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Estimating the Air Pollution Intake Dose in Three Port Cities in Europe with the Use of Ambient Fine Particulate Matter Measurements from Low-Cost Sensors †

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Abstract: In urban areas, people live under poor air quality conditions since exceedances in limit concentrations set by the European Union are usually recorded. In port cities, air quality is further deteriorated due to emissions from port activities. This work investigates the variation in fine Particulate Matter ($PM_{2.5}$) through the recordings of PurpleAir low-cost sensors in Aarhus, Hamburg, and Lisbon, which are in northern, central, and southern Europe, respectively, for the period of 2020–2022. Moreover, the calculation of the Intake Dose (ID) was attempted for active population groups of men and women aged from 21 to 61 years old. The results showed that the male population groups of active working ages generally inhale higher amounts of particulate matters.

Keywords: intake dose; particulate matter; port cities; air pollution; purple air; low-cost sensors

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1. Introduction

Continuous exposure to air pollution leads to adverse effects on human health and well-being. Almost the entire Earth's population is currently residing in urban areas where the air quality does not comply with the guidelines set by the World Health Organization (WHO) [1]. Numerous studies have thoroughly investigated the health effects of air pollution, especially the ones related to the exposure to fine particulate matter ($PM_{2.5}$). Due to the pollutant's ability to penetrate the bloodstream and reach deeper into the lungs, inhaling an extreme amount of $PM_{2.5}$ mass poses a significant risk to the human cardiovascular and respiratory systems [2]. Exposure to $PM_{2.5}$ is associated with premature deaths, ranging from 3 to 125 per 100,000 people in urban areas globally. More than half of these deaths are attributed to cardiovascular diseases (CVDs), such as ischemic heart disease, heart failure, cardiac arrhythmias, and hypertension [3–7]. Prolonged exposure to $PM_{2.5}$ increases the risk of health complications in individuals with pre-existing conditions and lower socioeconomic status, older adults, and racial and ethnic minorities [8,9].

Port cities are areas of particular interest, as emissions of pollutants from the shipping sector (ship arrivals/departures, traffic around the port, off-road activities in the port area) can prove extremely harmful to the active population groups working in the greater area. Shipping-related PM emissions were found to be responsible for around 60,000 cardiac- and lung-cancer-related fatalities each year, with most deaths occurring near European coastlines [10]. The development of low-cost air sensor networks leads to the expansion of the monitoring coverage in densely populated areas and has the potential to better inform citizens about the local air quality as well as improve our understanding of the impact that pollution episodes have on our health and the environment [11–13]. Moreover, measurements from low-cost sensors can provide the necessary data to conduct a thorough study about the local air quality.

In this work, an exposure study in three European port-cities (Aarhus, Hamburg, and Lisbon) was attempted, using data from PurpleAir low-cost sensors. For this reason, the $PM_{2.5}$ intake dose for active population groups of men and women was calculated.

2. Area of Study

The port cities of Aarhus, Hamburg, and Lisbon (Figure 1) are in northern, central, and southern Europe, respectively, and are characterized by different climatic conditions and population densities, parameters that, in combination with the anthropogenic activities, contribute to the formation of the local air quality. Aarhus, the second largest city of Denmark, has a population of 350,000 inhabitants and a mild, generally warm climate (average annual temperature: 9.0 °C). The port, which is at the center of the city, is the largest in the country. The selected PurpleAir monitoring station is approximately 5.0 km away, situated in the suburban neighborhood of Risskov. The port of Hamburg, Germany's largest seaport and the third largest in Europe, is located on the river Elbe approximately 120 km from the North Sea. The city has a population of 1.8 million and it is known for its mild winters and cool summers, high humidity, and fog (annual mean temperature: 9.8 °C). The monitoring station is located at the Sulldorf quarter, about 17.0 km from the port. The metropolitan area of Lisbon (capital of Portugal) is highly populated, having approximately 2.9 million inhabitants. Lisbon's port is the largest national one, and it is located on the shore of Tagus River near the exit to the Atlantic Ocean. The winters in Lisbon are short and mild but rainy and the summers are hot (mean annual temperature: 16.7 °C). The port of Lisbon is about 6.0 km away from the closest PurpleAir monitor located in the district of Graça in a typical suburban neighborhood.

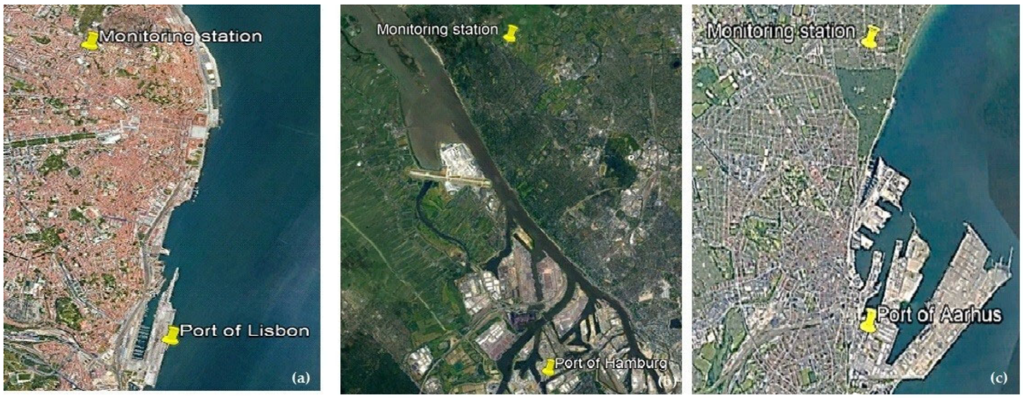

Figure 1. The areas of study: (**a**) Lisbon; (**b**) Hamburg; (**c**) Aarhus (Source: Google Earth Pro).

3. Methodology

3.1. Instrumentation

Data from three PurpleAir sensors located at the areas of study were used. PurpleAir sensors are one of the most widely used monitors with over 16,000 devices operating around the world and recording environmental data such as PM (1.0, 2.5, 10.0) concentrations, temperature, humidity, and pressure. They consist of an electronic two-channel data recording system and have the ability to work either connected to a network or offline. The sensors employ laser counters to monitor PM concentrations in real time by drawing a sample of air via a laser beam. The laser beam is reflected off any present particles onto a detection plate, and the detection plate measures the reflection as a pulse. The length of the pulse determines the particle's size and the number of pulses determines the particle count. The mass concentrations of $PM_{1.0}$, $PM_{2.5}$, and $PM_{10.0}$ are estimated using these particle measurements and, for these three particle mass concentration estimates, two data series (CF1 and ATM) are generated [14].

3.2. Calculation of Intake Dose

The intake dose calculation was based on Equation (1) [15]:

$$\boldsymbol{ID} = \dot{\boldsymbol{V}}_{\boldsymbol{E}} \cdot \boldsymbol{PM} \tag{1}$$

where $\dot{\boldsymbol{V}}_{\boldsymbol{E}}$ is the inhalation rate (L/min) and $\boldsymbol{PM}$ is the mean hourly concentration of particulate matter (μg/m^3). The inhalation rates are proposed by the U.S. Environmental Protection Agency (US EPA) in the Exposure Factors Handbook [16] (Table 1) and the PM concentrations are the ones measured by the PurpleAir sensors mentioned above. For this study, $\dot{\boldsymbol{V}}_{\boldsymbol{E}}$ was converted to m^3/hour. Based on Equation (1) and the PurpleAir data series for the years from 2020 to 2022, the ID of $PM_{2.5}$ was calculated for both males and females of different age groups, as presented in Table 1. The mean value of ID for the 8 h workday was calculated as well, for all sexes and age groups. It was assumed that the most active group in the ports are males and females aged between 31 and 41 years old, so the diurnal variation in ID was calculated and further examined.

Table 1. Mean inhalation rate values (m^3/day) for males and females for four different age groups.

Sex	Age Groups (Years)	Mean Inhalation Rate Values (m^3/day)
Male	21 to <31	18.82
	31 to <41	20.29
	41 to <51	20.94
	51 to <61	20.91
Female	21 to <31	14.57
	31 to <41	14.98
	41 to <51	16.20
	51 to <61	16.19

4. Results

The mean annual $PM_{2.5}$ concentrations for each port are presented in Table 2. Overall, the lowest mean annual $PM_{2.5}$ concentration was found in 2022. Comparing the mean annual $PM_{2.5}$ concentrations at the three ports, the highest values were observed at the port of Hamburg for the whole sampling period (2020–2022), followed by the port of Lisbon and the port of Aarhus. It is worth mentioning that, at the port of Aarhus, $PM_{2.5}$ concentrations were stable and below 9.00 μg/m^3. Concerning the port of Hamburg, the highest value of $PM_{2.5}$ concentration was estimated in 2021 (14.89 μg/m^3), whilst the lowest was in 2022 (11.51 μg/m^3). At the port of Lisbon, the mean annual $PM_{2.5}$ concentrations ranged from 9.36 μg/m^3 to 11.01 μg/m^3.

Table 2. Mean annual $PM_{2.5}$ (μg/m^3) concentrations at the 3 ports for the years 2020–2022.

Port	Year	Mean Annual $PM_{2.5}$ Concentrations (μg/m^3)
Aarhus	2020	8.89
	2021	8.59
	2022	8.31
Hamburg	2020	13.75
	2021	14.89
	2022	11.51
Lisbon	2020	11.01
	2021	10.50
	2022	9.36

In general, men seem to inhale higher doses of $PM_{2.5}$ compared to women. More specifically, the highest mean value of $PM_{2.5}$ ID for the 8 h workday was detected in the port of Hamburg (93.89 μg for men) and the lowest was detected in the port of Aarhus

(41.75 µg for women). Among all sexes and age groups, the port of Hamburg exhibited the highest mean values of ID, followed by the port of Lisbon and, lastly, the port of Aarhus (Figure 2).

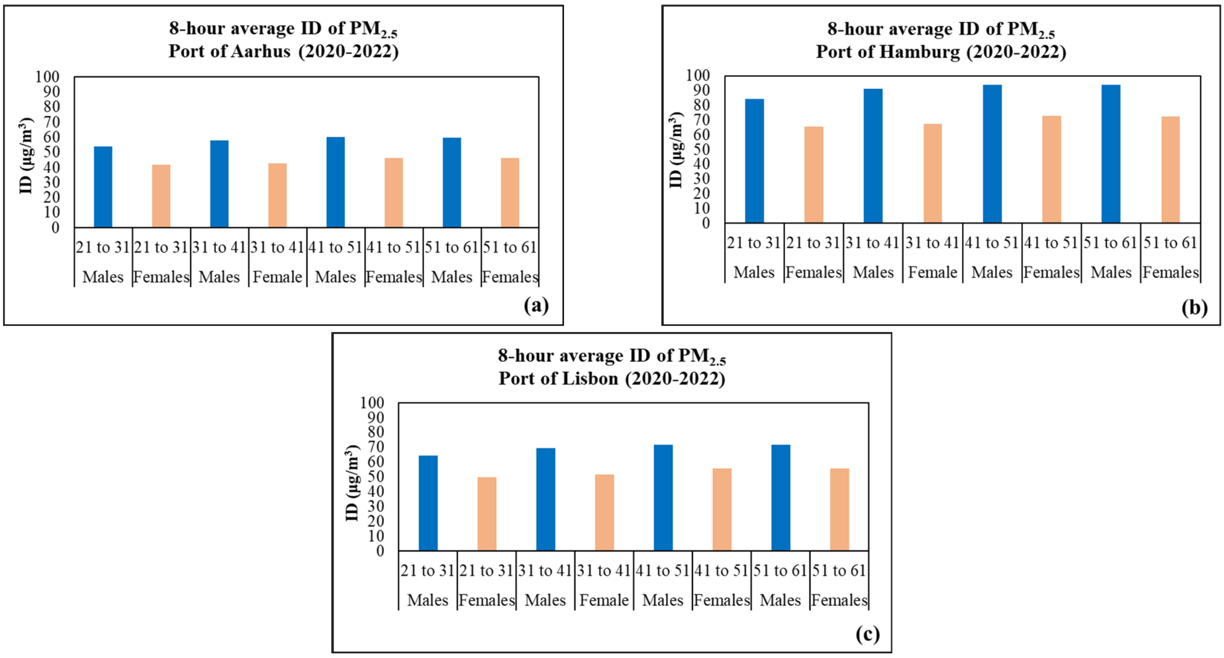

Figure 2. (**a**) Intake dose of $PM_{2.5}$ in the span of 8 h for males and females of all age groups at port of Hamburg; (**b**) intake dose of $PM_{2.5}$ in the span of 8 h for males and females of all age groups at port of Aarhus; (**c**) intake dose of $PM_{2.5}$ in the span of 8 h for males and females of all age groups at port of Lisbon.

As presented in Figure 3a, the values regarding the diurnal variation in the ID in men and women ranged from 13.14 µg/m^3 to 9.12 µg/m^3 and from 9.70 µg/m^3 to 6.73 µg/m^3, respectively, while the $PM_{2.5}$ mean concentrations ranged from 15.54 µg/m^3 to 10.82 µg/m^3. The peaks of the ID values for both males and females and of the $PM_{2.5}$ concentrations were detected at 5:00 UTC and the lowest values were detected at 14:00 UTC. In Figure 3b, the diurnal variations in the ID in men and women and in $PM_{2.5}$ mean concentrations of the port of Aarhus are presented. In men, the ID values ranged from 8.29 µg/m^3 to 6.19 µg/m^3; in women, they ranged from 6.12 µg/m^3 to 4.57 µg/m^3; and the $PM_{2.5}$ mean concentrations ranged from 9.82 µg/m^3 to 7.36 µg/m^3. The peaks in the ID values, in both males and females, and in $PM_{2.5}$ concentrations were detected at 21:00 UTC. The lowest values of ID and $PM_{2.5}$ concentration were detected at 13:00 UTC. The diurnal variations in ID in men and women and in $PM_{2.5}$ mean concentrations of the port of Lisbon are portrayed in Figure 3c. In men, the ID values ranged from 11.06 µg/m^3 to 6.36 µg/m^3; in women, they ranged from 8.16 µg/m^3 to 4.70 µg/m^3; and the $PM_{2.5}$ mean concentrations ranged from 13.14 µg/m^3 to 8.60 µg/m^3. The peaks in the ID values for both males and females and in $PM_{2.5}$ concentrations were detected at 20:00 UTC, whereas the lowest values of ID for both sexes and $PM_{2.5}$ concentrations were detected at 16:00 UTC.

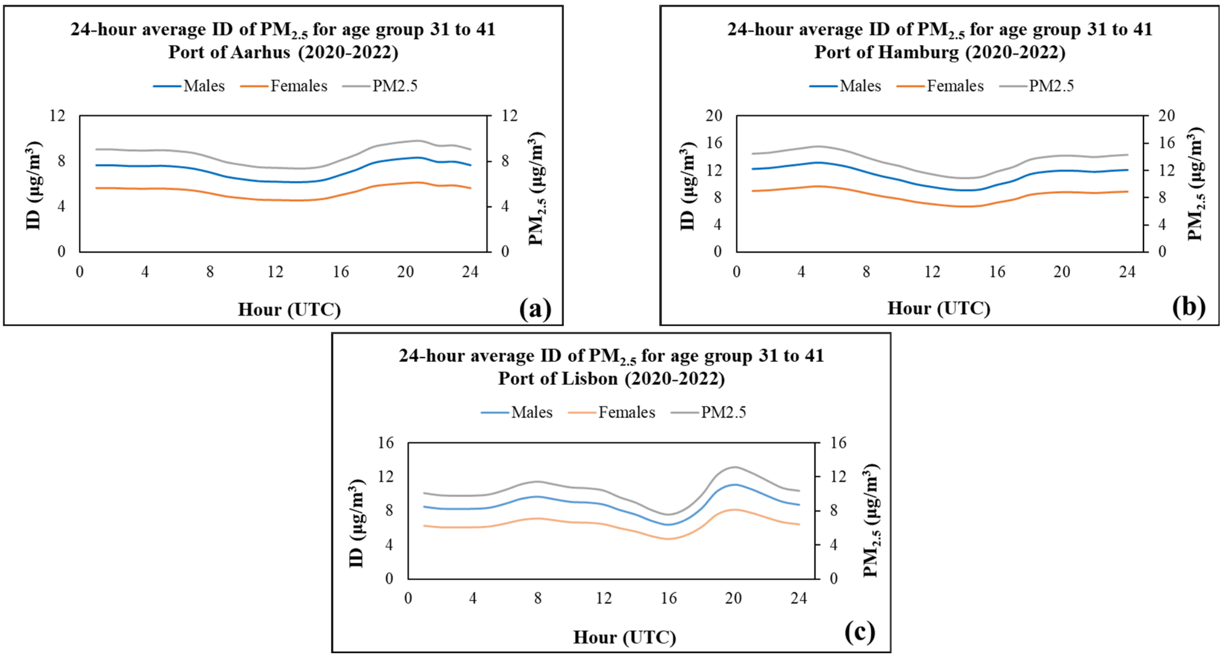

Figure 3. (**a**) Diurnal variation in $PM_{2.5}$ concentrations (2020–2022) and ID for age group of 31 to 41 in port of Hamburg; (**b**) diurnal variation in $PM_{2.5}$ concentrations (2020–2022) and ID for age group of 31 to 41 in port of Aarhus; (**c**) diurnal variation in $PM_{2.5}$ concentrations (2020–2022) and ID for age group of 31 to 41 in port of Lisbon.

5. Conclusions

The diurnal variation in $PM_{2.5}$ concentrations recorded from PurpleAir low-cost sensors in Aarhus, Hamburg, and Lisbon was studied for the period of 2020–2022 and the Intake Dose (ID) was calculated for four age groups. It was found that the port of Hamburg was the most polluted, followed by the ports of Lisbon and Aarhus. As for the personal exposure, for both males and females, the 41 to 51 age group was related to higher $PM_{2.5}$ inhaled doses. Among sexes, the male population of all age groups and in all ports inhaled higher doses of $PM_{2.5}$. Further studies will include the consideration of the individual activity at the calculation of the ID.

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