Extent of air pollution in Kandy area, Sri Lanka: Morphological, mineralogical and chemical characterization of dust

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Highlights

- Chemistry, mineralogy and morphology of natural dust are altered due to the anthropogenic influences.

RESEARCH ARTICLE

Extent of air pollution in Kandy area, Sri Lanka: Morphological, mineralogical and chemical characterization of dust

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Abstract: Dust is one of the most common sources of air pollution in cities, providing a considerable health risk. Kandy, Sri Lanka, has been declared as a UNESCO World Heritage Site. As a result, a study into causes of air pollution in Kandy and its environs is urgently required. We examined the composition of dust particles collected from the city and suburbs to determine the degree of particulate pollution. The abundance of particles and materials in various phases has previously been quantified in one dimension in an idealized sphere. The morphological examination of particulate matter is usually ignored. Eighteen road and thirteen household dust samples collected in the Kandy Municipal area were analyzed for elemental concentrations, as well as for mineralogical and morphological characteristics. Higher Ca, Zn, and Cu concentrations in the samples indicate anthropogenic (construction industry and traffic activities) influences on the dust. Mineralogically, fine and coarse dust fractions are dominated by clay minerals and quartz with feldspar. The majority of fibrous materials in dust are coated with secondary matter, resulting in short suspension duration in the atmosphere and, as a result, a reduction in the harmfulness of the fibers. In terms of mineralogy, morphology, and chemical properties, road and household dust samples are nearly identical. Despite the fact that dust is primarily derived from soil, its composition has been altered due to anthropogenic influences such as transportation and construction activities. As a result, dust containing clay particles can be regarded of as a fluxing and heavy metal accumulation medium. Although fibers have minor influence on human health and the environment, heavy metals have a significant impact. Though industrial and transportation activities in Kandy are remarkably low when compared to those in other major cities in Sri Lanka and megacities around the world, pollution levels in the city are comparably high. To reduce the vulnerability of the current pollution condition of the city, appropriate, long-term strategies for construction and transportation activities are required.

Keywords: Kandy; dust; heavy metals; fibers; urban environment.

INTRODUCTION

Dust is one of the most common air pollutants, derived from the interaction of solid, liquid, and gaseous materials produced by both natural and artificial processes (Banerjee, 2003). The decline of air quality in urban areas around the world has been one of the key challenges in recent decades.

As air quality deteriorates, many emerging countries face several environmental issues (Bhaskar and Mehta, 2010). Dust contributes significantly to fine particulate matter (PM) emissions (Wang *et al.*, 2005; Wang *et al.*, 2011).

Dust is a heterogeneous mixture of organic, inorganic, and biological particles that come from a variety of places. Natural sources of dust include weathering, erosion, and redistribution of adjacent soil, seawater spray, atmospheric wet and dry deposition, and natural rock dust. Transportation-related activities such as vehicular emissions and abrasion-induced wear of tires, brake pads, and other vehicle parts, as well as industrial and domestic activities, are the anthropogenic sources of dust (Chang *et al.*, 2009; Bhaskar and Mehta, 2010; Gupta, 2020). Coal and other fossil fuel-fired power stations, mining activities, the cement and lime industries, and construction activities all contribute to the secondary dust particle formation process.

After being released into the environment, dust particles may stay in the air for some time before settling and accumulating on surfaces. The morphological characteristics of dust particles, such as size, shape and aerodynamic diameter; environmental factors, such as climate, wind speed and direction; and anthropogenic factors, such as land use patterns and vegetation cover, all influence dust distribution and behaviour in the atmosphere (Kim *et al.*, 1998; McDonald and Biswas, 2004; Pereira *et al.*, 2007; Pey *et al.*, 2008).

As a result of rapid development in the last few decades, human activities that lead to changes in dust distribution in urban areas have resulted in substantial land use degradation in developing countries (Kim *et al.*, 2013). Dust poses a serious threat to the health of the urban population (Bosco *et al.*, 2005). In consideration of the health effects of dust, there are no safe threshold limits below which the health effects do not occur (WHO, 2017). After entering the body, both coarse and fine particles produce health impacts, further, finer particles are more hazardous since they can penetrate deep into the lung tissues. (De Costa, 2008; Wang *et al.*, 2016; Gope *et al.*, 2017). Dust pollution has been linked to an

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increase in chronic obstructive pulmonary disease, asthma, pneumonia, cardio-respiratory disease and respiratory-related disorders. (Balachandran *et al.*, 2000; Pope and Dockery, 2006; Brunekreef *et al.*, 2009; Boldo *et al.*, 2011).

Emission sources, atmospheric chemical processes, and climatic variables all have a role in dust generation and distribution (Harrison, 2006; Garland *et al.*, 2008). Due to its complexity, dust can cause a number of chemical reactions that result in secondary compounds (Chen *et al.*, 2006). Other contaminants can be carried by dust particles and physiochemical properties such as the nature, size, and surface roughness of various minerals and organic compounds determine their pollutant capability (McBride, 1994; Butte and Heinzow, 2002). Anthropogenic particles can also combine with mineral components to form unique combinations, which impact the distribution and behaviour of dust.

Due to differences in mineral solubility, lead in galena (PbS) is less accessible than lead in carbonate (PbCO₃) (Casteel *et al.*, 2006). The morphology of dust particles can be utilized to characterize behaviour, identify sources, creation mechanisms, climatic conditions, travel distance from the source and their potential health consequences (Ličbinský *et al.*, 2010).

The majority of urban environments of Sri Lanka are densely populated areas with significant levels of anthropogenic activity. The dispersal of dust is more affected by unplanned land use patterns and significant traffic congestion in cities. UNESCO has designated Kandy as a World Heritage City. As a result, it is essential to analyze the mode of air pollution in Kandy and its environs. In comparison to other cities in the country, it features unique urban and climatological surroundings.

The wind flow and circulation, in particular, differ from those in other major Sri Lankan cities (Pitawala *et al.*, 2013). The basin-like and bottleneck geomorphology of the city operate as obstacles to wind flow, which prefers to cycle within the metropolitan area. This may result in an increase in the gathering of air pollutants such as dust particles and heavy metals, which may stay in the air for prolonged periods of time due to a lack of space to blow them out, finally settling in the urban region (Abeyratne and Ileperuma, 2006; Weerasundara *et al.*, 2017). Despite the fact that Kandy has a unique environment in comparison to other cities, only a few studies on dust have been conducted (Pitawala *et al.*, 2013; Weerasundara *et al.*, 2017).

The morphologic evaluation of particulate matter is often neglected, despite the importance of dust morphology. This study is a new approach to understanding air pollution in the urban environment of Kandy city. Hence, a comprehensive characterization based on mineralogy and morphology of dust along with chemical studies has been carried out to get a better understanding of the possible sources, distribution patterns and levels of the urban dust. It would also be useful to introduce appropriate pollution prevention methods for the long-term development of urban ecosystems. Therefore, the major objective of the

present study was to understand the factors influencing the accumulation and distribution patterns of the urban dust, based on the mineralogical, morphological and chemical characteristics.

MATERIALS AND METHODS

Study area

The city of Kandy is the second most commercially important city in Sri Lanka, extending over an area of 26 km² with an urban population higher than 100,000 (Census, 2012). Kandy lies at an elevation of 500 m from mean sea level and belongs to the tropical rainforest climate. The study area has an average annual rainfall of nearly 1500 mm with an average annual temperature of 24.5 °C. The average annual percentage of humidity is 84.0%. The wind direction and speed are primarily controlled by the monsoonal conditions (Department of Meteorology, 2017). However, the wind circulation in the city is high as it is located in an area that shows a basin-like morphology which act as a barrier to the movement of the wind (Weerasundara *et al.*, 2017; Dissanayake *et al.*, 2019). Precambrian metamorphic rocks are underlying the setting of the Kandy and it is located in the Highland Complex (HC) of Sri Lanka. The major bedrock types found within the area comprise biotite and hornblende bearing gneisses, charnockitic and granitic gneisses as well as calcsilicate gneiss (Cooray, 1994; Kehelpannala, 2003).

Around 350,000 people are entering to the city in a daily basis, comprising about 90,000 for employment and over 60,000 for schools. The total vehicle entry level to city has increased to 56,000 vehicles per day and has a growth rate of 5% per annum (Kandy City Transport Study, 2011). As the city is located in a narrow valley, higher traffic congestion in the city is observed with high quantity of vehicles travelling within a small area at a very low speed. And also, buses are racing on first gear, stopping at all bus stops for a long time (Premasiri *et al.*, 2012).

Sample collection

A total of 31 dust samples were collected including 18 road dust (R) and 13 household dust samples. Sampling was done in 2019 during the dry period as the rain fall results in wash-off process which could lead redistribution and removal of the available road dust in the surfaces (Egodawaththa *et al.*, 2007). Road dust samples were collected within the center of the city and in the surrounding commercial areas with high traffic intensities where traffic lights are in the vicinity. Road dust samples were collected by sweeping the road surface using a plastic brush and a dustpan and collecting the dust into sealed polythene sample bags. Household dust samples were collected from selected residential neighborhoods of the Kandy urban area. These areas had higher elevations and lower traffic conditions as compared to the areas where road dust samples were collected. Dust gathered on window panels and top of other furniture in abandoned houses was also collected following the same procedure used to collect road dust samples. The dustpan and plastic brush were washed

using methanol after collection of dust at each location to minimize contaminations.

Chemical, mineralogical and morphological analysis

A portion of dust were first weighted and treated with 70% hydrogen peroxide (H_2O_2) for removal of the organic matter and set aside until the bubbling was over. When there were no more bubbling, the samples were washed by water and oven dried for 24 h in 105 °C. The samples were weighted and the difference in the weight was taken as the organic matter content. Organic matter contents were calculated as weight percentage of the initial dry weight.

Approximately 0.2 g of each sample was accurately weighed and digested for heavy metal analysis using aqua regia [3:1 HCl (34%) / HNO_3 (69%), v/v]. The extracts were analyzed by flame atomic absorption spectrophotometry (AAS-Perkin Elmer, Model 2380) to determine the total concentrations of Zn, Cu, Ni, Fe, Mn, Pb, Na, K, Ca and Mg. Calibration control standards were used for the linear calibration.

Table 1: Detection limits of the heavy metals in AAS.

Element	Detection Limit (mg L ⁻¹)
Pb	0.029
Cu	0.004
Mn	0.011
Zn	0.002
Ni	0.004

Mineralogy of the samples was studied under an optical reflection microscope (Nikon) at the Mineralogy Laboratory, Department of Geology, University of Peradeniya. Magnetic material was separated using a hand-magnet. The magnetic material content was calculated as a percentage.

Scanning Electron Microscope (SEM), model Zeiss EVO LS 15 was used to study the size variations, sorting of particles, shapes of the particles, surface features and to detect the presence of fibers. In the sample preparation for the SEM analysis, samples were placed on carbon plaster to coat with 20 nm thin layer of gold (Au) and palladium (Pd). The Energy Dispersive X-ray spectroscopy (EDX) which was equipped with the SEM was used in the study of the elemental composition of the appropriate fibers and magnetic grains and grain surfaces.

Assessment of the heavy metals

Enrichment Factor (EF)

The following equation was used to calculate the EF of the heavy metals (Kantor *et al.*, 2018).

$$EF = [x/Fe]_{\text{Sample}} / [x/Fe]_{\text{Upper Continental Crust (UCC)}}$$

where, x is the concentration of the element. In the present study, iron (Fe) was used as the normalizing element, since Fe has a relatively high natural concentration, and

further, it is not expected to be substantially enriched from the anthropogenic process and sources (Abraham and Parker, 2008). UCC values of elements were obtained from Rudnick and Gao (2005) for the comparison. The following classification from Barbieri *et al.* (2015) is given for the EF (Table 1).

Table 2: EF categories (Barbieri *et al.*, 2015).

Value	Soil dust quality
EF < 2	Deficient to minimal enrichment
2 < EF < 5	Moderate enrichment
5 < EF < 20	Significant enrichment
20 < EF < 40	Very high enrichment
EF > 40	Extremely high enrichment

RESULTS AND DISCUSSION

Organic matter content

Higher organic matter contents in road dust were mainly found in samples collected near road junctions, areas of high traffic intensity and areas around traffic lights (Figure 1). Wind is the main natural factor of the transportation of dust particles and consequently, road junctions act as a barrier to smooth wind flow. Therefore, dust that transport with wind tends to deposit in the vicinity of the junction. Vehicle movement is one of the main factors that contribute the production of road dust. The shearing action between the tyre and the road surface creates loose materials that are then transported into the air by the turbulence caused by the movement of vehicles. Vehicles are subjected to constant starting and stopping with breaks in locations with high traffic intensities or traffic signals, resulting in increased shearing activity and intensive dust particle formation. The organic materials in the dust produced by such actions are concentrated with tyre materials, road particles such as bitumen and soil organic matter. The turbulence created by movement of vehicles would not be adequate to lift and transport the generated coarse dust particles since the momentum of vehicles is minimal. Thus, the organic stuff in road dust formed by shearing will be deposited in situ. Organic materials made up of functional groups, such as COO-, would create complexes with heavy metals that are more bioavailable than the metal itself (Alloway, 1995). The organic matter content of road dust in the study area (Table 2) is higher than that of road dust in the Colombo metropolitan area (CMA), Sri Lanka (Herath *et al.*, 2015), Delhi, India (Shandilya *et al.*, 2013), West Midlands, United Kingdom (Shilton *et al.*, 2005) and Manchester, England (Robertson *et al.*, 2003).

Magnetic material content

Samples with high concentrations of magnetic material were typically found in samples obtained from major highways with heavy traffic congestion (Figure 2). This suggests that there is a correlation between magnetic material abundance and traffic congestion (Spasov *et al.*, 2004). The sample location closest to the railway station

Figure 1: Map showing the distribution of organic materials in the study area.

Figure 2: Map showing the distribution of magnetic materials in the study area.

has higher concentrations of magnetic materials. High magnetic material concentration samples were typically found in those obtained from main highways with heavy traffic congestion (Figure 2). This indicates that there is a relationship between magnetic material abundance and traffic congestion (Spassov *et al.*, 2004). The sample location closer to the railway station has higher concentration of magnetic material. According to Moreno *et al.* (2015) the high value obtained in this area is mostly attributable to the creation of magnetic material in the abrasion of sliding and wear at the brake-rail wheel and rail wheel-rail interfaces. The high turbulence caused by train movement is mainly responsible for particle transport. Corrosion of trains that have been stationary for a long time may also result in high concentrations of magnetic material.

Chemical characteristics

Calcium (Ca), followed by Fe, is the most abundant element in both road and domestic dust samples. In both types of samples, the heavy metal concentrations are in the following order: $Zn > Mn > Cu > Ni > Pb$. Except for Cu, all heavy metals are higher in road dust than in residential dust (Table 3). In both road and residential dust, key element concentrations change in the order $Ca > Fe > Mg > K > Na$. Iron (Fe), Cu and Zn concentrations are higher in residential dust than in road dust.

Despite the low concentrations of Na, Mg, K and Mn (Table 3), they are comparable with the background values, and can be considered as derived from natural processes. The concentrations of these metals are low due to the mixing

of other materials derived from anthropogenic sources. Even though Fe is found in low concentrations compared to the background levels, high anthropogenic influence can be attributed to the presence of magnetic materials in the dust. However, Ca shows higher enrichment with respect to the background levels (Table 3). The presence of high Ca concentrations may be due to the construction process, as destruction of existing structures can release enormous amounts of dust into the environment (Guttikunda and Goel, 2013).

Zinc (Zn), Cu, Ni and Pb can be considered as anthropogenically derived metals as they have much higher measured concentrations compared to the background values (Table 3). There must be anthropogenic inputs of

these metals to possess such higher levels of concentrations in the road and household dust. It indicates that chemical composition of the naturally derived dust has been altered due to the anthropogenic influence.

The present study reveals that Kandy has higher concentrations of Zn, Cu, Fe and Mn (Table 4). The elements, Zn and Cu, in road dust could be derived mostly by vehicular emissions (Charlesworth and Lees, 1998; Al-Khashman, 2007). Even though Colombo and other megacities in the world have significantly higher traffic activities, industries, construction activities and population density, concentrations of Zn, Pb and Cu in dust are comparably lower than those of Kandy city (Table 4 and 5). The atmospheric deposition shows comparable values with the

Table 3: Organic matter and magnetic material contents in the road and household dust.

Sample type	Organic matter content			Magnetic material content		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Road dust	29.06%	4.63%	15.04%	5.89%	2.41%	4.25%
Household dust	21.60%	8.26%	15.50%	6.75%	3.48%	4.79%

Table 4: Concentrations of major and heavy metals (mg/kg) of samples studied.

Major metals	Road dust		Household dust		Background
	Range	Average	Range	Average	
Mg	5,160 - 12,182	8,909	6,876 - 11,301	8,547	11,000
Na	772 - 2,213	1,202	428 - 1,962	1,140	26,500
K	1,323 - 6,032	3,113	2,501 - 6,035	4,364	13,000
Fe	27,772 - 50,074	36,704	29,991 - 63,052	40,347	86,000
Ca	20,879 - 127,596	50,706	22,768 - 107,949	45,164	27,200
Heavy metals					
Pb	15 - 126	49	22 - 72	40	25
Cu	235 - 447	319	299 - 409	352	11
Mn	403 - 724	541	451 - 578	507	800
Zn	236 - 1,557	775	406 - 3065	783	68
Ni	252 - 364	305	245 - 330	300	50

Table 5: Comparison of mean concentrations (mg kg⁻¹) of heavy metals in dust in different cities in Sri Lanka.

Study	Area	Type	Zn	Cu	Pb	Fe	Mn
Pitawala <i>et al.</i> , 2013	Colombo	Household	18.1	2	2.3	32000	191
	Kandy	Household	738.9	29.8	3.5	39000	145.9
Herath <i>et al.</i> , 2015	Colombo	Road	476	174	71	29268	689
Priyadarhana <i>et al.</i> , 2015	Colombo suburbs	Road	284.01	101.86	34.39	NA	NA
Weerasundara <i>et al.</i> , 2018	Kandy	Atmospheric deposition	1116.9	123.6	234.4	13774.9	273.6
This study	Kandy	Road	775	319	49	36704	541
	Kandy	Household	1113	352	40	40347	507

dust samples, proving atmospheric deposition contribution to the presence of heavy metals of dust in the study area (Table 4). It also proves that the suspended particles only disperse over the urban area and deposit within the city itself due to the basin-like geomorphology of the area. However, the suspended dust particles in the Colombo city may disperse over a large area and reduce the concentration of accumulation with the wind flow and the higher wind velocities due to its geographical location near the coast (Pitawala *et al.*, 2013).

Sources of heavy metals

As Zn is used as a vulcanization agent in vehicle tyres (Alloway, 1990), the higher wearing rate and corrosion rates in high-temperature tropical areas, such as Kandy, may contribute to the high Zn content in the dust (Li *et al.*, 2001). Furthermore, due to the morphological conditions of the study area, the sharp bends and steep slopes of roads may exacerbate tire wear (Pitawala *et al.*, 2013). Usage of Zn in alloys, parchment papers, glass, dry cell batteries and electrical apparatus may also contribute to the higher content of Zn in household dust (Adriano, 1986). Moreover, food wastages containing higher levels of Zn would contribute to higher levels of Zn in the dust.

The sources of copper (Cu) in the road dust could be corrosion of metallic parts of cars derived from engine wear, thrust bearing, brushing and bearing metals (Al-Khashman, 2007). Contamination of Cu in the household dust is influenced by the general condition of the house such as, distance from the road, level of traffic and cleaning habits (Ibanez *et al.*, 2010). The main source of Pb could be pigments present in paints. The white and the yellow lines marked on the road using paint are subjected to intense alteration of conditions in the study area due to the tropical climate. In addition, vehicles tend to cross white lines with higher friction in sharply curved bends may cause higher Pb value in the area. Another potential source of Pb pollution in the environmental samples including dust is the combustion of gasoline that contains tetraethyl lead as an anti-knock agent (Tuzen, 2003). Although leaded gasoline is not being used, at present, in Sri Lanka, Pb released when it was used earlier is still in the sediments and is circulated within the Kandy area because of its basin-like morphology. Also, the Pb levels may have been influenced by the usage of lead-based paints which consist of lead chromate (yellow

pigments) and other Pb pigments. Further, Ni pollution on local scale is caused by emissions from vehicle engines that use nickel gasoline and by the abrasion and corrosion of Ni from vehicle parts (Al-Kashman, 2007).

Assessment of heavy metal levels

When considering at the overall distribution of heavy metals, samples collected from heavily trafficked places (R4, R8, R11 and H4), the main bus station (R14), train station (R15) and an abandoned construction site (H3) indicate higher values of all heavy metals (Figure 3).

EF (enrichment factor) values, which are used to evaluate anthropogenic input and pollution degree, reflect the degree of heavy metal pollution in an area (Yang *et al.*, 2016). Higher EF values of all the heavy metals were identified in R7, R8, R11, R14, R15, R18, H3 and H4 sample locations (Figure 4). These locations are in places with high traffic congestions. Heavy metals, which have $EF > 10$, were always believed to derive from human activities (Yang *et al.*, 2016).

Highly significant Pearson correlation values (> 0.6) were found between Cu and Zn, Cu and Pb, Pb and Ni, and, Zn and Pb. All these correlations between sample locations and between heavy metals show that the origin of the metals in the investigated area is highly related to the transport activities.

Mineralogical characteristics

Modal mineralogical analyses of coarse fraction of dust ($> 75 \mu\text{m}$) reveal that the samples are dominated by quartz (36%) and opaque minerals (Figure 5). Minor amounts of calcite are also present, which may be either naturally derived or secondary products from construction materials. The fine fraction of the dust samples is dominated by clay minerals.

Mineralogy of the soils of the study area differs from the underlying bed rocks since the ferromagnesian minerals except mica have been subjected to intense weathering due to tropical climatic conditions (Pohl and Emmerman, 1991). Despite the presence of iron oxide minerals of the bed rocks as accessory minerals, their content in the dust is relatively high. It may be due to their resistance

Table 6: Comparison of mean concentrations (mg kg^{-1}) of heavy metals in dust in mega cities of the world.

Study	City	Pb	Zn	Cu
Wang <i>et al.</i> , 1998	London	897	1866	300
Nazzal <i>et al.</i> , 2014	Toronto	182.8	232.8	162.2
Chattopadhyay <i>et al.</i> , 1999	Sydney	389	657	147
Suryavanshi <i>et al.</i> , 2016	Delhi	120	284	191
Kim <i>et al.</i> , 1998	Taejon	52	214	57
This study	Kandy	49	775	319

to weathering. However, some iron fragments from the metallic materials also appeared as iron oxide minerals.

There is no significant difference in the mineralogical composition between the two different dust samples (Figure 5). This indicates that the factors including geographical location, land use, nature of traffic and antecedent during the dry period affect the composition of dust particles (Amato *et al.*, 2011). However, the mineral composition of the dust samples does not depend on their location.

Anthropogenic influence on the percentage of the mineral and other inorganic solids in both types of samples is not considerable, and both types of samples may have derived from soil of the basement of the area (Xie *et al.*, 2000). The modal percentage of the minerals of the samples is in the range of 70% to 85% and they are common rock forming minerals of the study area. Most of these particles are covered by fine dust particles rich in organic matter that have been released from anthropogenic sources. Poor sorting, high degree of angularity in the particles, presence

Figure 3: Maps showing the distribution of heavy metals (Zn, Ni, Pb and Cu) in the study area.

Figure 4: Variation of EFs of different heavy metals in the both road and household dust samples studied.

Figure 5: Average percentages of mineralogical and anthropogenic components of (A) road and (B) household dust samples.

Figure 6: SEM image of (A) porous nature of the surface coating of the fibers in the road dust samples, (B) surface coated cloth fibers which the fibrous nature has been disappeared, (C) fracturing of the surface of a fiber in the sample, (D) the aggregate which contain the materials derived from biological materials; roots and pollen.

of fresh or slightly weathered feldspar and chlorite suggest that the dust samples have been transported for short distances.

Morphological characteristics

According to SEM investigations (Figure 6), dust particles are in a variety of sizes and shapes. The dust particles of all types of samples are covered by surface coatings (Figure 6A). As a result, the fibrous nature of some particles has been changed (Figure 6B). The surface coatings of the particles

may have occurred due to the high atmospheric humidity that can increase adhesiveness of the particle surface due to the capillary effect (Kollensperger *et al.*, 1999). Capillary water can retain in particles, and it will tend to attract and react with finer particles forming the surface coating. Fibers of household dust have lower surface coating, than those in road dust samples. It may be due to low capillary water in such type of dust. The SEM / EDX data showed the presence of high C and O in the fibrous materials and on the surface coating indicating the organic origin of the

fibers. Irregular anhedral and subhedral mineral particles and clusters of particles (Figure 6D) may have originated from natural sources (Furutani *et al.*, 2011) and the aggregates may have formed due to adhesive and cohesive nature of water. However, particles having smooth surfaces (e.g. mica) contain lower content of coating compared to those having rough surfaces. The reason for this may be the adhesion forces that are higher on rough surfaces than on flat surfaces (Shi *et al.*, 2015). Naturally derived particles tend to have smooth surfaces, while particles derived from anthropogenic processes have a rough surface. Therefore, naturally derived particles have lower thickness of surface coating while anthropogenically derived particles have thick surface coating. Particle aggregates could be identified as the particles that were cemented together by cementing materials such as organic matter, calcite or salt (Meza-Figueroa *et al.*, 2016). Some aggregates were bound together by fibrous grains. These aggregates were concentrated with fibers, mineral particles, anthropogenic particles and some particles with a biological origin (Figure 6D).

In addition to the porous nature of the surface of the particles (Figure 6A), breaking of the mineral grains were observed through their cleavage planes (Figure 6C). This indicates a low level of stress during the collision between grains, grains and roads and grains and vehicles. Further, the surfaces of fine grains have been subjected to abrasion. The surface coatings of the flat and smooth surface particles are lower than that of the rough surface particles.

CONCLUSIONS

Characterization of particles of both household and road dusts of the Kandy urban area indicates that both types do not differ much in terms of mineralogy, morphology and chemical composition. Concentrations of Ca, Cu and Zn are significantly higher than the background levels. High concentrations of Ca indicate that construction activities of buildings contribute much to the chemical composition of dust. The particles in the atmosphere are deposited after short residence time and transportation due to the wind circulation of the urban area. The tendency for the suspension of fibrous materials gradually decreases due to the coating of finer particles observed on their surfaces.

Even though dust is primarily originated from soil, it had been altered by anthropogenic and natural processes, such as traffic emissions, construction processes, and wearing and weathering of man-made materials. Further, dust particles can be considered as a fluxing agent and storing sites of heavy metal, as they consist of considerable amount of clay minerals derived from the soil. Alteration processes, such as, incorporation of the heavy metals and formation of the surface coating turns the primary particles, into secondary particles.

Natural conditions, mainly the underlying geology and climatic conditions, have masked the anthropogenic influence on the chemical, mineralogical morphological characteristics of both road and household dust in the Kandy urban environment. Therefore, interpretation of the

dust pollution processes in the area by human interaction is complicated.

In the development projects for Kandy, measures should be taken to reduce the traffic congestion within the city as well as the number of vehicles entering the city, to improve the quality of life in urban population and city dwellers, and to build a sustainable city.

RECOMMENDATION

Plastics and microplastics were identified to be the most common sources of fibrous materials in the dust studied. Future research on microplastics in dust should be conducted to gain a better understanding of the current state of air pollution and its impact on human health.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest in preparing this article.

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