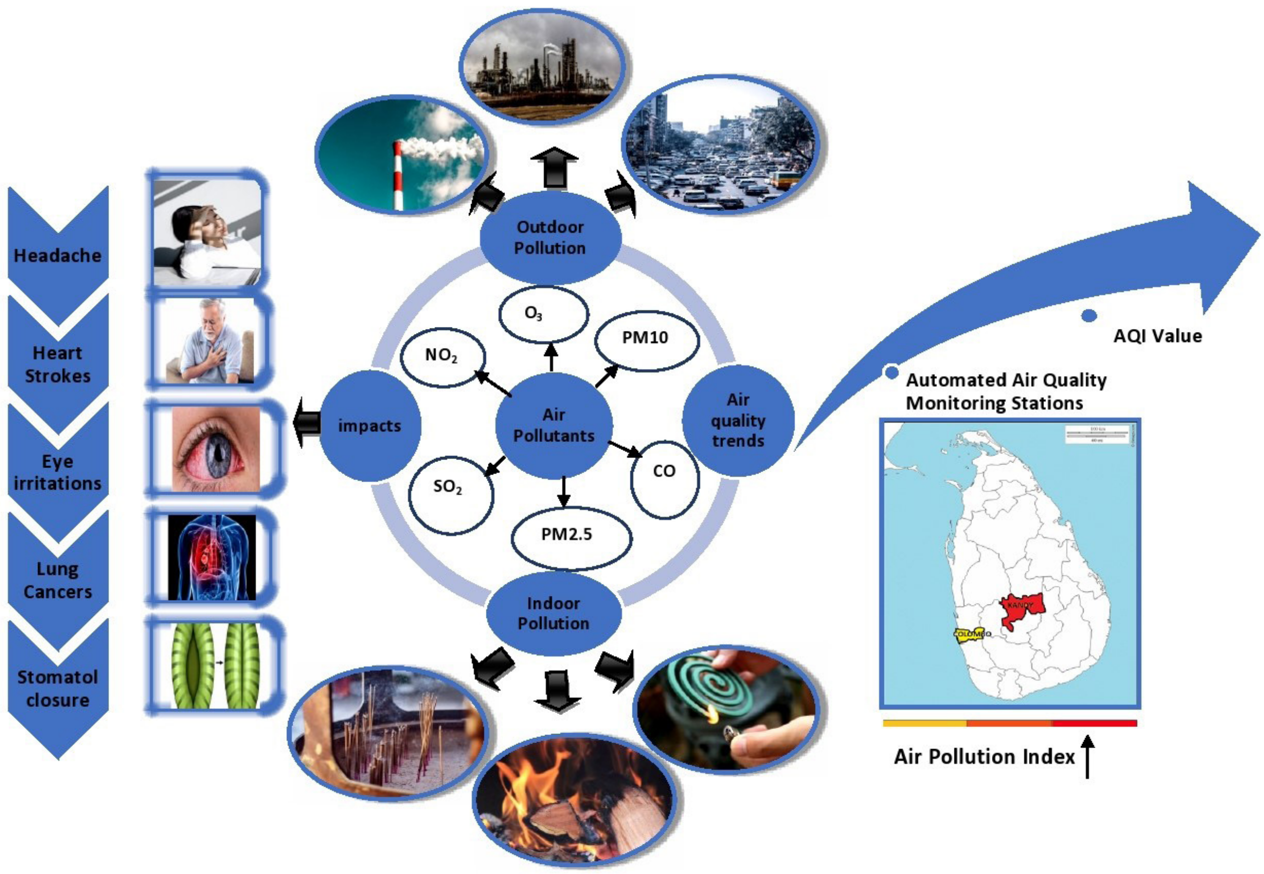
REVIEW ARTICLE

Review of air pollution studies in Sri Lanka

O.A.Ileperuma



Highlights

- Air pollution causes respiratory illnesses and also cardiovascular diseases
- Regular air pollution monitoring in Colombo and Kandy reveal that the AQI values often exceed the safe limits
- Pollution levels are highest during the north-east monsoonal period owing to transboundary air pollution
- Indoor air pollution, particularly cooking with firewood causes many respiratory illnesses
- Biomonitoring of air pollution affords an economical way to assess air quality

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Review of air pollution studies in Sri Lanka

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Abstract: Air pollution is a growing problem in Sri Lanka mainly due to the phenomenal increase in the number of motor vehicles and traffic congestion. Regular air pollution monitoring at automated air quality stations commenced in 1997 with two monitoring stations in Colombo. Results for the period 1997-2003 showed that the levels of sulphur dioxide, nitrogen dioxide, and ozone are steadily increasing while the carbon monoxide levels are decreasing. These pollutants are below their air quality standards except for fine particles (PM10 and PM2.5) which are always above the national standard. Air quality in Kandy is worse than that of Colombo owing to its geographical location, increased vehicle population and traffic congestion. In Kandy, sulphur dioxide, nitrogen dioxide and ozone levels exceeded the standards on 41%, 14% and 28% of the occasions during the period 2001-2005. Presence of carcinogenic polyaromatic hydrocarbons from both kitchen smoke and vehicular exhausts is a definite health hazard. Mean total concentrations of 16 prioritized PAHs (PPAHs) ranged from 57.43 to 1246.12 ng/m^3 with a mean of 695.94 ng/m^3 in urban heavy traffic locations in Kandy. There are increasing cases of respiratory diseases such as chronic obstructive pulmonary disease due to air pollution in Kandy. Indoor air pollution involving firewood use in congested kitchens is a major health hazard and a few limited studies show that wheezing, bronchitis and asthma incidence is found in children exposed to kitchen smoke. Air quality monitoring using bioindicators is a useful low-cost method to evaluate the pollution levels and the effects of air pollution on plants and vegetation needs more attention.

Keywords: Air pollution, Air quality standards, Air quality trends, Indoor air pollution, Health effects of air pollution, Biomonitoring

INTRODUCTION

Air pollution refers to the release into the atmosphere of various gases and fine particles at rates that exceed the natural capacity of the environment to dissipate, absorb and dilute them. They can affect the health of people and have economic and aesthetic effects. The gaseous air pollutants of primary concern are sulphur dioxide, nitrogen dioxide and carbon monoxide which are directly emitted owing to combustion of fossil fuel in automobiles, power plants, industries and biomass burning. Ozone formed in the lower atmosphere is a secondary air pollutant generated from the photochemical reactions of primary air pollutants like NO_2. Fossil fuel combustion also yields fine particles, especially those with less than 10 µm in diameter which can penetrate deep inside the lung and causing many undesirable health effects. An average person inhales about 10,000 litres of air daily and its purity profoundly affects the health of people.

New estimates in 2018 reveal that globally 9 out of 10 people breathe air containing high levels of pollutants. Worldwide, around 8 million deaths have been attributed to air pollution with 4.3 million deaths arising from indoor air pollution (WHO, 2019). The latter arises mainly due to biomass burning in kitchens without adequate ventilation. In Sri Lanka, firewood use for cooking accounts for about 78% of households and this produces highly toxic air pollutants affecting the health of people even in rural areas where there is no significant outdoor air pollution.

Air pollution causes not only respiratory illnesses like asthma, bronchitis, pneumonia and chronic obstructive pulmonary disease (COPD) but also responsible for cancer, stroke and heart attacks, diabetes, low birth weight of babies and even baldness. Diesel smoke consists of unburnt hydrocarbons like polyaromatic hydrocarbons which are known carcinogens. Some of the work on air pollution in Sri Lanka have been reviewed (Ileperuma, 2004, Ileperuma and Mubarek, 2019).

AIR POLLUTION SOURCES

The sources of air pollution can be categorised into three basic groups: transport, industry (including power generation) and domestic use. In Sri Lanka, during 2011, emissions from motor vehicles accounted for 55-60% of air pollution, while 20-25% was due to industries and 20% was from domestic sources (Ministry of Environment, 2012). Sri Lanka produced over 95% of its power needs from hydroelectricity in 1993 and this has gradually decreased, and hydropower now accounts for only about 50% and sometimes even less. For example, in 2018, the generation mix from hydro, thermal and coal were 5149, 1886 and 4764 GWh respectively (Central bank, 2018) which shows that more power is produced by burning fossil fuels thereby creating more pollution. Over 50% of the vehicles, 70% of industries and several thermal power plants are located in the Colombo Metropolitan area. (Pereira and Tiruchelvam, 1998). Furthermore, furnace oil has a high percentage of around 3.5% sulphur and more SO_2 is generated from

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thermal power plants burning furnace oil.

Transport sector generates the most amount of air pollution which is due to the ever-increasing number of vehicles on our roads whereas the road system has not significantly improved. Table 1 gives the total number of registered vehicles in Sri Lanka. It is clear that the number of motor vehicles has increased considerably during the last two decades. Now the registered number of motor cycles is around 3 million which is nearly five times what we had in the year 2000. Similarly, the number of cars have increased to around 600,000 which is a 300% increase from 2000. This phenomenal increase in the number of motor vehicles has resulted in more pollution, traffic jams and loss of productivity. Vehicles travelling in traffic jams produce more soot, carbon monoxide and unburnt hydrocarbons compared to vehicles travelling smoothly with a uniform speed of about 40 km/h.

The biggest increase is in the number of motorcycles, which account for about 50% of the entire fleet followed by three wheelers. The number of motorcycles increased by about 290% and three wheelers by 380%, during the period 2003-2008. Air pollution caused specially by these two categories of vehicles is considerable because most of them have two stroke engines resulting in more PM10/PM2.5 and CO generation into the atmosphere. Uncontrolled increase in the number of vehicles will be the biggest challenge in the future. The economic loss due to traffic congestion in Colombo has been estimated (Kumarage, 2013) to be around Rs.32 billion annually and increased health cost for treating patients affected by air pollution will be an immense economic burden to the government.

Another major factor affecting the environment is the increased use of fossil fuels such as coal and oil in thermal power plants for power generation. According to the National Energy policy and strategies of Sri Lanka, increased demand will necessitate power generation using more and more fossil fuels.

REGULATORY MECHANISMS AND INSTITUTIONAL FRAMEWORK

The six major air pollutants CO, NO_2, SO_2, O_3 and PM10 and PM2.5 are designated as criteria air pollutants because their concentrations in the atmosphere are useful as indicators of air quality. These are the pollutants typically monitored at automated air quality monitoring stations. To protect people from the adverse effects of air pollution, countries have adopted air quality standards and Sri Lanka gazetted National Ambient Air Quality Standards (NAAQS) in 1994 and these were modified in 2008. These give the maximum allowable concentrations of air pollutants with an adequate margin of safety for five criteria air pollutants and given in Table 2.

National Environmental Act (NEA) No. 47 was enacted in 1980 to establish legislation to protect, conserve and manage the Environment of Sri Lanka and the Central Environmental Authority (CEA) was established in 1981. One of the environmental initiatives of the World Bank was the establishment, in 1994, the Metropolitan Environment improvement programme (MEIP). As a result, clean air 2000 action plan which aimed to reduce all air pollutants in the Colombo metropolitan area by the year 2000 was established.

Initiatives under the clean air action plan of 2000 and subsequent plans in 2007 and 2015 resulted in several actions to reduce air pollution in cities. These include, lowering of sulphur in fuel from 0.5% to 0.25%, banning two stroke three wheelers, terminating the addition of lead to petrol and commencing the vehicle emissions testing (VET) programme. In addition, two automated air quality monitoring stations were commissioned with one at Colombo Fort (peak station) and the other at Bauddhaloka Mawatha (background station) in 1997.

Table 1: Total operation fleet by class of vehicles (Sources: Statistical abstracts, Department of Census and Statistics and Central Bank Economic and Social Statistics of Sri Lanka, 2019)

Vehicle type	1991	1994	1997	2000	2018
Motor cycles	379,494	480,775	550,178	635,018	2,729,762
Three wheelers	10,679	17,336	49,014	65,169	971,954
Cars (petrol)	88,817	98,065	137,772	168,349	582,575
Cars (diesel)	4,872	13,359	16,341	23,656	
Vans (petrol)	17,083	14,921	10,910	8,048	363,553
Vans (diesel)	52,893	88,890	128,932	164,129	
Buses/Lorries (diesel)	45,566	65,668	79,459	107,135	273,241
Total	599,404	779,014	972,608	1,171,504	4,921,085

Table 2: Air quality standards in Sri Lanka (Gazette No. 1562/22 of 2008.08.15)

Pollutant	Averaging time	Maximum allowable concentration (microgrammes per cubic metre)/ ppm
Fine particles (PM 2.5)	Annual	25
	24 hours	50
Coarse particles (PM 10)	Annual	50
	24 hours	100
Nitrogen dioxide	24 hours	100 (0.05)
	8 hours	150 (0.08)
	1 hour	250 (0.13)
Sulphur dioxide	24 hours	80 (0.03)
	8 hours	120 (0.05)
	1 hour	200 (0.08)
Ozone	1 hour	200 (0.10)
Carbon monoxide	8 hours	10,000 (9.00)
	1 hour	30,000 (26.00)

AIR QUALITY TRENDS

The first air quality measurements can be traced back to a study by the University of Colombo where lead levels in air were determined (Samarakkody, 1994). The results obtained show that the ambient lead concentration in a residential area, of the Colombo urban environment was about 200 $\mu g/m^3$and about 400 $\mu g/m^3$ in the vicinity of a main road, whereas the threshold value of ambient lead published by the Central Environmental Authority is 2 $\mu g/m^3$ for a 24 hour sampling period. National Building Research Organization (NBRO) carried out a study (Samarakkody *et al.,* 1998) on the sulphation rate (SR) and dust fall (DF) at 49 locations in the city of Colombo and some of the locations reported high levels of sulphur dioxide. The highest average value of 0.45 mg/100 cm^2/day was obtained at Slave Island junction. Dust fall too showed increased levels at locations with high traffic density.

Mathes *et al*. (1993) carried out a study on ambient air quality levels at locations selected from major traffic junctions in Colombo. Based on survey data, a high correlation between total suspended particulate (TSP) levels and traffic density in Colombo was observed. For example, the traffic volume along major roads such as Maradana Road, Reid Avenue, Galle Road, and Lotus Road constitute about 41,770, 38,800, 37,700, and 34,650 vehicles, respectively, during a 12-h period in a day. The study revealed that observed TSP and non-methane hydrocarbons (NMHC) exceeded the WHO air quality standards. In addition, all 16 priority polyaromatic hydrocarbons (PAHs) were found in 75% of the samples and 82% of the samples had carcinogenic compounds like benzopyrene, dibenzopyrene and benzofluoroanthene. The mean average of PAH compounds was 720 ng/m^3 with a variation of 270-2270 ng/m^3.

Regular air quality monitoring in the Colombo city commenced in 1997 with two automated air quality monitoring stations and data were collected until 2008 when these stations became non-operational. Results indicated (Figures 1-3) that the SO_2 and NO_2 levels showed a steady increase (Jayaratne and Ileperuma, 2007). The NO_2, CO and O_3 concentrations were always below their air quality standards while there have been some exceedances of SO_2.

However, these data which consider 24-hour averages which averages data, including nighttime data where the pollution generated is much lower, do not give a true picture of the exposure of people to air pollution. People are exposed to far higher levels of pollution as seen from the highest values of pollutants recorded which exceed the air quality standards. The increasing trend of air pollutants is mainly due to the rapidly increasing vehicle fleet in Sri Lanka which increased from 978,544 in 1997 to 8.1 million in 2019 and nearly 50% of all vehicles are registered in the western province. Carbon monoxide levels exhibited a slightly decreasing trend which is most likely due to the addition of newer vehicles with more efficient engines and hence more efficient combustion of fuel. There is a global trend where the CO levels are declining. Another explanation for this trend is the increase in hydroxyl free radicals in the atmosphere, as a result of increasing ultra-violet radiation reaching the lower atmosphere. This increases the hydroxyl free radical levels which are the natural scavengers of CO where the CO reacts with hydroxyl free radicals giving CO_2.

PM10 concentrations too show a steady increase and fall within a range of 50-120 $\mu g\ m^{-3}$ exceeding the Sri Lanka annual air quality standard of 50 $\mu g\ m^{-3}$ (Figure 4). This can be attributed to increased traffic congestion and the reduction of the average speed of vehicles and resulting

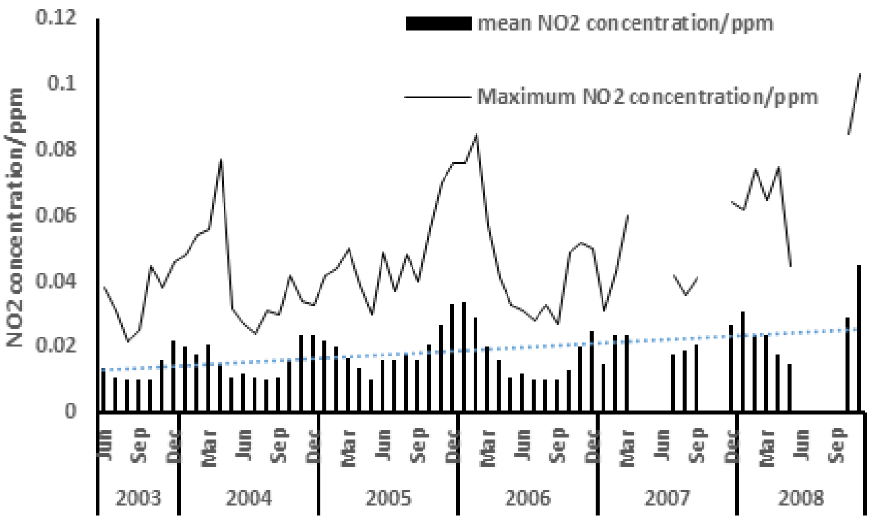


Figure 1: Variation of NO_2 for the period 2003-2008 in Colombo (Source: Central Environment Authority).

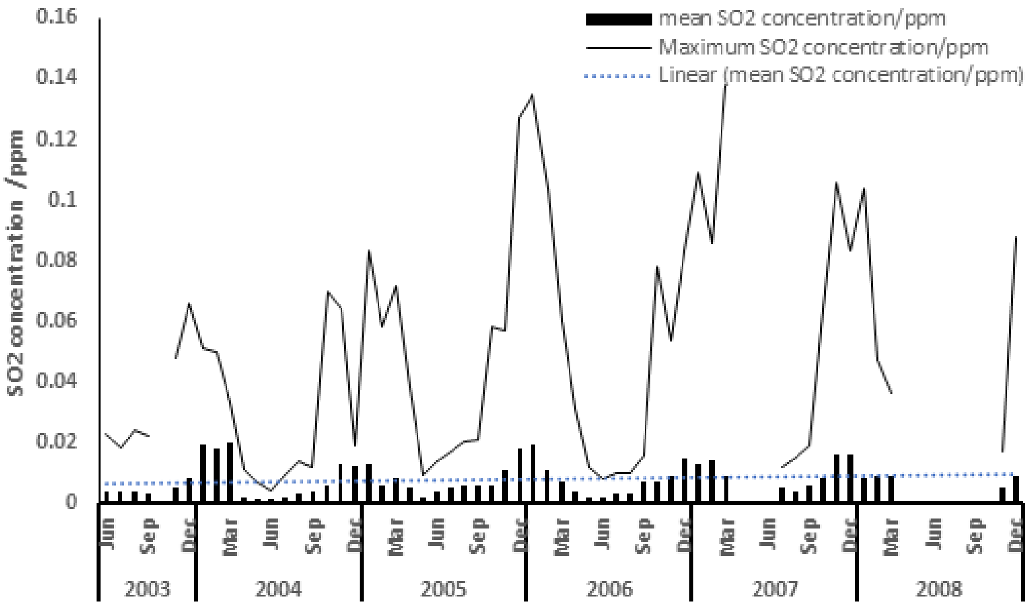


Figure 2: Variation of SO_2 for the period 2003-2008 in Colombo (Source: Central Environment Authority).

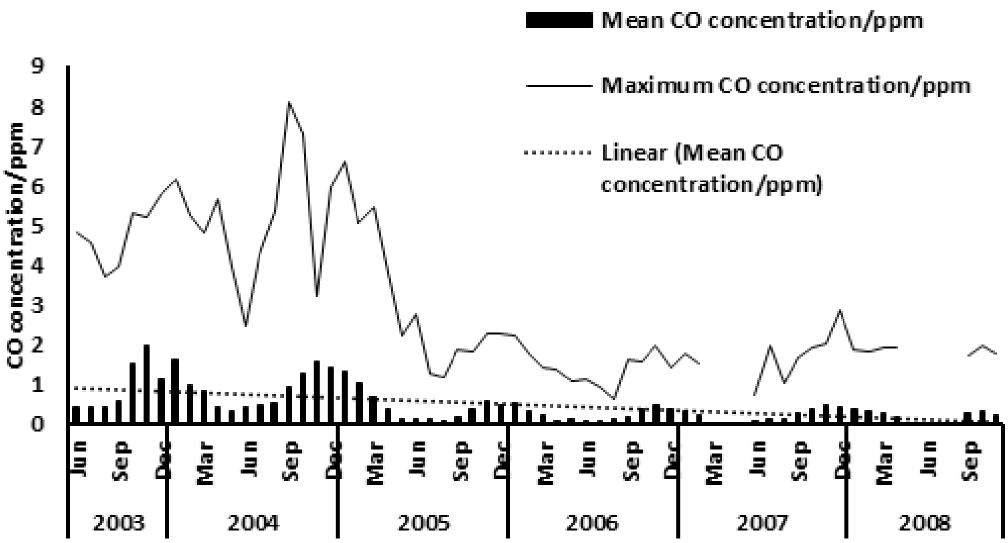


Figure 3: Variation of CO for the period 2003-2008 in Colombo (Source: Central Environment Authority).

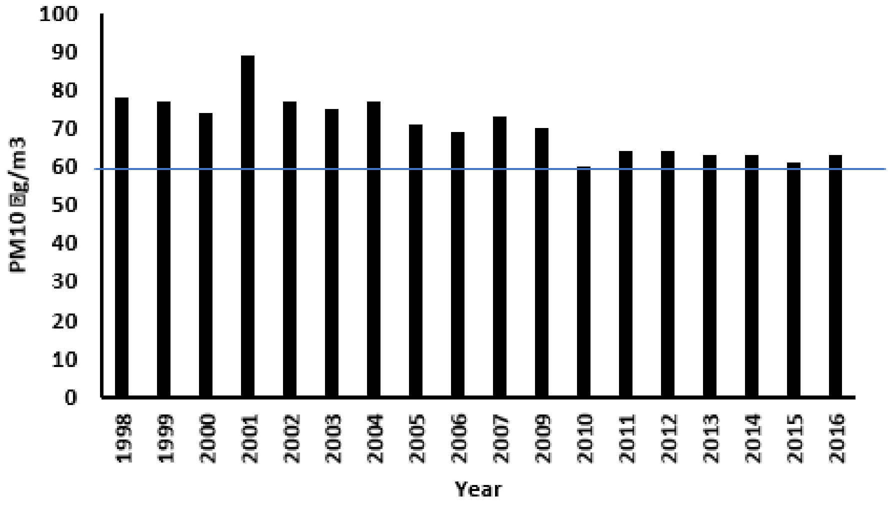


Figure 4: Variation of annual average of PM10 for 1998-2016 at the Colombo Fort air quality monitoring station, horizontal line at AQ standard for PM10 at 50 µg/m³ (Source: Central Environmental Authority).

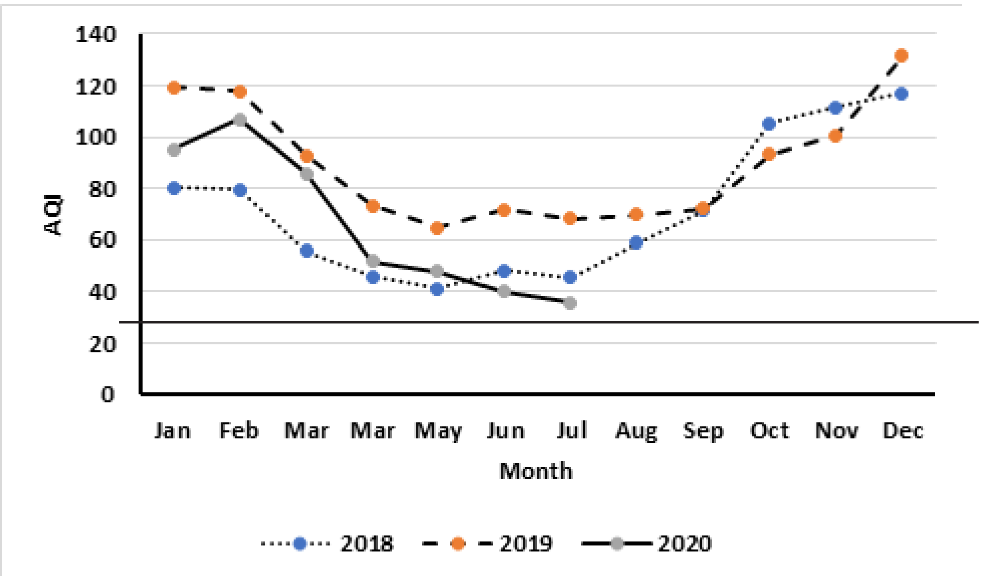


Figure 5: Variation of AQI based on PM2.5 for Colombo for the period 2018-2020.

in incomplete combustion of fuel.

Unlike SO_2 and NO_2, PM10 annual averages (Figure 4) always exceed the air quality standard which has implications to human health. Based on the data from this station, the average annual ambient PM_{10} levels in Colombo over the years have remained relatively stable ranging from 72 to 82 µg/m³. The World Health Organization (WHO) recommends that the average annual ambient PM_{10} level be <20 µg/m³while the Sri Lanka standard is set much higher at 50 µg/m³. Similar results have been obtained from Nugegoda (95 µg/m³) while the values from Kandy were in the range of 50 -75 µg/m³ (July 2008) which shows an increasing trend with a range of 55- 100 µg/m³ recorded in July 2010. This is expected owing to the larger traffic volumes and the resultant traffic congestion in Kandy.

Air pollutant levels in the city of Colombo shows a distinct seasonal variation with the highest concentrations recorded during the north-east monsoonal period of November to February and the lowest during the south-west monsoon (Figures 1 & 2). Transboundary air pollution from the Indian sub-continent brings pollution from India and other Asian countries is responsible for this trend. Another reason is the spreading of air pollutants, produced in the power plants situated in the northern part of Colombo, towards the air quality monitoring station during the north-east monsoon.

More recently, deterioration of the air quality in Colombo was highlighted partly due to extremely high air pollution levels experienced by New Delhi during the period November to January of 2019. Air quality index (AQI) was first developed by the United States Environmental Protection Agency (US-EPA) to give the air pollution information to the general public in a simpler way. AQI values are reported on an hourly basis from the US embassy's website from the data obtained at its air pollution monitoring site located near Borella. These values are generally based on the PM2.5 concentrations which refer to the levels of fine particles less than 2.5 microns and having the highest impact on human health. Figure 5 gives the variation of AQI levels for the years

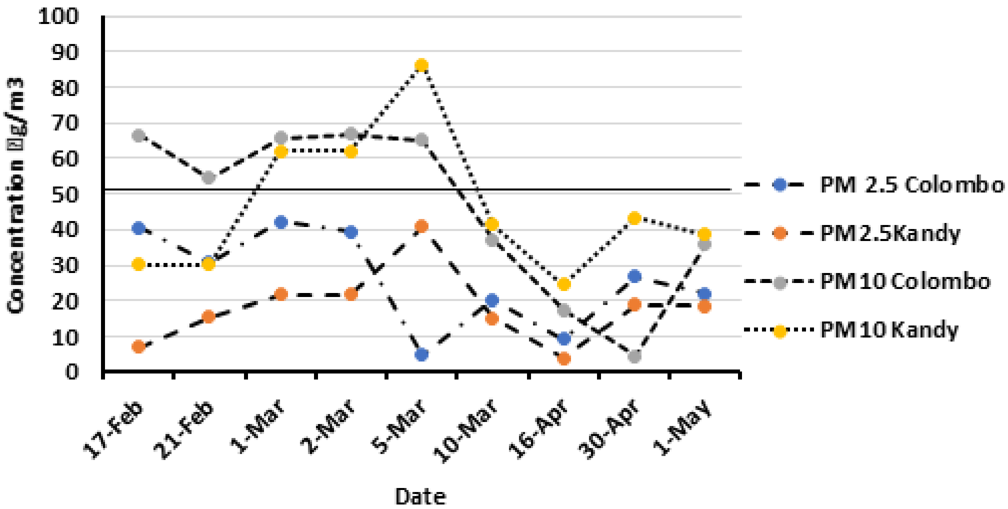
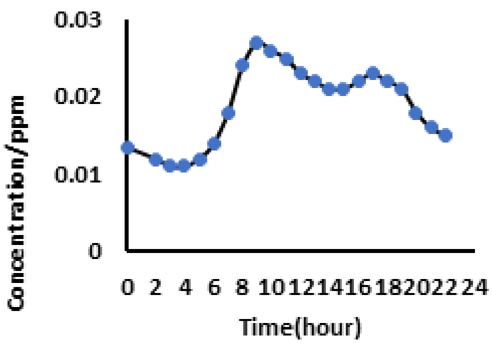
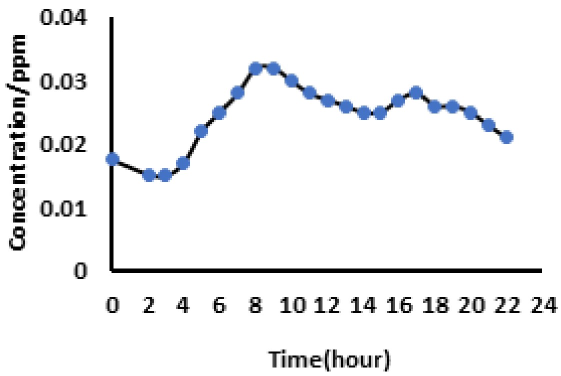


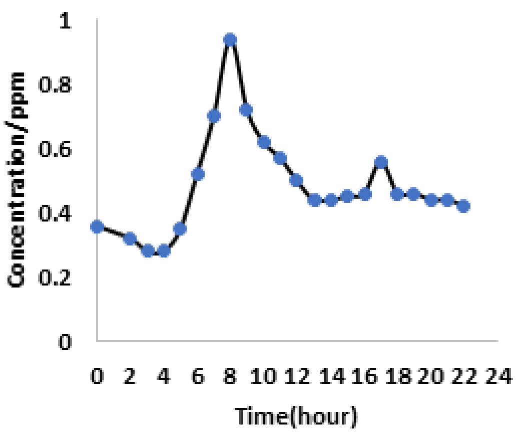
Figure 6: PM2.5 and PM10 values at the Battaramulla and Kandy monitoring stations in 2019 (Source: Central Environmental Authority).



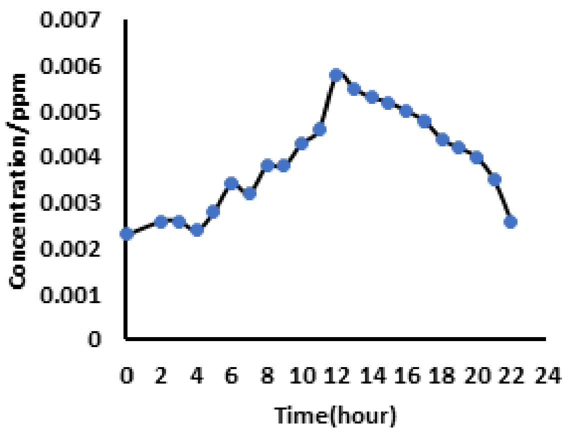
(a) Variation of NO_2 concentration with time



(b) Variation of SO_2 concentration with time



(c) Variation of CO concentration with time



(d) Variation of O_3 concentration with time

Figure 7: Diurnal variation of air pollutants with the time of the day in 2007 at the Colombo Fort monitoring station.

2018, 2019 and a part of 2020. High values for AQI were reported even in 2018 coinciding with transboundary air pollution during the north-east monsoon. AQI values above 100 are categorised as unhealthy to sensitive groups such as asthmatics and heart patients are adversely affected.

In 2018, two automated air quality monitoring stations were installed at Battaramulla and Kandy. Except for PM10 and PM2.5, other criteria air pollutants did not show any exceedances. Analysis of PM10 and PM2.5 at these stations reveal that most of the values exceeded the Sri Lanka standards (Figure 6). Although these values are the 24-hour averages, the highest values for these two parameters are at least twice this value during heavy traffic times. The data for Kandy are often higher than the corresponding values for Colombo. The data available from March 23rd were much lower because of the curfew and other travel restrictions which reduced the air pollution to low levels.

DIURNAL VARIATION OF AIR POLLUTANTS

Figure 7 gives the diurnal variation of the air pollutants, SO_2, NO_2, CO and O_3 with time of the day (Jayaratne, 2005). It is seen that peaks for NO_2, SO_2 and CO are observed at around 8 a.m. when both office and school traffic overlap. There is a smaller hump at around 5-6 p.m. which is mainly due to office traffic. It is also seen that the NO_2 peak in the morning dips more rapidly than for SO_2. When the sun comes up, NO_2 undergoes photolysis and starts producing ozone according to the following reaction sequence.

$$NO_2 \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

Therefore, the steady rise of ozone (Figure 6d) can be explained, and this reaches a maximum at noon when solar intensity is highest.

OTHER AIR QUALITY STUDIES

There have been several reports of air quality studies carried out from different parts of Colombo and Kandy with limited data sets and these will be discussed in the following section.

An analysis of the air quality at two locations, Gonawala and Manelwatta in the Kelaniya area during the 1997-2004 period (Perera et. al., 2004) showed an increase of NO_2 from 12 $\mu g/m^3$ to 18 $\mu g/m^3$ and SO_2 from 8 $\mu g/m^3$ to 18 $\mu g/m^3$ with higher levels recorded during the north-east monsoonal period. The proximity of these two locations to the diesel power stations, increased motor traffic and transboundary pollution may be responsible for this trend.

Premasiri et al. (2003a) have carried out a study to determine the ratio of suspended particulate matter: TSP:PM10:PM2.5 in the Colombo city. The average value of this ratio is 4:3:2. It was revealed that PM10 fraction is about 70% of the total particles and out of which 65% is PM2.5 which is the most harmful fraction to human health. It is clear that most of the black smoke emitted from motor vehicles is in the form of PM2.5. Monitoring data during the period 1997-2008 indicate that the Colombo Fort monitoring station PM10 values were about 40% higher than the data obtained from the background station at the Meteorological department. Similar to other pollutants like SO_2 and NO_2, PM10 fraction also shows a seasonal change with the higher values of 120 - 160 $\mu g/m^3$ obtained during the north-east monsoon. and 30 - 40 $\mu g/m^3$ during the south-west monsoon. The annual average of PM10 at the Colombo Fort station in the year 2000 was 84 $\mu g/m^3$ and at Meteorological Department, Colombo this value was 54 $\mu g/m^3$. Both these values exceed the Sri Lanka standard for PM10.It has been found that 40% of the PM10 fraction is composed of PM2.5 particles and black carbon accounts for over two-thirds of the total PM2.5 (Seneviratne *et al.,* 2004). Biomass burning for cooking, exhaust from motor vehicles and road dust contribute to the observed trends in the chemical composition of the particles.

Jaffna, which is located close to the Indian sub-continent is expected to have a higher influence from the pollution clouds coming from neighboring India. RAINS-ASIA model 7.52, a computer model to determine sulphur depositions in the form of both wet and dry depositions has been used to calculate sulphur depositions in several cities including Jaffna(Ileperuma, 2015).The results reveal that acidic depositions both as sulphate in acid rain and gaseous SO_2 are increasing. This model predicts that for most cities in Sri Lanka, acidic depositions will increase nearly four-fold during the period from 1990 to 2030. Most of the acid precursors originate in the Indian sub-continent where there is increased power generation using coal power plants. An often-neglected contribution comes from the ships which traverse one of the busiest sea-lanes in the World, located in close proximity to the southern tip of Sri Lanka. Fuel used in ships has high sulphur content, typically between 2.5 – 3.5% and their contribution to acid deposition is highly significant. It was found, as expected, Galle which is situated close to the shipping lanes recorded the highest emissions of sulphur from ships accounting for 40% of the total sulphur deposition in 1990. Using the same model, this share is predicted to increase to 60% by the year 2030. By comparison, other coastal cities such as Colombo and Jaffna in 1990, had respectively 14% and 2% of their sulphur depositions from ship movements.

Compared to Colombo, Kandy city which is located in a valley of 26 km^2 surrounded by mountain ranges has a higher degree of air pollution. Kandy is a heritage city and a densely populated area with a daily flow of over 100,000 vehicles with a limited road network resulting in a high degree of traffic congestion and hence elevated levels of air pollution. Abeyratne and Ileperuma (2001) reported the concentrations of SO_2, NO_2 and O_3 as determined by passive gas sampling for the 2001-2005 period and the values exceeded the air quality standards of these pollutants on 41%, 14% and 28% occasions respectively (Ileperuma and Abeyratne, 2006). These values are at least 3-4 times higher compared to the corresponding values observed in Colombo for the same period. Air pollution produced in Colombo, which is located by the sea having a flat terrain gets effectively dispersed and diluted by the sea breeze and accounts for the observed lower levels of air pollution. On the other hand, locating the peak station at Colombo Fort which is less than 200 m from the sea may give artificially low values and does not give a representative picture of air pollution in the Colombo city.

Polycyclic aromatic hydrocarbons (PAH) are emitted from vehicle emissions and from firewood smoke and they get adsorbed on the fine carbon particles which can penetrate deep inside the lung. These are carcinogenic and represent a major risk factor to human health. Wickremasinghe *et al.,* (2012), determined the levels of priority PAHs and PM10 at twenty locations in the city of Kandy and its suburbs. Mean total concentrations of 16 prioritized PAHs (PPAHs) ranged from 57.43 to 1246.12 ng/m^3 with a mean of 695.94 ng/m^3 in urban heavy traffic locations, 105.55 ng/m^3 in urban light traffic locations, 337.45 ng/m^3 in suburban heavy traffic stations, 154.36 ng/m^3 in suburban light traffic stations, 192.48 ng m^3 in rural high firewood burning area and 100.31 ng/m^3 in rural low firewood burning area. The mean PM_{10} concentration in the Kandy city was 129 μg/m^3 which exceeds the Sri Lanka standard. These levels are higher than the observed values in coastal cities such as Naples and Athens but comparable to the values of the highly polluted Mexico City. At places of high traffic congestion, the PAH value increased to 1246 ng/m^3 and PM10 to 221.7 μg/m^3. Since aromatic hydrocarbons are responsible for cancer and mutagenic activity, this is a serious health hazard. In this study, it was found that the PM2. 5 concentration always exceeded the standard of 25 μg/m^3 with a mean value of 29.0 μg/m^3 for the period between 2000-2005. This indicates that fossil fuel combustion sources dominate the fine particle emissions in Kandy. Determination of source apportionment has revealed that high traffic volume is responsible for high PAH levels in the urban areas and firewood cooking in rural areas.

Atmospheric particulate matter (PM10) fraction determined from 25 sites in Kandy show that the values exceeded the current 24 h standard of 100 μg/m^3 at 13 of the 25 sites (Elangasinghe and Shanthini, 2008) and these values are also related to traffic density. The highest PM10 concentration of 340 μg/m^{3}was obtained at the Katugastota bridge with a traffic density of 2640 vehicles/h. Moreover, most locations with high traffic congestion had PM10 concentrations in excess of 200 μg/m^3, which is more than twice the air quality standard for PM10. The AQI value for such a high concentration of PM10 is classed as very unhealthy.

People living in urban areas and roadside households are continuously exposed to vehicular emissions. Passengers who travel through high traffic urban areas in public buses with open windows are also exposed to air pollutants from automobile emissions. Premasiri et al. (2015) determined the passenger exposure levels to air pollutants during heavy traffic within the Colombo Metropolitan City. Study results indicate that exposure levels of NO_2 and SO_2 are in the range of 96-550 μg/m^3 and 30-700 μg/m^3 respectively. Suspended particulate matter (SPM) exposure levels were in the range of 400- 850 μg/m^3. All these levels are well above the corresponding levels in ambient air of the region studied. The bus route from Colombo to Gampaha was observed as the highest polluted route, when compared to other routes, where the highest concentrations of SO_2, NO_2 and SPM recorded were 716 μg/m^3, 542 μg/m^3 and 832 μg/m^3 respectively. These values are above acceptable levels and their health effects may be significant.

Pitawela *et al.* (2013) studied indoor air pollution arising from household dust to determine the level of heavy metal pollution in homes located in Colombo and Kandy. The average concentrations of Pb, Cr, Mn, Cu, and Zn were found to be 2.3, 0.8, 191, 2, and 18.1 ppm respectively, in the household dust samples of Colombo city. The average concentrations of the above elements in the household dust of Kandy urban area were 3.5, 0.7, 347, 94.2 and 738 ppm respectively. Fe, Na and Ca concentrations in both cities show higher values; 3.2, 0.3 and 0.05 wt. % respectively, in Colombo and 3.2, 2.8 and 2.6 wt. % respectively, in Kandy. The concentrations of measured elements of Colombo samples are relatively low compared to those found in Kandy though the Colombo city is heavily urbanised. Authors claim that the influence of sea breeze and high humidity may have dispersed these pollutants in Colombo while in Kandy due to the valley effect there is more concentration of the pollutants.

HEALTH EFFECTS OF AIR POLLUTION

Air pollution is a major cause of death and disease globally. An estimated 4.2 million premature deaths globally are linked to ambient air pollution, mainly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children. Worldwide, air pollution accounts for 29% of deaths from lung cancer, 25% deaths from ischaemic heart disease and 43% of the deaths from chronic obstructive pulmonary disease. Pollutants of public health concern are particulate matter (PM10 and PM2.5), SO_2, CO, NO_2 and O_3.Fine particles are now classed as the cause of lung cancer by WHO's International Agency for Research on Cancer (WHO, 2005). While PM10 particles go deep inside the lung and remain there, PM2.5 fraction can enter the blood stream causing cardiovascular, cerebrovascular and respiratory diseases. In Sri Lanka, there are no long-term epidemiological studies carried out to assess the outcome of health effects due to air pollution. Several brief reports on the health effects are available and will be discussed here. The currently available epidemiological studies have been reviewed by Nandasena *et al*. (2013).

Chandrasiri, (2006) has calculated the impact of PM10 and PM2.5 in monetary terms on the health damage as Rs. 9 billion and Rs. 21.8 billion per annum respectively. This study done in 2004 included the cost of investigations, doctor's costs, cost of drugs and other expenditure such as transport, accommodation etc.

The addition of lead compounds to fuel was discontinued in 2002. Still, household dust along main roads contain appreciable amounts of lead. Since the skeleton acts as a reservoir of lead, during pregnancy, lead can enter the blood stream of the foetus. Venous and umbilical cord blood samples of 24 mother-baby combinations from Colombo have been analysed and only one mother-baby combination had no lead in their blood (Senanayake *et. al.,* 2004).After the introduction of unleaded petrol, atmospheric lead levels were reduced by around 80% in the Colombo city (NBRO, 2007). Measurements of blood lead levels in children living in a traffic congested area of Colombo showed (Senanayake *et al.* 2007) that 6% of the children had blood lead levels above 10 µg/dL and in 2003, not a single child had a blood lead level >10 µg/dl.

Senanayake *et al.* (2001) correlated the hospital attendance for wheezing needing nebulizer therapy at the Lady Ridgeway Children's hospital with pollutant levels recorded for ambient air in Colombo in 1998. The highest recorded levels of sulphur dioxide and nitrogen dioxide in ambient air showed a significant correlation with the highest hospital attendance rates, and the lowest pollutant levels with the lowest hospital attendance rates.

Nandasena *et al.* (2012) carried out a longitudinal exposure study on children (n=612) from 2009 to 2010 in urban and semi-urban settings in Sri Lanka. The urban area, in Colombo, reportedly has high levels of ambient air pollution, and the semi-urban area, in Panadura is presumed to have much lower levels of ambient air pollution. PM2.5 was measured in the primary living area in a sub-sample of households (n = 198). Indoor PM2.5 measurements from 132 urban homes showed a mean of 84.4 µg/m^3 and a range of 25.2 µg/m^3 to 620.6 µg/m^3. The 66 rural homes had a mean of 94.4 µg/m^3 and a range of 5.9 µg/m^3 to 755.0 µg/m^3. The highest indoor PM2.5 measurements were reported from homes that burned biomass for cooking in the urban setting (mean of 243.2 µg/m^3 and a range of 40.7 µg/m^3 to 620.6 µg/m^3). It was found that children in the urban area had a significantly higher prevalence of wheezing when compared to those in the semi-urban area.

Another study (Ranathunga *et al.,* 2019) reports on the effect of firewood cooking on the respiratory illnesses of children under 5 years where simultaneous air quality measurements were also carried out. It was found that infection induced asthma was significantly higher in homes using biomass and kerosene as fuels for cooking when compared to the use of LPG for cooking. Houses using biomass had a significantly higher level of CO (mean 2.77 ppm) and PM 2.5 (mean 1.09 mg/m^3) as compared to cleaner cooking where the corresponding values were CO (1.44 ppm) and PM2.5 (0.30 mg/m^3).

Dharshana and Coowanitong (2008) showed that PM10 has the strongest association to bronchitis, emphysema and other chronic obstructive pulmonary diseases in children with a correlation coefficient of 0.717 at 99% confidence. This study attributes that asthma in nearly 20% of patients at the Lady Ridgeway hospital could be due to exposure to high PM10 levels.

Siritunga *et al*. (2006) studied the effects of outdoor air pollution on the respiratory health of school children selected from a rural and an urban area in the Kandy district and correlated the results with the ambient air pollution levels. A total of 510 children from each area was the sample and their respiratory illnesses were recorded using the diary method. Average pollutant concentrations of SO_2, NO_2 and O_3 were three to five times higher in the city school premises compared to the rural area and these can be readily correlated to the respiratory symptoms. Thus, in the city school, occurrence of cough was 1.8 times higher, nasal discharges were 1.4 times higher and throat irritation was 1.8 times higher.

Mistry *et al.* (2004) compared the prevalence of asthma among 13 to 14 year-old children in Galle (n = 1162) where the ambient air pollution is low with children in Chandigarh (n = 575) Children in Galle were at an increased risk for life-time wheezing (Galle-28.7%, Chandigarh-12.5%). Firewood cooking in Galle as opposed to use of cleaner fuels like LPG in Chandigarh may be the reason for this observation.

A study (Perera *et al.* 2007) involving bus drivers, three-wheeler drivers, street vendors and shopkeepers at Ratmalana using passive sampling revealed that bus drivers were the most affected by NO_2 (57.36 µg/m^3) and SO_2 (82.70 µg/m^3). This was followed by three-wheeler drivers (NO_2 - 50.18 µg/ m^3; SO_2 - 78.36 µg/m^3), shop keepers (NO_2 - 54.91 µg/m^3; SO_2 - 63.29 µg/m^3) and outdoor vendors (NO_2- 37.66 µg/ m^3; SO_2 - 35.25 µg/m^3). Also, a high prevalence of respiratory illnesses was reported among bus drivers.

STUDIES ON INDOOR AIR POLLUTION

People spend more time indoors and often indoor air is even more polluted than outdoor air. In Sri Lanka about 78% of the households use firewood for cooking often in congested poorly ventilated kitchens and this constitutes the major source of indoor air pollution. Around 370 chemicals have been identified from wood smoke and Table3 gives some of the pollutants in wood smoke (EPA report).

Indoor air pollution arising from firewood burning stoves is a serious health issue affecting the health of people. WHO has estimated that the number of deaths owing to indoor air pollution in 2004 was 4300 (WHO, 2007) in Sri Lanka. Wood smoke has exceptionally high levels of air pollutants such as CO, fine particles and polyaromatic hydrocarbons such as benzo(α)pyrene, which are known carcinogens. Some studies have reported PM2.5 concentrations as high as 122.3 µg/m^3 in households using firewood compared to 47.3 µg/m^3 where cleaner fuels are used for cooking (Nandasena *et. al.,* 2011). Carbon monoxide causes headaches and the peroxyacyl nitrates cause eye irritation. Both of these are common symptoms experienced by people during firewood cooking. Through years of exposure, this can lead to lung cancer due to the toxic aromatic hydrocarbons. A positive correlation between lung cancer and coal cooking has been reported from the the Xuan Wei county in China (Francesco, 2012). In India, ill-effects of indoor air pollution result in about 2 million premature deaths per year, wherein 44% are due to pneumonia, 54% from chronic obstructive pulmonary disease (COPD), and 2% from lung cancer (Smith, 2000). The most affected groups are women and younger children, as they spend maximum time at home. Children too are affected since they spend more time with mothers in the kitchen. Diseases like pneumonia, bronchitis, asthma and other pulmonary diseases are quite common among these two categories where firewood or other types of biomass are used for cooking.

Table 3: Pollutants produced during the combustion of 1 kg of wood.

Pollutant	Amount produced
Carbon monoxide	80-370 g
Benzene	0.6-4.0 g
Acetic acid	1.8-2.4 g
Lead	0.1- 3.0 mg
Anthracene	20-50 μg
Phenanthrene	20-3400 μg
Benzo(α)anthracene	400-2000 μg
Dibenzoanthracene	20-2000 μg
Benzofluoroanthracene	400-2000 μg
Benzo(α)pyrene	300-5000 μg

There is a large body of evidence (Elledge *et al.*) that indoor air pollution (IAP) from biomass fuel use is a major cause of premature deaths, and acute and chronic diseases. The biomass use in Sri Lanka is limited to wood while coal, charcoal, and cow dung are not used as in India. Some studies have been conducted in Sri Lanka in an attempt to associate biomass fuel use with cataracts, low birth weight, respiratory diseases and lung cancer (Nandasena *et al*., 2010).

In addition to firewood, a common source of fine particles is burning mosquito coils and incense sticks inside homes. Mosquito coils are used by 2 billion people worldwide and 12 billion coils are used every year. The composition of a typical mosquito coil has pyrethroids, coal dust/coconut husk, binders and resins. Liu *et al.* (2003) reported that burning one mosquito coil generates the same amount of PM2.5 as around 100 cigarettes and the emission of formaldehyde is equivalent to burning 50 cigarettes. In addition, the levels of polyaromatic hydrocarbons are high enough to affect the health of people. Even at trace levels, long-term exposure to these compounds could increase cancer risk. Benzo[a]pyrene, benzo[b]fluoranthene, and benzo[k]fluoranthene were detected in the particulate phase of mosquito coil smoke. Burning incense sticks inside homes is unhealthy and they produce a lot of fine particles and also polyaromatic hydrocarbons*,* benzene, and CO.

In the last few years, there is concern about microplastics present in both outdoor and indoor air, which is the latest air pollutant. These are typically defined as particles which have sizes from 1 μm to 5 mm in length and include even very small nanosized particles (Fries and Nash, 2019). Over time, microplastics accumulating in our lungs begin to damage the air sacs (alveoli) of the lungs. This can increase the risk of developing lung conditions like emphysema and lung cancer.

Although the definitive health effects of microplastics have not been investigated so far, some of the smallest microplastics with sizes <2.5 μm (PM2.5) can even enter the blood stream. These can contribute to hardening of arteries (atherosclerosis) and may result in heart diseases. Some of these microfibres can carry dangerous pollutants like polycyclic aromatic hydrocarbons to the body which can lead to cancer.

STUDIES ON HEALTH EFFECTS OF INDOOR AIR POLLUTION

Use of firewood in kitchens is a major risk factor for respiratory diseases. In one study (Lankathilaka *et al.,* 2000) of a Colombo suburb, it was found that the average TSP level in houses using firewood was 0.606 mg/m^3 and in houses not using firewood was 0.245 mg/m^3. The respirable dust concentration exceeded the WHO standards in 84% of households using firewood and 54% of the households not using firewood. There is a direct correlation between these two types with the respiratory symptoms of inhabitants.

Karunasekera *et al*.(2005) carried out a school-based cross-sectional study of asthmatics (n = 441) and non-asthmatics (n = 1510) in the Gampaha district and reported that the presence of firewood smoke in the bed room during cooking (OR 1.4, 95% CI 1.1-1.9), use of mosquito coils (OR 1.5, 95% CI 1.2 - 1.9), and a dusty environment (OR 1.8, 95% CI 1.4 - 2.3) significantly increased the risk of asthma. The exposure assessment was carried out using a questionnaire, but no air quality in the home environment was measured.

Ranasinghe and Mahanama (2004) reported an association ($p < 0.05$) between exposure to kitchen smoke and cataract by comparing cataract patients (cases, n = 197) with patients with other eye problems (controls, n = 190) admitted to the National Eye Hospital, Colombo. Results were based on a questionnaire and no air quality measurements were made.

Pathirane and Mahanama (2006) carried out a cross-sectional study and reported that the availability of a separate kitchen (OR = 2.7, 95% CI = 1.6-4.7), using less clean cooking fuel (OR = 3.9, 95% CI =1.8 - 8.5) and not having adequate ventilation in the cooking area (OR = 2.7, 95% CI =1.3 - 5.3) were significant predictors of low birth weight in the Kegalle and Kalutara districts.

OCCUPATIONAL HEALTH STUDIES

Fine particles produced from industries and their effects on health have not received much attention. Siribaddana *et al.* (2013) studied the influence of quartz dust from a quartz crushing factory in the Kandy district. Silicosis is a well-recognised pneumoconiosis associated with exposure to silica dust. Silicosis can be fatal, and workers should wear appropriate protective wear during work. Out of 250 employees 25 (10%) had respiratory symptoms. Chest X-rays of 14 workers (5.6%) showed abnormalities suggestive of silicosis. One worker had X-ray changes suggestive of progressive massive fibrosis.

BIOMONITORING OF AIR POLLUTION

Some plant species are sensitive to specific single pollutants or to mixtures of pollutants. They have the great advantage to show clearly the effects of phytotoxic compounds present in ambient air. Mosses and lichens accumulate heavy metals and other compounds very efficiently because of their large specific surfaces and slow growth. As such, they serve mostly as passive biomonitors to provide an indication of the pollutant impact at the ecosystem level. Lichen diversity, in particular, has been used as an indicator of air pollution levels and accumulation of pollutants in its phallus indicates the degree of air pollution. There is increasing interest in developing bioindicator plants to assess the level of air pollution and biomonitoring with plants is a low-cost effective method to estimate level of air pollutants and their impact on biological receptors. For example, injury on Bel-W3 tobacco plant (*Nicotiana tabacum L.*) is usually the first indication that a region has developed an ozone problem (Mulgrew and Williams, 2000).

Attanayake and Wijeratne (2013) studied the lichen diversity of corticolus (tree bark lichens) and correlated it with the SO_2 and NO_2 levels in air. A negative correlation was found to exist between the lichen diversity expressed as Index of Atmospheric Purity (IAP) and the concentrations of SO_2 and NO_2 levels at the study sites.

The Index of Atmospheric Purity (IAP) value obtained for the whole area of the Horton Plains Nature Preserve was 54.22 which implies that the lichen diversity is high, and the air pollution is low (Jayalal *et al*;2017). Air quality determination using passive samplers showed low levels of SO_2 and NO_2. The lowest IAP value of 28.3 was recorded where the SO_2 concentration is the highest. These results demonstrate the application of IAP as a measure of air pollution which is a cheaper and a simpler method to estimate air pollution. Air pollution levels were found to be high during the south-west monsoon and this is due to pollution clouds moving inland from highly urbanised areas of the western province. The high diversity of lichens and the minimum levels of air pollutants suggested that the forest health of HPNP is at a favourable level.

EFFECT OF AIR POLLUTION ON VEGETATION

While there is an abundance of work carried out on the effects of air pollution on humans, there is relatively little work done on the effects of air pollution on vegetative crops, forests and vegetation. Air pollution affects plants mainly through the uptake of pollutants into the leaves through stomata. Sulphur dioxide and ozone are the two most important air pollutants which affect plants (Emberson *et al.,* 2004). In general, short term exposure to sulphur dioxide promotes stomatal opening while long term exposure can cause partial closure. By contrast, the effects of nitrogen dioxide are often small or insignificant. In the case of ozone, which is a strong oxidant, short term exposure stimulates a rapid reduction in stomatal aperture while longer term exposure causes stomatal response to become sluggish. In the only study from Sri Lanka, Abeyratne and Ileperuma (2006b) studied the effects of air pollution and ozone on common vegetables using a two compartment growth chamber where one chamber was supplied with purified air while the other was exposed to ambient air. In the ozone experiment, purified air was mixed with ozone using an ozone generator. The effects on plant height and dry weight were measured. The results show clearly that those growing in the chamber with filtered air show healthier growth. Visible symptoms observed during the experiment can be categorised into eight symptom groups: stippling, yellowing, browning, reddening, malformation of leaves, stunting, elongation of stem and leaf abscission. Young plants of all species were more sensitive to ozone than mature plants. However, in all plants examined, mature leaves were first affected and further exposure to ozone resulted in leaf abscission followed by plant death.

The impacts of air pollutants on stomata are complex and vary depending on a wide range of factors. To determine the pollutant effects on stomatal opening, attempts were made (Abeyratne and Ileperuma, 2006c) to observe the stomatal response under different pollutant concentrations. Nail varnish method was employed to observe the stomatal pore size in *Argyreia populifolia* leaves at three sampling sites with different pollution concentrations. Sampling was carried out during a six-month period. Hourly variations of SO_2 and O_3 were measured using the active sampling method. Mature leaves exhibited significant variations in the pore widths at the three sites depending on the SO_2 concentrations. Stomatal movement in young leaves is less affected by the SO_2 concentrations. This method gives a low-cost rapid method to assess air pollution in localised points.

CONCLUSIONS AND FUTURE DIRECTIONS

The quality of air we breathe, determines not only the health of the lungs, but also of other organs in the body. Increased vehicle population and the absence of a satisfactory road network to cater to this increase has considerably increased the air pollution levels in major cities. Regular monitoring of air quality can give an assessment of the quality of the air we breathe but the number of automated air quality monitoring stations is woefully inadequate. Indoor air pollution should receive more attention since it can affect the health of people who use firewood for cooking. People exposed to diesel smoke are at the risk of developing cancer. The health costs of increased pollution are also considerable, and this can exceed the costs of taking steps to improve the road infrastructure. Improvement of the public transport system is the most efficient method to tackle vehicular pollution. Media have an important role in educating the public about the dangers of both indoor and outdoor air pollution.

There is an urgent need to carry out more epidemiological studies to correlate air pollution levels with illnesses. Adequate measures to protect people from adverse effects of air pollution such as wearing face masks should be promoted. The determination of microplastics in air is also an additional area for future research.

Proposed Clean Air 2025 action plan aims to reduce urban, industrial and indoor air pollution and maintain air quality at desirable levels. This has identified a comprehensive plan to be achieved through an effective stakeholder participatory mechanism and ensuring source identification, quantification and monitoring of harmful air pollutants along with an appropriate regulatory framework. Further, it recognises the need for research and development and capacity building in air quality management (AQM) assisted by sub-regional, regional and global linkages.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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