Do the Street Sweeping and Washing Work for Reducing the Near-ground Levels of Fine Particulate Matter and Related Pollutants?

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ABSTRACT

This research focuses on the properties of near-ground fine particles (PM$_{2.5}$), ultrafine particles (UFP), black carbon (BC), and polycyclic aromatic hydrocarbons (PAHs) in traffic area. The effects of street sweeping and washing on pollutant levels are evaluated. The X Road with sewage ditch was selected for the stationary samplings to determine the differences between the atmospheric PM$_{2.5}$ mass concentration, their composition, and potential sources before/after street cleaning processes, as well as the effect of the sewage existence. Results show that there were certain reductions of PM$_{2.5}$ after the street washing, especially for the road section with drainage ditch. The chemical mass balance model then pointed out the traffic contribution on PM$_{2.5}$ significantly reduced on the downwind site (from 25.7% to 16.5%). Besides, the spatial distribution of the near-ground PM$_{2.5}$, UFP, BC, and PAHs were monitored by a mobile platform on an appropriate long, straight, and not heavily traffic Road Y. The monitoring took place at 1 h-before, during washing/sweeping, at 1 h-after, at 1 d-after, at 2 d-after three cleaning strategies, including only sweeping, washing-before-sweeping, and sweeping-before-washing. The monitoring then mapped out the hot spot distribution of pollutants. The PM$_{2.5}$ mass, UFP number, BC, and PAH concentrations before the street sweeping is 155 $\mu$g m$^{-3}$, 1.2 $\times$ 10$^4$ # cm$^{-3}$, BC 3633 ng m$^{-3}$, and 36 ng m$^{-3}$. The UFP number concentration of suspended particles after street washing had a trend to reduce, avoiding the deterioration of air quality. The strategy, “sweeping-before-washing”, was the best operation method among three to suppress the UFP number concentration by 42%, while all three strategies could effectively reduce the PAH levels. The primary pollutants are more easily reduced by the street-cleaning process, while the secondary one did not.

Keywords: PM$_{2.5}$, Ultrafine particle, Black carbon, Polycyclic aromatic hydrocarbons, Street washing

1 INTRODUCTION

The previous studies have pointed out that long-term exposure of the human body to high concentration of suspended particulates will have a negative impact on the human body (Zhang et al., 2022). The World Health Organization estimates that about 2,400,000 people die each year due to air pollution of fine suspended particulate matter (Sierra-Vargas and Teran, 2012), ranking 13th in the world. Suspended particles (PM) are composed of small particles and droplets (including acids, organic substances, metals, soil or dust) in the air; they are classified according to size, have a great correlation with human health, and are indicators of air pollution classification (Kamaludin et al., 2020). Moreover, the concern for fine (PM$_{2.5}$, particles with the aerodynamic diameters,
dp < 25 µm) and ultrafine particles (UFP, dp < 100 nm) has become more relevant but knowledge of the relation between particle sources and near-ground particle number concentration levels is still incomplete.

Chiayi city has no other process related emissions such as those in the industrial zone except for the garbage incineration plant within its jurisdiction (Wu et al., 2021). Based on the geographical environment and location, there were over four industrial areas are in the north and northwest of the city. Considering that the monsoon wind direction is mostly northwest and north wind, open burning in the industrial area and nearby agricultural land may be the contributing pollution source of PM$_{2.5}$. In addition, the number and density of motor vehicles in the city are also among the top three in the country. The street dust on the paved road is rolled by vehicles and disturbed by the atmosphere, the dust whirls and escapes in the adjacent atmosphere (Karanasiou et al., 2012), causing negative effects on air quality and human health. Traffic-related pollutants, such as black carbon (BC) and ultrafine particles (UFP, particles with diameters < 100 nm) are indicated to have hazardous trace organic/inorganic compositions in previous studies (Krylow and Generowicz, 2019). The polycyclic aromatic hydrocarbons (PAHs) are also one group of the carcinogens in the street dust that can enter the human body through respiratory system, threatening human health (Vega et al., 2021; Pinthong et al., 2022). To find out whether street washing is helpful for controlling soil dust, X road and Y road were chosen as the sampling streets, with and without drainage ditch, street sweeping only, sweeping before washing and washing before sweeping are set as the control groups while the concentration of PM$_{2.5}$ upwind and downwind were measured as well.

In high concentration seasons, road dust is the main source of contribution to the originality of line sources (Kupiainen et al., 2016). Therefore, on high-concentration emission days, regions will increase the frequency of street washing/sweeping to reduce the contribution of road dust to fine suspended particles in the atmosphere.

Atmospheric PM$_{2.5}$ is one of the important air pollutants that has harmful effects for human health through its physical, chemical, and biological properties. The composition of PM$_{2.5}$ is very complicate which includes water soluble ions (e.g., NH$_4^+$, NO$_3^-$, and SO$_4^{2-}$), metal ions, and organic and carbonaceous content (OC and EC, respectively). A high correlation has been shown to exist between OC and EC in PM$_{2.5}$ (Yao et al., 2016; Huang et al., 2018; Liu et al., 2019). Soil dust particles re-suspended from the exposed ground surfaces, seawater droplets, and emissions from boilers and motor vehicles are directly source-released.

To clarify the source of PM$_{2.5}$, this study analyzed the compositions of air samples taken from four consecutive days in July and the data was then used in the chemical mass balance (CMB) analysis to assess the emission types and inputs from a variety of sources. The information obtained will be useful in developing plans to reduce emission from various pollution sources and explore the influence of street washing on controlling particle matters in the air.

2 MATERIALS AND METHODS

2.1 Sampling at Stationary Sites

Four representative sampling stations were selected in X Road, Chiayi city, sampling streets are divided into drainage and non-drainage areas, synchronous sampling were conducted at the upwind and downwind as shown in Fig. 1. Chiayi city is in the front of the Jianan Plain in the southwest of Taiwan. The Tropic of Cancer is about 1 km away from the south of the city. It belongs to the subtropical climate zone. The city is square, 15.8 km wide from east to west, 10.5 km long from south to north, and covers an area of 60.0256 km$^2$. As the source of surface fugitive dust may be affected by different seasonal wind directions, the southwest (source of southwest wind season) and northeast (source of northeast wind season) of Chiayi city are mainly selected for collection (Ku et al., 2021).

In order to obtain the effectiveness of different street cleaning operation modes, plans are doing street washing on streets with or without drainage ditch, another control group was street sweeping only, sweeping before washing and washing before sweeping. Finally, mobile monitoring and sampling on Y Road are carried out to explore the analysis of the spatiotemporal distribution of fine suspended particles. The sampling period ran from 10$^{th}$ to 13$^{th}$ four consecutive days in July 2016, eight groups of particulate matter sampling data are extracted before street washing.
Fig. 1. The stationary sampling sites around X road section.

Fig. 2. PM$_{2.5}$ mass concentrations and chemical composition at the stationary sites. (shown as “BSW” in Fig. 2) and after street washing (shown as “ASW”) according to the upwind (shown as “UP”) and downwind (shown as “DW” in Fig. 2) locations and whether there is drainage ditch. Four days average particle concentration is processed and combined in the upwind or downwind data.

2.2 Sample Pretreatment and Mass Quantifications

The sample test will be conducted at the four sampling stations every day for 24 hours in four days, and it will take four days to complete the test for 96 hours within total. The PQ200 particulate
samplers (BGI, Boston, MA) was used to collect the PM$_{2.5}$ on both Teflon membrane and quartz fiber filter papers at each station. After sampling on Teflon filter membrane, put it into a plastic bottle cleaned ultrasonically with deionized water after precision weighing, then inject 10-mL deionized water and seal the bottle cap tightly, and treat it with ultrasonic extraction for 90 minutes to extract water-soluble ions on Teflon filter paper (Lin et al., 2022). After extraction, pour the extraction solution into a 10-mL syringe, the particles in the sample were removed by filtration with a 0.45 mm membrane. Then, the filtrate was quantitatively determined with ion chromatography (Dionex, Model DX-120) in series with a conductivity detector for the water-soluble ionic composition.

Elemental Vario MIRCO Cube element analyzer is used for analyzing the carbon composition on the quartz fiber papers, in cooperation with AS200 automatic sampler and DP700 integrator. The filter samples for carbon analysis were cut into two slides. The total carbon (TC) content was determined by the CO$_2$ level, which were transformed from the carbon contents in the first slide of PM$_{2.5}$ by the oxidation at 600°C, the outflow of the instrument. The second slide of filter was pretreated in a 300°C oven with an inert environment to remove the OC and get the residual EC content by the same process. Therefore, the OC content could be calculated by TC minus EC.

The same as water-soluble ion composition analysis, taking a proper amount of filter paper sample and conduct it with microwave digestion, using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500A) to analyze the concentration of heavy metal components of PM$_{2.5}$ in the air (Lores-Padín et al., 2022).

### 2.3 Inverse Trajectory Simulation of Pollution Sources

When a high pollution concentration occurs at the receptor point at a certain time, a pollutant air mass passes through the receptor point, or the receptor point is affected by the emission of nearby pollution sources (Liao et al., 2021). Wind trajectories at the sample station essentially help to analyze the pollutant source. It can be predominantly found through an archive trajectory that, if there is an actual occurrence of pollutant sources from an exact place or contributes few aspects to pollution. The reverse trajectory mode simulation method commonly used is HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) developed by National Oceanic Atmospheric Administration (NOAA) Air Resources Laboratory (Dhammapala et al., 2022).

This study takes the occurrence time of the highest PM$_{2.5}$ suspended particle concentration as the starting time, plot the moving track of the air mass by pushing back the coordinates obtained for 24 hours, and output the coordinate position once every hour to plot the two-dimensional transmission path of the air mass.

### 2.4 Chemical Mass Balance Receptor Model

The chemical mass balance (CMB) receptor model is a tool that is commonly employed to enable both qualitative and quantitative analyses of PM$_{2.5}$ concentrations and its components at a location, because of the physicochemical characteristics of the emission sources (i.e., emission source profiles) and the field measurement data (Belis et al., 2020). It is based on an effective-variance least squares method (EVLS). CMB is ideal for localized nonattainment problems and a tool in applications where steady-state Gaussian plume models are inappropriate. The CMB receptor model has widely been used to the studies of ambient PM$_{2.5}$ phenomena in US, Europe, and Asia (Viana et al., 2008; Belis et al., 2013; Hopke, 2016).

### 2.5 Mobile Monitoring Platform

In this study, the electric vehicle is used as a mobile measurement platform to avoid the impact of vehicle emissions on the sampling data. Erecting high time resolution instrument (TSI DustTrak Model 8530, TSI P-trak, Model 8525, EcoChem PAS Model 2000, microAeth® Model AE51) behind the electric tricycle to measure the concentration of air pollutants. Relevant instrument parameters are shown in Table 1.
Table 1. Monitoring device parameters.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Measuring parameters</th>
<th>Sampling interval</th>
<th>Detection limit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSI DustTrak, Model 8530</td>
<td>PM$_{2.5}$ concentration</td>
<td>1 s</td>
<td>0.001 to 400</td>
<td>mg m$^{-3}$</td>
</tr>
<tr>
<td>TSI P-trak, Model 8525</td>
<td>Particle number concentration (0.02–1.00 µm)</td>
<td>1 s</td>
<td>0 to 0.5 × 10$^5$</td>
<td># cm$^{-3}$</td>
</tr>
<tr>
<td>EcoChem PAS, Model 2000</td>
<td>Polycyclic aromatic hydrocarbon (PAH)</td>
<td>6 s</td>
<td>3</td>
<td>ng m$^{-3}$</td>
</tr>
<tr>
<td>microAeth® Model AE51</td>
<td>Black carbon (BC)</td>
<td>10 s</td>
<td>0.001</td>
<td>µg m$^{-3}$</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

3.1 Atmospheric PM$_{2.5}$ and their Contents at the Stationary Sites

3.1.1 With drainage ditches

It can be seen from Fig. 2 that the concentration of PM$_{2.5}$ is 4.95–7.85 µg m$^{-3}$ when washing streets with drainage ditches. Before street washing, the upwind area is 7.85 µg m$^{-3}$, street with drainage ditch is 7.72 µg m$^{-3}$, the main components of upwind area and street with drainage ditch are water soluble ions (28.2%, 40.4%), and the water soluble ions are mainly SO$_4^{2-}$ (15.8%, 24.6%), NO$_3^-$ (5.59%, 4.94%) and NH$_4^+$ (2.51%, 2.53%) (Fig. 3); Carbon composition (Fig. 4) is 14.6% (4.64% for EC, 9.92% for OC) and 18.0% (6.39% for EC, 11.6% for OC) respectively; The metal composition (Fig. 5) is 7.11% and 20.1% respectively. Among the metal components, Na, K, Fe, Al, Zn and Mg are the most abundant crustal elements, accounting for over 97% of the total metal components.

After street washing, the upwind area is 4.95 µg m$^{-3}$, street with drainage ditch is 5.85 µg m$^{-3}$, the main components of the upwind area and street with drainage ditch are water-soluble ions (29.4%, 67.3%), and the water-soluble ions are mainly SO$_4^{2-}$ (20.0%, 45.4%), NO$_3^-$ (4.12%, 4.01%) and NH$_4^+$ (3.89%, 9.32%); Carbon composition is 14.6% (5.49% for EC, 9.06% for OC) and 18.0% (8.29% for EC, 9.65% for OC) respectively; The metal composition is 13.6% and 13.6% respectively. Among the metal components, Na, K, Fe, Al, Zn and Mg are the most abundant crustal elements, accounting for over 94% of the total metal components.

3.1.2 No drain ditches

The PM$_{2.5}$ levels at upwind and exposure sites were 11.9 µg m$^{-3}$ and 14.1 µg m$^{-3}$, while the main components were water soluble ions (40.1 and 32.1%). The water-soluble ions are composed of SO$_4^{2-}$ (29.51 and 24.0%), NH$_4^+$ (7.801 and 5.62%) and NO$_3^-$ (1.531 and 1.06%). Additionally, the carbon compositions were 14.6% (4.59% for EC and 9.97% for OC) and 18.0% (5.76% for EC and 12.3% for OC) at two sites, respectively. The metal compositions were 6.30 and 6.64%, respectively. Among the metal components, Na, K, Fe, Al, Zn and Mg are the most abundant crustal elements, accounting for over 93% of the total metal components.

Fig. 3. Ionic compositions of the atmospheric PM$_{2.5}$ at the stationary sites.
After street washing, the upwind area is 14.1 µg m⁻³, while the near-street with drainage ditches is 16.2 µg m⁻³. The upwind and exposure sites of the street without drain ditches were mainly composed of water-soluble ions (47.1 and 42.0%). The water-soluble ions were mainly composed of SO₄²⁻ (35.5 and 31.4%), NH₄⁺ (9.76 and 9.01%), and NO₃⁻ (0.85 and 0.62%). On the other hand, the carbon compositions were 14.6% (6.44% for EC and 8.11% for OC) and 18.0% (8.87% for EC and 9.08% for OC) at two sites, respectively. The metal compositions were 5.04 and 4.81%, respectively. Among the metal components, Na, K, Fe, Al, Zn and Mg are the most abundant crustal elements, accounting for over 95% of the total metal components.

According to the manual sampling, it can be found that the road section with drainage ditches...
can indeed reduce the PM$_{2.5}$ mass concentration after street washing, this result indicates that the street washing could inhibit the street dust raising from the ground, soil dust and street dust will be raised from the ground again on the street section without drain ditch. But it is still impossible to analyze the impact of street washing on the PM$_{2.5}$ concentration in the street from the component analysis. The following part will further simulate the pollution source with the receptor model and verify the effect of street washing through mobile monitoring.

3.2 The Secondary Sulfate and Nitrate

The sulfur oxidation ratio (SOR) and nitrogen oxidation ratio (NOR) reflect the secondary transformation degree of gaseous pollutants SO$_2$, NO$_2$ to SO$_4^{2-}$, NO$_3^-$. It indicates high potential for the oxidation, which leads to secondary inorganic aerosol formation in the atmosphere, while the values of SOR and NOR are over 0.25 and 0.1, respectively. The SOR and NOR at the upwind place before street washing with drainage ditch are 0.111 and 0.027, and the SOR and NOR in the exposed area are 0.159 and 0.024. After street washing, the SOR and NOR at the upwind are 0.113 and 0.011, and the SOR and NOR in the exposed area are 0.256 and 0.013. The SOR and NOR at the upwind place before street washing without drainage ditch are 0.328 and 0.012, and the SOR and NOR in the exposed area are 0.320 and 0.010. After street washing, the SOR and NOR at the upwind are 0.356 and 0.008, and the SOR and NOR in the exposed area are 0.361 and 0.007. During the sampling, the derivative sulfate generation potential is high, which is due to the high photochemical intensity in summer, resulting in a high concentration of OH free radicals (Jiang et al., 2019). The reason SO$_4^{2-}$ in aerosol would increase is SO$_2$ has higher potential to transform SO$_4^{2-}$ because of solar radiation and further neutralized by ammonium and eventually form secondary aerosols. In the other hand, NO$_3^-$ and NH$_4^+$ would decrease because of temperature increased. The reason is NO$_3^-$ and NH$_4^+$ will volatilize from surface of PM. Therefore, the sulfate conversion rate is high. The nitrate conversion rate is low.

3.3 Source Contributions and Reduction by Street Cleaning

For the street cleaning efficiency analysis, the fine suspended particle sampling station analyzed the pollution source of suspended particles (PM$_{2.5}$) in the chemical mass balance receptor mode. This time, four point fine suspended particle sampling was carried out, and the PM$_{2.5}$ pollution source analysis results of the sampling station were summarized in Fig. 6. During the sampling period, the air flow trace line for 24 hours is shown in Fig. 7, which shows that the wind was southerly in summer. The polluted air mass exposed by the Chiayi Station mainly flowed from Tainan City, Kaohsiung and other regions, including Kaohsiung Industrial Zone and large coastal industrial zone, and occasionally westerly wind flowed to the city from the Taiwan Strait (Shen et al., 2020).

According to the results of the receptor model, the main pollution source in the upwind area before street washing with drainage ditch is mobile source emissions (25.8%), followed by secondary nitrate (16.8%), secondary sulfate (10.5%) and soil dust (7.03%). The main pollution sources in the exposure area are mobile source emissions (25.7%), followed by secondary nitrate (18.2%), secondary sulfate (11.5%) and soil dust (7.31%). The main pollution source in the upwind area after street washing with drainage ditch is mobile source (17.0%), followed by secondary nitrate (15.5%), secondary sulfate (9.69%) and soil dust (5.97%). The main pollution sources in the exposure area are mobile source emissions (16.5%), followed by secondary nitrate (16.3%), secondary sulfate (10.4%) and soil dust (6.08%). It can be seen that after street washing, the traffic sources and secondary salts have a significant reduction trend. The mobile sources at the upwind are reduced by 8.8%, the secondary salts are reduced by 2.11%, and the soil dust is reduced by 1.06%; The mobile sources in the exposed area decreased by 9.2%, the secondary salts decreased by about 3%, and the soil dust decreased by about 1.23%.

The results of the receptor model show that the main pollution source in the upwind area before street washing without drainage ditch is mobile source emissions (26.3%), followed by secondary nitrate (16.5%), secondary sulfate (9.69%) and soil dust (7.16%). The main pollution source in the exposure area is mobile source emissions (25.4%), followed by secondary nitrate (17.8%), secondary sulfate (10.6%) and soil dust (7.22%). The main pollution source of upwind area after street washing without drainage ditch is mobile source (16.9%), followed by secondary
Fig. 6. Source contribution evaluated by CMB model of the atmospheric PM$_{2.5}$ at the stationary sites.

Fig. 7. Wind trajectories during the sampling periods.
nitrate (17.3%), secondary sulfate (10.2%) and soil dust (5.91%). The main pollution source in the exposure area is mobile source emissions (15.9%), followed by secondary nitrate (17.6%), secondary sulfate (10.6%) and soil dust (5.84%).

The results of receptor model analysis show that, regardless of the drainage ditches, among the pollution source contributions after street washing, traffic sources, secondary nitrates, secondary sulfates and soil dust are all lower than those before street washing, and the secondary sulfate and nitrate contributions were reduced by 9.50% and 10.4% respectively.

From the above, the receptor model analysis shows that the pollution from traffic sources is reduced after street washing, but there is almost no difference between upwind and downwind sites, it still cannot analyze the impact of street washing on the PM$_{2.5}$ mass concentration in the street from the component analysis, so we further analyzed the effectiveness of street washing in suppressing particulate matter concentrations through mobile monitoring.

### 3.4 Hotspot Mapping by Mobile Monitoring

The Y Road is an east-west road, which is less affected by the interaction of dust caused by wind direction. Three scenarios are carried out on Y road section to reduce the variables affected by traffic sources. The sampling time is an hour before washing/sweeping, during washing/sweeping, an hour after washing/sweeping, and one hour each on the first day 25$^{th}$ and the second day 26$^{th}$ after washing/sweeping, to find out the duration of dust suppression by washing/sweeping.

The sampling route of Y Road is divided into three sections, the first section is the street sweeping only, the second section is street sweeping before washing; the third sampling situation is washing before sweeping. The sampling route and sampling situation are shown in Fig. 8. The measurement results of the mobile platform for street washing operations on Y Road are shown in Fig. 9 and Fig. 10. The Kolmogorov-Smirnov normality test is used to verify the normal distribution of the data to be compared (Rosenthal, 1968), the results show an abnormal distribution ($p < 0.001$), so the Kruskal-Wallis test is used for verification (Lin and Zhang, 2011). The PM$_{2.5}$ mass concentration before the street sweeping is 155 $\mu$g m$^{-3}$, and number concentration is $1.2 \times 10^{4}$ # cm$^{-3}$, BC concentration is 3633 ng m$^{-3}$, PAHs concentration is 36 ng m$^{-3}$. The PM$_{2.5}$ mass concentration during street sweeping is 158 $\mu$g m$^{-3}$ and number concentration is $1.5 \times 10^{4}$ # cm$^{-3}$, BC concentration is 7546 ng m$^{-3}$, PAHs concentration is 53 ng m$^{-3}$. The results indicated that the four suspended particle indicators (PM$_{2.5}$ mass concentration, number concentration, BC concentration, and PAHs concentration) are all higher than that before street sweeping. The PM$_{2.5}$ mass concentration of sweeping before washing is $2.3 \times 10^{4}$ # cm$^{-3}$, BC concentration is 7837 ng m$^{-3}$, and PAHs concentration is 171 ng m$^{-3}$. The number concentration of washing before sweeping is $1.8 \times 10^{4}$ # cm$^{-3}$, the BC concentration is 9895 ng m$^{-3}$, and the PAHs concentration is 79 ng m$^{-3}$, which may be related to the exhaust emissions of street washing car (Karanasiou et al., 2014).

After washing/sweeping operations, the PM$_{2.5}$ mass concentration decreased only when the street washing vehicle was not used and only in the street sweeping mode, from 155 to 136 $\mu$g m$^{-3}$, while the mass concentration was slightly higher when using street washing vehicle than those
before washing/sweeping 157 and 154 µg m⁻³, respectively. The concentration of number concentration, BC concentration and PAHs concentration decreased in three modes, the number concentration of the three different washing/sweeping modes are \(9.5 \times 10^4\), \(7.8 \times 10^4\), and \(1 \times 10^4\) # cm⁻³, respectively. BC concentrations are 2864, 2756, and 2557 ng m⁻³, respectively. PAHs concentrations are 5.6, 20, and 11 ng m⁻³, respectively. This result shows that street sweeping alone or street sweeping combined with street washing can effectively suppress the dust of fine suspended particles.

The PM₉.₅ mass concentration, number concentration, BC concentration and PAHs concentration were measured every other day after washing/sweeping the streets, data indicated they were all lower than those after washing/sweeping. The average mass concentration of PM₉.₅ decreased from 150 to about 60 µg m⁻³, and the average number concentration decreased from \(1.5 \times 10^4\) # cm⁻³ to about \(0.6 \times 10^4\) # cm⁻³, the average concentration of BC decreased from 3970 to 1900 ng m⁻³, and the average concentration of PAHs decreased from 41 to 9.5 ng m⁻³. Concentration measurements after two days showed the same results, they were lower than those after washing/sweeping the streets on the first day, which is presumed to be related to the background concentration of the day.

Fig. 9. The temporal variations of the PM₉.₅ mass and UPF number concentrations with three street-cleaning sequences at Y road.
Fig. 10. The temporal variations of the BC and PAH mass concentrations with three street-cleaning sequences at Y road.

Background value concentration of 24th, 25th, 26th got from the TAQM - Taiwan Environmental Protection Agency are 74, 87, 60 (air quality index, 51–100 means air quality is acceptable, however, for some pollutants there may be a moderate health concern for a few people who are unusually sensitive to air pollution, defined by the U.S.-EPA 2016 standard). The background value concentration indeed shows a drop two days after washing/sweeping, which is proved that concentration measurements results correlate with the effect of background concentration.

The PM$_{2.5}$ mass concentration decreased about 10% only after sweeping/washing street, the other two cleaning modes show negative effects during cleaning operation, so the mass concentration is higher during sweeping/washing street. The number concentration in the sweeping before washing mode has the highest decline rate after an hour, about 42%, the BC concentration in the washing before sweeping mode has the highest decline rate after an hour, about 45%, the PAHs concentration in the sweeping mode has the highest decline rate after an hour, about 80%. However, PM$_{2.5}$ mass concentration gradually decreases after the cleaning operation, the background concentration decreased 31% in two days, the downward trend is the same as that of the background concentration, it is speculated that the decrease in the concentration on the 1st and 2nd days after the cleaning operation is not the reason for the cleaning operation to suppress the number concentration of fine suspended particles.
The street sweeping/washing operation can reduce the PM$_{2.5}$ mass, BC, and PAHs concentrations in the near-ground air on the road, among them, the sweeping before washing mode can effectively reduce the BC concentration and PAHs concentration by about 30% and 55%. However, street sweeping/washing operation helped little for the number concentration of fine suspended particles.

The suspended particle concentration is further drawn into a spatial distribution map, as shown in Fig. 11. The PM$_{2.5}$ mass concentration of Y Road is about 150–200 µg m$^{-3}$, the effect of street cleaning within an hour has a certain effect on inhibiting the PM$_{2.5}$ mass concentration, but the mass concentration and number concentration of fine suspended particles during street washing are much higher than those before street washing.

The PM$_{2.5}$ mass concentration is less than 50 µg m$^{-3}$ on the second day after cleaning operation, which is less than the mass concentration of PM$_{2.5}$ on the first day about 50–100 µg m$^{-3}$. The results are the same as the background concentration; it was pointed out that the PM$_{2.5}$ mass concentration was lower than those before sweeping/washing street for a period, but the street sweeping/washing had no significant effect on suppressing the number concentration of fine suspended particulates for the next day.

![Fig. 11. The spatial distribution of the PM$_{2.5}$ mass and UPF number concentrations (a) before, (b) during, (c) 1 h-after, (d) 1 d-after, and (e) 2 d-after sweeping/washing street.](image-url)
4 CONCLUSIONS

The near-ground PM$_{2.5}$ mass concentrations, chemical composition and sources are evaluated first by a stationary sampling design at X road with the condition of with/without the drainage ditch. In the control group without drainage ditch, the difference between upwind and downwind is more obvious than those with drainage ditch. This result points out that the street washing was less effective on the road section without drainage ditch since the road dust would be resuspended while the road surface was getting dry. The CMB indicates that the traffic emissions have a great impact on PM$_{2.5}$ in the downwind. It can be seen from the results that the road section with drainage ditches can indeed reduce the PM$_{2.5}$ mass concentration after street washing.

Moreover, a mobile monitoring platform analyzes the spatial distribution of the near-ground PM$_{2.5}$, UFP, BC, and PAHs at Y Road 1 h-before, during washing/sweeping, 1 h-after, 1 d-after, 2 d-after three-strategies of street washing/sweeping. Results show the high PM$_{2.5}$ mass and UFP number concentrations occur during the street washing, because of the effect of the emission from the street washing diesel-fueled vehicle. The UFP number concentrations reduce after street washing, avoiding the deterioration of air quality. The “sweeping before washing” was the most effective operation mode among three to suppress the UFP by 42%. Additionally, all three washing strategies effectively reduce the PAH levels, but have not significant inhibitions on PM$_{2.5}$ and BC levels. Consequently, the primary pollutants are more easily reduced by the street-cleaning process, while the secondary one did not. This study supports the effectiveness of street sweeping-washing process on the UFP and PAHs reduction in the near-ground air.

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