Mn ~ Cu showed the greatest percentage increase in their concentrations (34–60%) while As > W > Sr > Ni > Co > Rb > Cd > Cr > Pb > Mo > Ce > Sb varied between 18 and 40%. The major health related effects of inhalation of many of the listed elements (Na, Al, Pb, Cd, Ni and Cr) to the lungs, kidney and heart are well known and potentially of concern.[8]

According to the few studies that have been performed regarding the elemental and organic constituents of incense smoke produced through burning, it was found that the major components are inorganic compounds with some carcinogenic elements.[5c,9] The Lau and Luk study in 2001 was the only literature source that showed joss paper burning released a significant source of elements such as Fe, Cu, Zn and Pb.[10]

Rain. Rainwater that falls in Singapore is collected in local catchment areas (which comprise two thirds of Singapore's total land area) and makes up approximately 20% of Singapore's water needs.[11] Analysis of the rainwater showed that the average pH value over the sampling period was 4.34 ± 0.52 (pH of

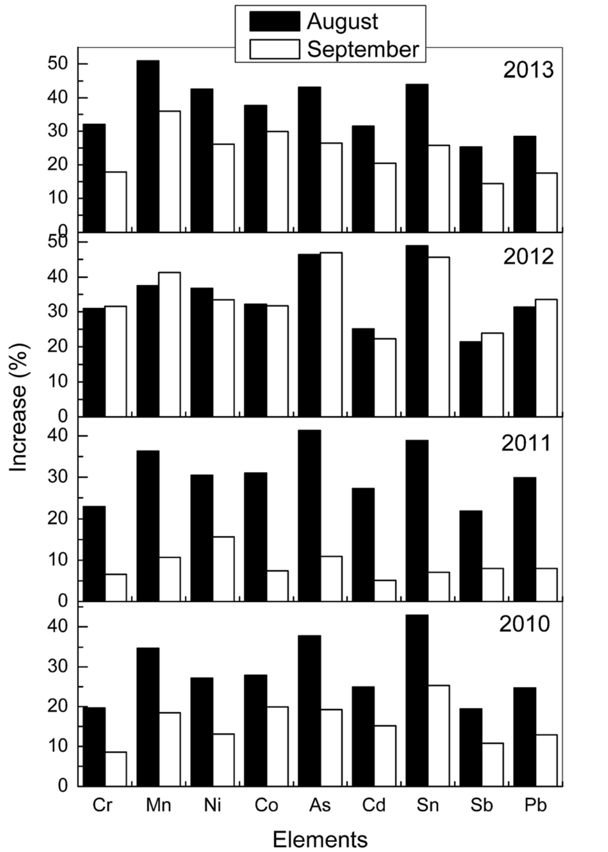

Fig. 2 Percentage increase in the elemental chemical composition of PM during August and September (Ghost month festival).

individual rainwater events ranged from 3.22 to 6.24), with the acidity mainly originating from sulfuric acid levels (45%), and with a smaller contribution from nitric acid (19%).[12] The ionic concentration of rainwater samples measured by ion chromatography (IC) for the five years followed a trend of SO_4^{2-} > Cl^- > NO_3^- for anions and Ca^{2+} > Na^+ > K^+ > NH_4^+ > Mg^{2+} for cations. The ions were found in their highest values mostly during August and September. It is noteworthy that the concentration of Mg^{2+} increased significantly and the cation order changed to Ca^{2+} > K^+ > Na^+ ~ Mg^{2+}> NH_4^+ for the August/September period. Elemental analysis of the rainwater samples by ICP-OES and ICP-MS showed the same trend for the August/September periods. Zn, Ca, K, Mg, Fe and Al were the major elements followed by Sn > V > Na ~ Mn ~ Ti ~ Cu > As > W > Ni > Co > Cd > Cr > Pb.

The results indicated that substantial increase in the concentration of ions and elements in rainwater samples was observed in the beginning, mid and at the end of Ghost month for all years which can be assigned as due to burning large amount of joss paper and incense throughout Singapore (a strong fragrant smoke smell pervades during these days).

Fig. 3 displays the fluctuation of concentration of the major ionic components of rainwater samples collected during the Ghost month. The red vertical lines in Fig. 3 correspond to the 1st, 15th and final day of the Ghost month for each year as

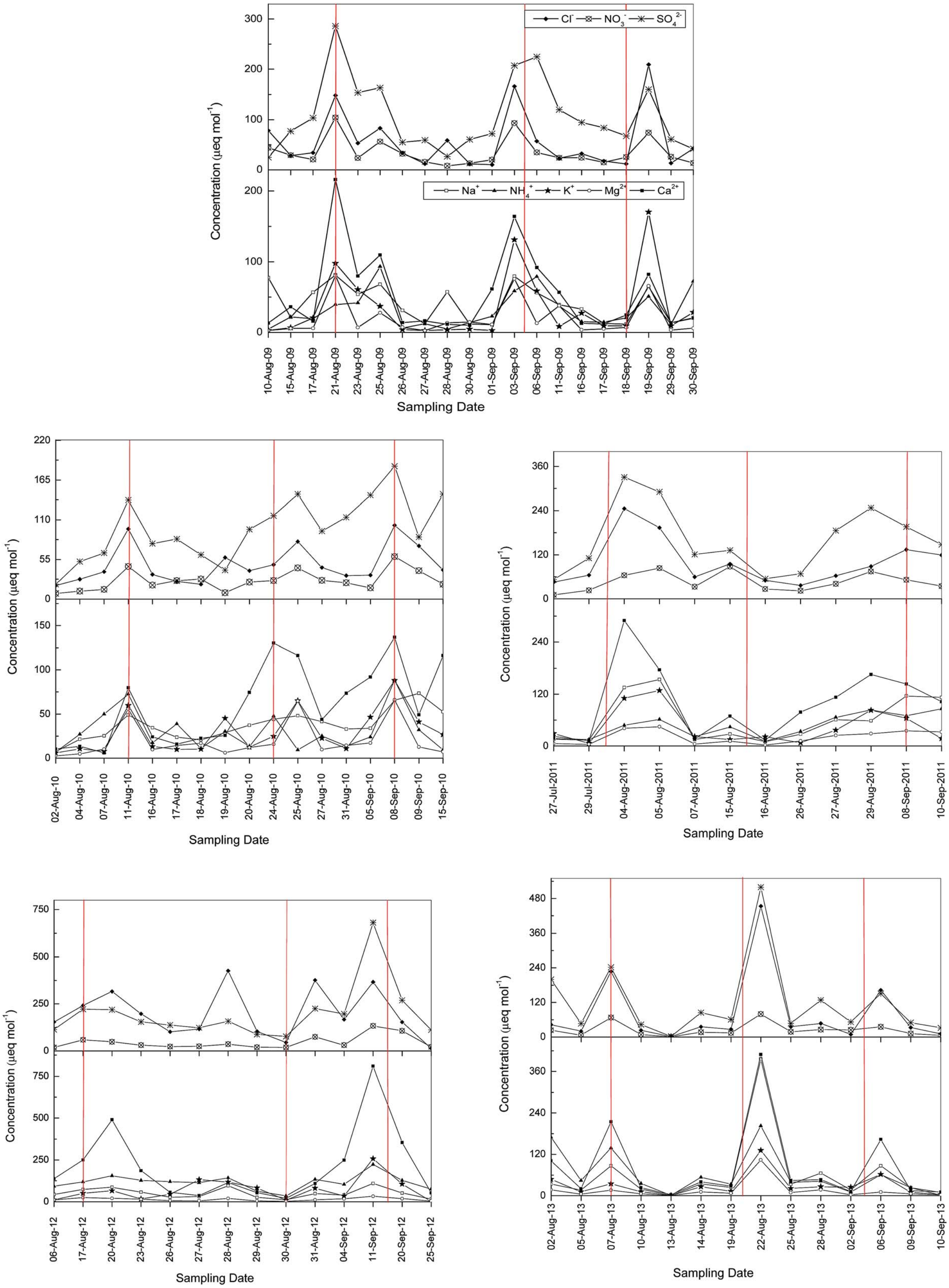

Fig. 3 Concentration profiles of rainwater chemical composition during the Ghost Month Festival.

indicated in Table 1. The highest concentration was observed in rain events after the 1st, 15th and end day of the Ghost month due to massive burning of joss paper and incense in those special days. However, the relationship between precipitation events and the Hungry Ghost Festival is complicated because, unlike the $PM_{2.5}$ data which are collected continuously, the rain frequency does not necessarily perfectly match the days with the highest burning. Nevertheless, the high frequency of rain events in Singapore in the August–September period over the 5 year period did indicate that there is a notable correlation between an increase in the ionic concentration of the precipitation and the major burning events (Fig. 3).

The concentrations of cations and anions both fell significantly after the first or second rain event. The highest ionic concentrations were measured during the Ghost month in 2012 because of the coincidence of the Ghost month and the transboundary haze period. Na^+ and Ca^{2+} are present in much higher concentrations in the cation concentration profile, while K^+ shows a higher concentration as an index of biomass burning in year 2012. Mg^{2+} also shows a high concentration during these events.

It can be seen from the plots in Fig. 3 that there were differences in the absolute concentrations of ions detected in the rainwater from year to year, which is likely to occur due to two major reasons. Firstly, the background levels in the rain samples can vary due to local industrial events unrelated to the Hungry Ghost Festival as well as from transboundary pollution from Indonesia or Malaysia. Secondly, the quantities of materials released into the atmosphere each year due to the festival burning are not the same and will vary depending on the number of fires, the quantities of materials burnt, the exact locations of the fire pits, the period of time that ash is left before clean-up, and the exact meteorological conditions. Therefore, the absolute concentrations are less significant than the percentage increase observed during the times of burning for both the $PM_{2.5}$ as well as the rain samples.

3.2 Phase II

The second phase of this project was commenced in January 2011 to determine the elemental chemical composition of the unburnt and burnt (bottom ash) samples from joss paper and incense collected during the Ghost month in order to further investigate the link with the annual spikes in pollution in the August/September period (compared to the yearly averages).

Incense and joss paper analysis (unburnt). Prior to the analysis of bottom ash samples, the elemental composition of the unburnt incense and joss paper commonly used during the ghost month festival was determined. Table S5 in the ESI† provides the distribution of the elements for different types of joss paper and incense. From the data in Table S5(a)† it is apparent that the Ca content is the highest in the unburnt joss paper and incense. Generally, the elemental composition order for the unburnt joss paper samples is Ca > Al > Na > Mg > K > Fe > Ti > Ba/Cu > Sr > Ga/Zn > Mn > Sn > Mo > Zr > Pb > Cr > V > Co > Ce > Ni > La > Y > As > Rb > Nd > Cd > Sc > Pr > W > Sb > Se > Cs > Hg while the elemental composition for unburnt incense is Ca > K > Al/Fe > Mg > Na > Mn > Ba > Ti > Sr > Zn > Rb > Ga > Cu > Pb > Cr > V > Ce > Ni > W > As > Nd > Y > Co > Cs > Hg > Sn > Cd > Sc > Se > Sb. These results indicate that after Ca, K has the higher average composition in incenses while Al has the higher average composition in joss paper.

Hsueh *et al.*[13] studied the composition (Na, Ca, Mg, Al, K, Fe, Cu, Pb, Sr, Mn and Zn) and the distribution of the emitted particles (aerodynamic diameter 0.01–100 μm) during the burning process of joss paper. Their results showed that elements were partly released in emitted particles mostly in the form of $PM_{2.5}$ (>70% for Na, Al, Pb, and Cu) and smaller particles. Fang *et al.*[3c] also demonstrated that the finer particulates ($PM_{2.5}$) make up the majority of emitted particulates in temples.

According to these findings and the list of the elements presented in this study, the composition of the particulate matter generated from joss paper and incense burning is alarming. In addition, it has been reported that the presence of transition metals (Cu, Fe and Zn) which might act as catalysts increase the formation of some organic chemicals such as polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs).[14]

Bottom ash from the burnt incense and joss paper. Bottom ash samples are the solid product remaining from the burning process of joss papers and incense. It can be seen from Table S5(b) in the ESI† that the trend in the metallic chemical composition of the bottom ash from burnt joss paper and incense is similar to that observed for the unburnt joss paper. Hsueh *et al.*[13] showed that most of the elements released after burning of joss paper are also present in the bottom ash.

It can be seen in Table S5(b)† that there are some differences in the transition metal content (such as Sn, Pb, Cr, Ni and W) between the different joss paper bottom ash samples. This composition difference is likely related to the varying textures and the paint that are used in the different types of the joss papers. Lau and Luk concluded that the pollution composition varied depending on the exact type of the joss paper.[10]

Analysis of bottom ash data from incenses indicated that incense No. 3 showed higher concentrations of Ba, Cu, Sr, Ga, Zn, Mn and W than the other samples. From Table S5(b) in the

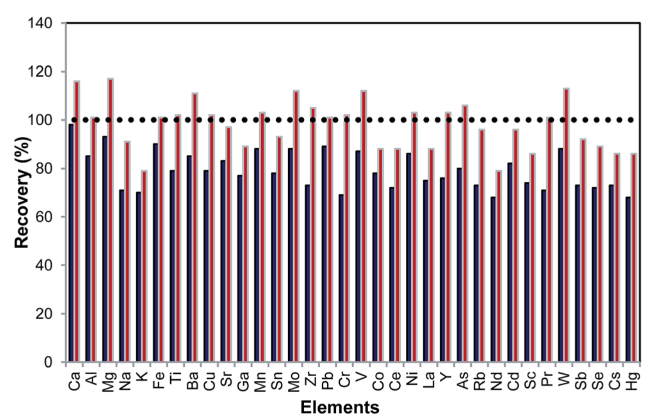

Fig. 4 Recovery test for bottom ash (■) and unburnt original (■) of JP7.

ESI,† it can also be concluded that the incense bottom ash has lower concentrations of Cu, Zn, Pb, Cr and Co than the bottom ash from joss papers, while Mn, Ni and As were present in higher concentrations than the bottom ash from joss papers.

Since there is not any Certified Reference Material (CRM) available for paper/cardboard, recovery tests were performed for both bottom ash and unburnt joss paper and incense to validate the method. An identical trend was observed for various types of joss paper and incense. Table S6 in the ESI† shows the recovery for different types of joss paper and incense that varies from 68 to 98% and from 79 to 123% for bottom ash and unburnt joss paper and incense, respectively. Fig. 4 shows a representative

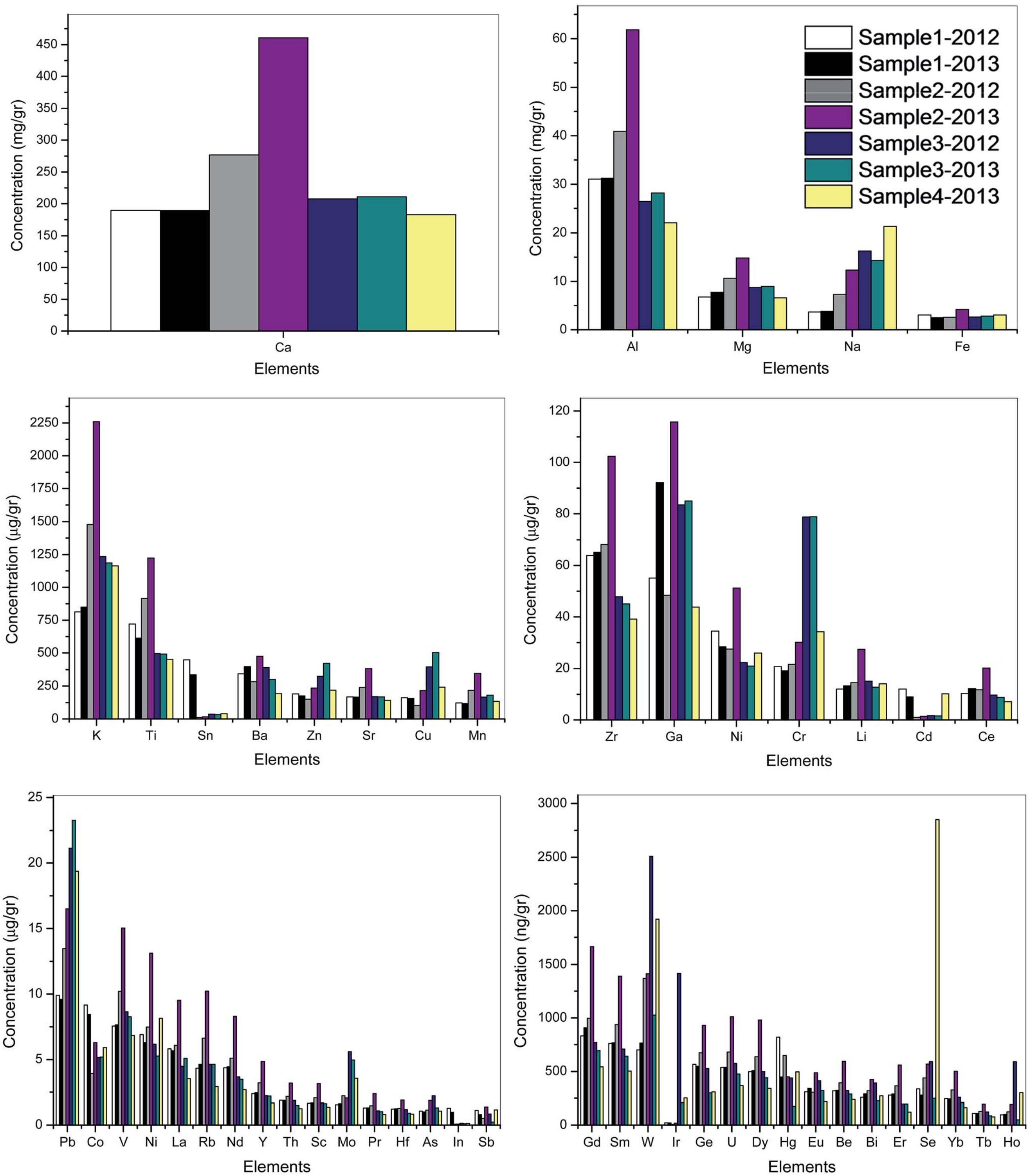

Fig. 5 Concentration profiles of bottom ash samples collected during the Hungry Ghost Festival in years 2012 and 2013 in different parts of Singapore.

example for bottom ash of joss paper (JP7) which shows that the recovery is often less than 90%, with Na, K and Cr having the lowest recovery. Hsueh *et al.*[13] suggested that bottom ash digestion is more difficult than digesting the unburnt material because of the strong post burning binding energy.

Bottom ash samples collected from burning events. 7 bottom ash samples were collected during the Hungry Ghost Festival from burning containers in different parts of Singapore. Fig. 5 gives the comparison of the chemical composition of the 7 collected bottom ash samples. Notably, as well as the major elements, all of the trace elements including the HAPS listed in Fig. 2 were detected in the burnt and unburnt incense and joss paper samples. The elemental contents were categorized into 5 groups according to their concentration range.

(a) Ca was present in the highest amount (high mg g^{-1}).

(b) Al, Mg, Na and Fe were present in the next highest concentrations (mg g^{-1}).

(c) K and Ti were the major elements in the third group followed by Ba, Zn, Sr, Cu and Mn. Surprisingly Sn showed very high concentrations (~400 μg g^{-1}) for the first two samples while for the rest of the samples the Sn concentration varied from 11 to 40 μg g^{-1}, which likely relates to different types of joss paper and incense that were used for burning.

(d) The concentrations of Pb, Co, V, Ni, La, Rb, Nd, Ba, Y, Th, Sc, Mo, Pr, Hf, As, In and Sb were less than 25 μg g^{-1} and are considered as the moderate concentration.

(e) The last group has been listed as low concentration elements (ng g^{-1}) including Gd, Sm, W, Ir, Ge, U, Dy, Hg, Eu, Be, Bi, Er, Se, Yb, Tb and Ho.

As part of an effort to preserve racial and religious harmony in multicultural Singapore, the National Environmental Agency (NEA) provides burning pits and containers to encourage people to burn joss papers and incense sticks responsibly during festivals. Frequently, the designated containers provided are not sufficient and people resort to burning joss papers and incense sticks on the pavements, grass fields or common corridors at the ground level near their residential high rise buildings.

However cleaners are also deployed to clear up the residual ashes in the neighbourhood on a daily basis; although in some areas the ashes are left inside the containers for the whole month and are blown by the wind. These ashes are treated as normal waste and are disposed in either in incinerators or in an offshore sanitary landfill where the components can penetrate into the groundwater.[15] Unfortunately, some people believe that drinking a slurry of burned joss paper mixed with water (water is added to bottom ash) can be used to cure diseases, protect themselves, rejuvenate their relationships and other remedies.[16]

3.3 Ti Kong Dan Day and Ching Ming Festival

An inspection of the dataset showed that a similar pattern of increase in the metallic composition in both particulate matter and rain water samples was observed for Ti Kong Dan Day (9th day of Chinese New Year, birthday of the Jade Emperor) and Ching Ming Festival (on the 104th day after the winter solstice or the 15th day from the Spring Equinox, usually occurring around April 4th or 5th of the Gregorian calendar) since residents follow the same custom of making burning offerings. However, during these two events the burning mainly takes place in furnaces of the temples. While a large amount of combustion occurs, the impact is much lower than the Hungry Ghost Festival because the burning occurs in closed furnaces equipped with filtration systems.

4 Conclusions

A five year continual investigation of rainwater and atmospheric $PM_{2.5}$ indicated consistently higher concentrations for many elements during August and September, which can be linked to the extensive outdoor burning events that occur during the Hungry Ghost Festival. The individual elements detected in the $PM_{2.5}$ over the Hungry Ghost period were 18–60% higher than those of the average background.

In general, Ca is present in the highest concentration in the unburnt joss paper followed by Al. For incense, Ca is also present in the highest concentration followed by K. The concentration of Cu, Zn, Mn, Mo, Pb, Cr, V, Co, Ni and Cd fluctuated in the different types of joss paper and incense, presumably according to the raw material and production process. The chemical composition and the order of concentration of the elements detected in the bottom ash of the burnt joss paper and incense are similar to those observed for the unburnt joss paper and incense.

A major conclusion of this study is that the pollution generated by open burning of joss paper and incense requires more attention. There is currently a lack of corroborating information about the impact on air quality and air pollutants emitted from open burning of joss paper and incense burning. Furthermore, there are limited literature reports of evidence for epidemiological links between respiratory disease and skin allergies and burning of incense and joss paper in an indoor or outdoor environment. However, unofficially it has been reported that a greater number of patients during this festival period seek treatment for ailments such as asthma, eye irritation, and nasal and skin allergies.[17]

In order to respect religious practices and not to disturb devotees (pilgrims) bottom ash samples were collected after the festivals. However, it is believed that in order to better investigate the health effects caused by inhalation of particulate matter emitted from burning; the sampling would preferably be carried out in the festival venues at the same time.

Burning joss paper and incense has been part of religious ceremonies for thousands of years but some regulatory monitoring may be required to control air and water pollution and reduce the health effects for the greater good of the entire population. This issue needs government agencies, temple boards, religious leaders, research scientists and private firms working together to reduce the pollution as much as possible. With the utmost respect to this religious practice the concern is about the control of the pollution and care of devotee's health.

Possible solutions have been proposed, including the following:

(a) Increased public education on air quality and the composition of bottom ash (especially if ingested as a slurry).

(b) Providing closed furnace with a filtering system in convenient areas.

(c) Using eco-friendly materials for production of joss paper and incense and control of the production process.

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References

1 (*a*) J. J. Schauer, M. P. Fraser, G. R. Cass and B. R. T. Simoneit, *Environ. Sci. Technol.*, 2002, **36**, 3806–3814; (*b*) M. Zheng, R. G. Cass, J. J. Schauer and E. S. Edgerton, *Environ. Sci. Technol.*, 2002, **36**, 2361–2371; (*c*) A. Cincinelli, S. Mandorlo, R. M. Dickhut and L. Lepri, *Atmos. Environ.*, 2003, **37**, 3125–3133; (*d*) C. A. Pope, *Aerosol Sci. Technol.*, 2000, **32**, 4–14; (*e*) C. I. Davidson, R. F. Phalen and P. A. Solomon, *Aerosol Sci. Technol.*, 2005, **39**, 737–749.

2 (*a*) J. N. Galloway, G. E. Likens and M. E. Hawley, *Science*, 1984, **226**, 829–831; (*b*) J. L. Moody, A. A. P. Pszenny, A. Gaudry, W. C. Keene, J. N. Galloway and G. Polian, *J. Geophys. Res.*, 1991, **96**, 769–786; (*c*) F. L. T. Gonçalves, M. F. Andrade, M. C. Forti, R. Astolfo, M. A. Ramos, O. Massambani and A. J. Melfi, *Environ. Pollut.*, 2003, **121**, 63–73; (*d*) P. R. Salve, A. Maurya, R. Sinha, A. G. Gawane and S. R. Wate, *Bull. Environ. Contam. Toxicol.*, 2006, **77**, 305–311; (*e*) A. Malik, V. K. Singh and K. P. Singh, *Bull. Environ. Contam. Toxicol.*, 2007, **79**, 639–645; (*f*) Y. W. F. Tham and H. Sakugawa, *Bull. Environ. Contam. Toxicol.*, 2007, **79**, 670–673.

3 (*a*) C. S. Li and Y. S. Ro, *Atmos. Environ.*, 2000, **34**, 611–620; (*b*) C. W. Fan and J. J. Zhang, *Atmos. Environ.*, 2001, **35**, 1281–1290; (*c*) G. C. Fang, C. N. Chang, Y. S. Wu, C. J. Yang, S. C. Chang and I. L. Yang, *Sci. Total Environ.*, 2002, **299**, 79–87.

4 (*a*) H. H. Yang, R. C. Jung, Y. F. Wang and L. T. Hsieh, *Atmos. Environ.*, 2005, **39**, 3305–3312; (*b*) C. C. Lin, S. J. Chen, K. L. Huang, W. J. Lee, W. Y. Lin, J. H. Tsai and H. C. Chaung, *Environ. Sci. Technol.*, 2008, **42**, 4229–4235; (*c*) M. D. Lin, J. Y. Rau, H. H. Tseng, M. Y. Wey, C. W. Chu, Y. H. Lin, M. C. Wei and C. H. Lee, *J. Hazard. Mater.*, 2008, **156**, 223–229; (*d*) S. C. Lung and S. C. Hu, *Chemosphere*, 2003, **50**, 673–679; (*e*) T. C. Lin, F. H. Chang, J. H. Hsieh, H. R. Chao and M. R. Chao, *J. Hazard. Mater.*, 2002, **95**, 1–12; (*f*) G. C. Fang, Y. S. Wu, M. H. Chen, T. T. Ho and J. Y. Rau, *Atmos. Environ.*, 2004, **38**, 3385–3391.

5 (*a*) R. Caggiano, M. D'Emilio, M. Macchiato and M. Ragosta, *Environ. Monit. Assess.*, 2005, **102**, 67–84; (*b*) F. Eldabbagh, A. Ramesh, J. Hawari, W. Hutny and J. A. Kozinski, *Combust. Flame*, 2005, **142**, 249–257; (*c*) G. C. Fang, C. N. Chang, C. C. Chu, Y. S. Wu, P. P. C. Fu, S. C. Chang and I. L. Yang, *Chemosphere*, 2003, **51**, 983–991; (*d*) O. W. Lau and S. F. Luk, *Atmos. Environ.*, 2001, **35**, 3113–3120.

6 B. Wang, S. C. Lee, K. F. Ho and Y. M. Kang, *Sci. Total Environ.*, 2007, **377**, 52–60.

7 http://www.epa.gov/airtoxics/orig189.html.

8 (*a*) M. Costa, *Human Exposures and Their Health Effects*, ed. M. Lippmam, John Wiley & Sons, Inc, Hoboken, NJ, USA, 2nd edn, 2000, pp. 811–850; (*b*) S. G. Donkin, D. L. Ohlson, C. M. Teaf, Properties and effects of metals, *Principles of toxicology: environmental and industrial applications*, ed. P. L. Williams, R. C. James and S. M. Roberts, John Wiley & Sons, Inc, Hoboken, NJ, USA, 2nd edn, 2000, pp. 325–344; (*c*) M. E. Gerlofs-Nijland, M. Rummelhard, A. J. F. Boere, D. L. Leseman, R. Duffin, R. P. F. Schins, P. J. A. Borm, M. Sillanpaa, R. O. Salonen and F. R. Cassee, *Environ. Sci. Technol.*, 2009, **43**, 4729–4736; (*d*) S. K. Park, M. S. ONeill, P. S. Vokonas, D. Sparrow, R. O. Wright, B. Coull, H. Nie, H. Hu and J. Schwartz, *Epidemiology*, 2008, **19**, 111–120.

9 (*a*) R. E. Rasmussen, *Bull. Environ. Contam. Toxicol.*, 1987, **38**, 827–833; (*b*) C. Y. Mimi, D. H. Garabran, T. B. Huan and B. E. Henderson, *Int. J. Cancer*, 1990, **45**, 1033–1039.

10 O. W. Lau and S. F. Luk, *Atmos. Environ.*, 2001, **35**, 3113–3120.

11 (*a*) C. Tortajada, *Int. J. Water Resour. Environ. Eng.*, 2006, **22**, 227–240; (*b*) I. O. B. Luan, *Int. J. Water Resour. Environ. Eng.*, 2010, **26**, 65–80.

12 B. Khezri, H. Mo, Z. Yan, S.-L. Chong, A. K. Heng and R. D. Webster, *Atmos. Environ.*, 2013, **80**, 352–360.

13 H. T. Hsueh, T. H. Ko, W. C. Chou, W. C. Hung and H. Chu, *Environ. Chem. Lett.*, 2012, **10**, 79–87.

14 M. T. Hu, S. J. Chen, Y. C. Lai, K. L. Huang, G. P. Chang-Chien and J. H. Tsai, *Aerosol Air Qual. Res.*, 2009, **9**, 369–377.

15 (*a*) J. Robson, *Hist. Religions*, 2008, **48**, 130–169; (*b*) *Taoism*, ed. Z. Mou, (Trans: J. Pan, S. Normand), Leiden [The Netherlands], Boston, Brill, 2012, pp. 293–308.

16 (*a*) http://app2.nea.gov.sg/energy-waste/waste-management/overview; (*b*) http://app2.nea.gov.sg/energy-waste/waste-management/solid-waste-management-infrastructure.

17 http://www.healthxchange.com.sg/News/Pages/More-ailments-during-Hungry-Ghost-Festival.aspx.

