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Original scientific paper

CALCULATION OF EMISSIONS INTO THE AIR OF NON-ROAD MOBILE MACHINERY FROM THE LANDFILL

Marko Balaban[1], Valentina Balaban Radić[1], Draženko Bjelić[1], Aleksandar Bursać[1], Brankica Gegić[1], Milenko Jaćimović[1], Aleksandar Lukač[1], Dragana Marić[1], Dragana Nešković Markić[2], Željka Šobot Pešić[1], Željko Jovičić[2]
[1]PU "Dep-ot" Regional landfill Banja Luka, Bosnia and Herzegovina; dep-ot@teol.net
[2]Faculty of Health Sciences, Apeiron Pan-European University, Banja Luka, Bosnia and Herzegovina

ABSTRACT: Waste disposal is just one of the segments in solid municipal waste management system. During the entire life cycle of waste, starting from waste generation, through storage, collection, transport, recycling, treatment and disposal, several different pollutants are emitted. By disposing solid waste, non-road mobile machinery (NRMM) emits various pollutants into the air such as CO_2, CO, NMVOC, PM, PAHs, heavy metals, etc. These substances can pose certain problems for human health and the environment. The subject of this study is the calculation of air emissions of CO_2, CH_4, N_2O, NMVOC, PM10, CO, Cd, Cr and PAHs (chrysene and benz[a]anthracene) from NRMM which are included in the activities of receiving and disposing of waste at the Banja Luka landfill. The study evaluates the emission of pollutants using the EEA guidelines for the assessment of the emission of pollutants into the air, based on the consumption of diesel fuel during the year. This study, which is based on the calculation of NRMM emissions at the Banja Luka landfill, should serve as an example not only to other landfills but also to sectors that use NRMM on the importance of keeping track of pollutant emissions. The goal is to look at these emissions and introduce changes and improvements in this sector by replacing old NRMMs with new ones, optimizing operation, using diesel of satisfactory quality, etc.

Keywords: air pollution, non-road machinery, landfill, diesel fuel.

INTRODUCTION

Non-road mobile machinery (NRMM) is defined as any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on road (REGULATION EU 2016/1628). NRMM is widely used in the construction industry and agriculture. It is recognized as a significant source of pollutant emissions, which contributes to poor air quality. (Bie et al.,2022). The share of NRMM in the total European fuel consumption was 11% in the year 2010 (Ratzinger et al., 2021).

Emissions from non-road diesel engines include particulate matter (PM), oxides of nitrogen (NOx), volatile organic compounds (VOCs) and a range of air toxics (e.g. benzene, toluene and 1,3-butadiene) (Zhao et al., 2015). PM emitted from diesel combustion is mainly comprised of fine particles having an aerodynamic diameter of less than 2.5 μm (PM2.5). In 2010, the EU Commission attributed 100 million tons of CO_2 emissions in the EU-27 annually to NRMM (2 % of the EU27's total GHG emissions). This is comparable to the annual CO_2 emissions of Greece (European Parliament, 2020).

The International Agency for Cancer Research, which is part of the World Health Organization, recently classified diesel engine exhaust as a human carcinogen, based on sufficient evidence that exposure is associated with an increased risk of lung cancer (IARC, 2013). PM of variable but very small diameter, penetrate the respiratory system via inhalation, causing respiratory and cardiovascular diseases, reproductive and central nervous system dysfunctions, and cancer (Manisalidis et al., 2020). Emissions of NOx and

VOCs from the non-road diesel sector contribute to the formation of ground-level ozone, which is used as an indicator of photochemical smog. Heavy metals represent an important group of persistent toxic pollutants that occur in ambient air and other media, and one of the sources of these metals in the atmosphere is the burning of fuel in vehicles (Pulles et al., 2012). Polycyclic aromatic hydrocarbons (PAHs) are known worldwide for their potential carcinogenic and mutagenic effects (Correa & Arbilla, 2006). Chrysene (Chy) and benz[a]anthracene (B[a]A) are known or suspected that they are carcinogenic to humans (Liang et al., 2005). PAHs enter the environment mainly from processes involving combustion, and diesel engines are a significant source of PAH emissions into the atmosphere (de Souza & Corrêa, 2016). Aging of NRMM shows a strong impact on emissions, i.e. older vehicles emit far higher concentrations of polluting materials than newer ones (Tu et al., 2021).

Estimating emissions from NRMM and compiling emissions inventories is still a difficult task for most countries due to lack of data (Lončarević et al., 2022). The EEA edition of the 2019 air pollutant emission inventory guidebook is one of the most important documents regarding the NRMM emissions inventory. This guidebook lists three possible methods for estimating air emissions: Tier 1, Tier 2 and Tier 3, depending on available data (EEA, 2019). The Tier 1 method uses only basic NRMM data and fuel consumption. Tier 2 is more accurate, as it uses fuel consumption data for each equipment type and technology level. The Tier 3 method is the most detailed and uses more specific data, e.g. annual hours of use, motor size, and load factor setting, etc. Emission inventories are a key starting point for understanding the causes and possible mitigation of air pollution. They provide information about air pollution sources, which can be used in environmental assessment models and air quality models to obtain information about air pollution levels (Kuenen et al., 2022). NRMM is thought to eventually surpass road vehicles as the leading source of mobile pollution (Hagan et al., 2022; Zhang et al., 2020).

All local transport in Bosnia and Herzegovina is carried out by road. It is characterized by a large number of old vehicles and uncontrolled quality of liquid fuel (European Commission, 2021). There have been no serious studies on the measurement of ambient air quality at landfills so far. The current data refer to the measurement of the concentration of CO_2, CH_4, PM and CO during a certain period (e.g. during 24 hours once a month). Available data on the impact of NRMM that use diesel fuel is insufficient. There is an evident lack of analysis of the impact of these machines on the general level of contamination, as well as a lack of regulations that should better regulate this area.

The subject of this research is the calculation of air emissions (CO_2, CH_4, N_2O, NMVOC, PM10, CO, Cd, Cr, Chy and B[a]A) from NRMM at the Banja Luka landfill based on fuel consumption during the year according to EEA guidelines. By gaining an insight into the calculated air emissions of polluting substances on the example of the Banja Luka landfill, this work can serve as an example for considering NRMM in a wider area and in other sectors, not only in the waste management sector, where NRMM with diesel fuel are used.

MATERIALS AND METHODS

Description of the location and waste management in the Banja Luka region

The regional sanitary landfill is located in Ramići, about 10 km from the center of Banja Luka. This landfill is the second largest landfill in BiH. The waste that is deposited at this landfill is brought from three cities, Banja Luka, Gradiška and Laktaši, as well as from five municipalities (Srbac, Čelinac, Kotor Varoš, Kneževo, Prnjavor) (Figure 1). The total number of inhabitants in the region is 370,329. The total amount of disposed waste in 2020 and in 2021 was 121,086.71 tons, i.e. 125,487.94 tons (Table 1). The amount of discarded waste when converted per inhabitant per year is 327 kg/year (0.90 kg/day) in 2020 that is, 339 kg/year (0.93 kg/day).

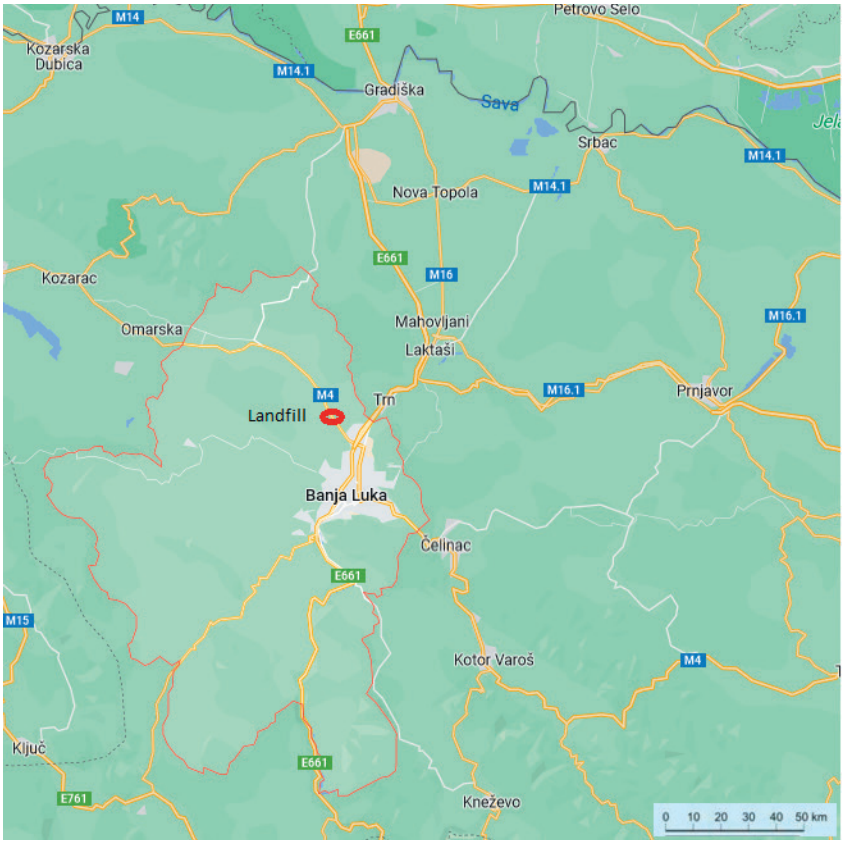

Figure 1. Location of cities and municipalities in relation to the landfill

The technological procedure of waste disposal includes receiving, unloading, pushing, spreading, compacting and covering of waste, in which NRMM is engaged. NRMM, which daily participates in waste disposal activities at the Banja Luka landfill, are: three bulldozers (manufacture date: year 2005, 2007 and 2020), two loaders (manufacture date: year 2005 and 2014), a backhoe (manufacture date: year 2005), compactor (manufacture date: year 2005), two trucks (manufacture date: yea 2005 and 2007), tractor (manufacture date: year 2005) and forklift (manufacture date: year 2015). The average age of eleven NRMM's at the Banja Luka landfill is about 13.5 years. These vehicles use diesel fuel. The total fuel consumption of NRMM's in 2020 was 118,571 L, and in 2021. 125,888 L of diesel fuel. Average monthly consumption of diesel fuel in 2020 was 9,881 L and in 2021. 10,491 L.

Fuel consumption per ton of disposed waste in 2020 was 0.98 L/ton of waste and in 20221. 1.00 L/ton of waste. The highest fuel consumption in 2020 and 2021 was 1.19 L/ton of waste in February, or 1.32 L/ton of waste, and the lowest amount was in September 2020. (0.79 L/ton of waste) and in August 2021 (0.80 L/ton of waste).

NRMM fuel consumption at the landfill location depends on the degree of waste compaction and the amount of soil that is excavated and/or moved for daily cover. A small amount of fuel consumption data from NRMMs that deposit waste was found in the literature. Typical values are in the range of 1-3 L of diesel fuel per 1 ton of landfilled waste (Manfredi et al., 2009; Niskanen et al., 2009). Emissions from vehicles (trucks) that bring waste, as well as emissions resulting from the decomposition of waste from the body of the landfill, were not taken into account in this paper.

Table 1. Total NRMM fuel consumption and the amount of disposed waste in 2020 and 2021

	2020			2021		
	disposed waste (tons)	Diesel consumption		disposed waste (tons)	Diesel consumption	
		Total (L)	L/ton waste		Total (L)	L/ton waste
January	8,417.18	9,004	1.07	8,488.49	8,468	1.00
February	8,920.18	10,589	1.19	8,882.37	11,693	1.32
March	9,672.30	7,766	0.80	10,330.82	11,823	1.14
April	8,538.34	5,632	0.66	9,623.28	9,885	1.03
May	9,638.22	9,871	1.02	10,784.43	10,757	1.00
June	10,624.57	11,677	1.10	10,772.18	10,184	0.95
July	11,222.13	11,172	1.00	11,524.42	9,925	0.86
August	11,405.60	10,717	0.94	11,224.48	8,963	0.80
September	11,184.04	8,851	0.79	10,991.66	10,252	0.93
October	11,444.35	12,595	1.10	11,193.18	10,846	0.97
November	9,813.88	9,197	0.94	11,029.27	12,280	1.11
December	10,205.92	11,500	1.13	10,643.36	10,812	1.02
Total	121,086.71	118,571	-	125,487.94	125,888	-
Average	-	9,881	0.98	-	10,491	1.00

Methodology for estimating the air emission from NRMM

Information on how to estimate emissions from anthropogenic and natural emission sources, in accordance with EU regulatory requirements, can be found in the EMEP/EEA Air Pollutant Emission Inventory Guide 2019 (EEA, 2019). It provides a methodology for estimating combustion and evaporative emissions from selected NRMM sources. The methodology for calculating emissions in the EMEP/EEA guide is divided into three Tiers (1, 2 and 3), depending on the level of available information. Tier 1 requires the least data. Emissions are estimated using an average emission factor per pollutant, making this the least accurate tier. Calculations are based on fuel consumption only. For Tier 2, the type of fuel and engine technology is required. The emission factors are separated into a more detailed classification for emission assessment purposes. A significant amount of information is required for Tier 3, and therefore much more accurate determinations of pollutant emissions are produced using this level. However, the amount of data available in this study only allowed calculations for Tier 1. When calculating emissions using the Tier 1 approach, emissions are estimated using the total fuel consumed in each of the source categories. The Tier 1 approach emission are estimated using the total fuel consumed (EEA, 2019):

$$E_{\text{pollutant}} = \sum_{\text{fuel type}} FC_{\text{fuel type}} \text{ x } EF_{\text{pollutane fuel type}}$$

where:

$E_{\text{pollutant}}$ - the emission of the specified pollutant,

$FC_{\text{fuel type}}$ - the fuel consumption for each fuel (diesel, LPG, four-stroke gasoline and two-stroke gasoline) for the source category,

$EF_{\text{pollutane fuel type}}$ - the emission factor for this pollutant for each fuel type (EEA, 2019; see Table 3-1).

The density of diesel fuel is 860 kg/m^3 in summer and 840 kg/m^3 in winter.

RESULTS AND DISCUSSION

The results of calculated air emissions of CO_2, CH_4, N_2O, NMVOC, PM10, CO, Cd, Cr, Chy i B[a]A, according EMEP/EEA guidelines and Tier 1, are shown in Table 2 and Figures 2-4.

CO_2 emissions directly depend on fuel consumption. As fossil fuels are burned, the carbon contained in them is almost entirely emitted as CO_2. Total CO_2 emissions in 2020 from NRMM at the Banja Luka landfill amounted to 318,395.41 kg, and in 2021. 337,946.96 kg. Of all the pollutants analyzed in this study, CO2 is the most extracted from NRMM, because 1 ton of diesel fuel produces 3,160 kg of CO_2. CO_2 is not defined as a toxic substance, but only as harmful. It is the main cause of the greenhouse effect and in higher concentrations is harmful to living organisms (Rymaniak et al., 2021). By disposal 1 ton of waste at landfill in Banja Luka, the NRMM emitted 2.63 kg of CO_2 into the air in 2020, i.e. 2.69 kg of CO_2 in 2021.

Small amounts of methane can be produced when the hydrocarbons in the fuels are not completely burned. The methane content of the fuel, the type of engine, the amount of unburned hydrocarbons passing through the engine, and post-combustion emission controls affect methane emissions. In uncontrolled engines, the proportion of methane emissions is generally highest at low operating speeds and when the engine is idling. Poorly tuned engines can have particularly high methane emissions (Jun et al., 2000). The total amount of methane was 8,362.92 g in 2020 and 8,876.45 g in 2021.

N2O is produced during fossil fuel combustion when nitrogen from the air or fuel is oxidized in the high temperature environment of the engine. Emissions are influenced by fuel type and engine type (Ongar et al., 2018). The total amount of N2O in 2020. was 13,602.34 g and in 2021. 14,437.61 g.

NMVOCs together with NOx participate in the formation of tropospheric ozone and other photochemical oxidants. NMVOC emissions are a function of the amount of hydrocarbons passing through the engine unburned. This condition depends on engine type, fuel type and post-combustion emission control. Emissions are generally highest at low speeds and when the engine is idling. Poorly tuned engines can have particularly high NMVOC effect (Jung et al., 2019). Total emission of NMVOC from NRMMs at the Banja Luka landfill in 2020. was 340,259.90 g, and in 2021. 361,154.08 g. By disposal 1 ton of waste at landfill in Banja Luka, the NRMM emitted 2.81 g of NMVOC into the air in 2020, i.e. 2.88 g of NMVOC in 2021.

Combustion of fossil fuels, especially coal, gasoline, and diesel is a major source of PM, which is a key contributor to global pollution, human mortality and disease (Vohra et al., 2021). The total amount of PM10 in 2020. was 211,994.92 g and in 2021. 225,012.78 g. By disposal 1 ton of waste at landfill in Banja Luka, the NRMM emitted 1.75 g of PM10 into the air in 2020, i.e. 1.79 g of PM10 in 2021.

CO is formed in the process of fuel combustion during partial and incomplete oxidation, i.e. incomplete combustion of carbon in fossil fuels. Emissions are highest when air-fuel mixtures contain less oxygen than is required for complete combustion. This condition generally occurs under idle, low speed and cold start conditions in engines. When emitted, CO contributes to the formation of tropospheric ozone before the molecules are further oxidized to CO_2 through natural processes in the atmosphere (Mehta et al., 2007). The total amount of CO in 2020. was 1,085.57 kg and in 2021. 1,152.23 kg. In addition to CO_2, the burning of fossil diesel fuel produces a large amount of CO (10.44 kg of CO is produced from 1 ton of diesel fuel). By disposal 1 ton of waste at landfill in Banja Luka, the NRMM emitted 8.97 g of CO into the air in 2020, i.e., 9.19 g of CO in 2021.

Burning fossil fuels also produces a significant amount of heavy metals, Cr and Cd (Elehinafe et al., 2020). Cr occurs due to wear of compression rings, gears and bearings, and can be related to lubricant content, catalyst additives and engine friction products (Lin et al., 2017). The total amount of Cd was 1.01g in 2020. and 1.07 g in 2021. The total amount of Cr was 5.04 g in 2020. and 5.35 g in 2021.

Table 2. Air emissions of CO_2, CH_4, N2O, NMVOC, PM10, CO, Cd, Cr, Chy and B[a]A

Pollutant	year	January	February	March	April	May	June	July	August	September	October	November	December	average	sum
CO2 (kg)	2020	23900.22	28107.44	20614.07	15305.52	26825.43	31733.42	30361.03	29124.52	24053.48	33432.17	24412.52	30525.60	26532.95	318395.41
	2021	22477.46	31037.90	31382.97	26863.48	29233.22	27676.04	26972.18	24357.85	27860.84	28789.62	32596.03	28699.37	28162.25	337946.96
CH4 (g)	2020	627.76	738.27	541.45	402.01	704.59	833.50	797.46	764.98	631.78	878.12	641.21	801.78	696.91	8362.92
	2021	590.39	815.24	824.30	705.59	767.83	726.93	708.45	639.78	731.79	756.18	856.16	753.81	739.70	8876.45
N2O(g)	2020	1021.05	1200.79	880.66	653.88	1146.02	1355.70	1297.07	1244.24	1027.60	1428.27	1042.94	1304.10	1133.53	13602.34
	2021	960.27	1325.99	1340.73	1147.65	1248.89	1182.36	1152.29	1040.60	1190.26	1229.94	1392.55	1226.08	1203.13	14437.61
NMVOC (g)	2020	25541.47	30037.60	22029.66	16356.57	28667.56	33912.58	32445.95	31124.53	25705.25	35727.98	26088.95	32621.82	28354.99	340259.90
	2021	24021.01	33169.30	33538.07	28708.21	31240.69	29576.58	28824.38	26030.52	29774.06	30766.63	34834.43	30670.18	30096.17	361154.08
PM10 (g)	2020	15913.31	18714.58	13725.32	10190.77	17860.98	21128.83	20215.06	19391.77	16015.35	22259.90	16254.41	20324.64	17666.24	211994.92
	2021	14966.00	20665.74	20895.50	17886.31	19464.15	18427.34	17958.69	16218.01	18550.38	19168.79	21703.18	19108.70	18751.07	225012.78
CO (g)	2020	81487.64	95832.14	70283.54	52184.08	91461.13	108194.88	103515.73	99299.86	82010.18	113986.77	83234.32	104076.84	90463.93	1085567.12
	2021	76636.75	105823.52	107000.04	91590.85	99670.49	94361.28	91961.48	83047.93	94991.34	98158.04	111135.96	97850.33	96019.00	1152228.02
Cd (g)	2020	0.08	0.09	0.07	0.05	0.08	0.10	0.10	0.09	0.08	0.11	0.08	0.10	0.08	1.01
	2021	0.07	0.10	0.10	0.09	0.09	0.09	0.09	0.08	0.09	0.09	0.10	0.09	0.09	1.07
Cr(g)	2020	0.38	0.44	0.33	0.24	0.42	0.50	0.48	0.46	0.38	0.53	0.39	0.48	0.42	5.04
	2021	0.36	0.49	0.50	0.43	0.46	0.44	0.43	0.39	0.44	0.46	0.52	0.45	0.45	5.35
Chy (g)	2020	1.51	1.78	1.30	0.97	1.70	2.01	1.92	1.84	1.52	2.12	1.55	1.93	1.68	20.15
	2021	1.42	1.96	1.99	1.70	1.85	1.75	1.71	1.54	1.76	1.82	2.06	1.82	1.78	21.39
B[a]A (g)	2020	0.61	0.71	0.52	0.39	0.68	0.80	0.77	0.74	0.61	0.85	0.62	0.77	0.67	8.06
	2021	0.57	0.79	0.79	0.68	0.74	0.70	0.68	0.62	0.71	0.73	0.83	0.73	0.71	8.56

PAHs emitted by diesel vehicles can be linked to their presence in unburned fuel (petro genic source) and can be formed during combustion (pyrogenic source). During engine use, the lubricating oil can accumulate significant amounts of PAHs. Combustion in diesel engines is very complex and involves a number of reactions and physical processes. The factors that favor the formation of PAHs during the combustion of diesel fuel are still not completely clear (de Souza & Corrêa, 2016). Based on diesel fuel consumption and emission factors (1 kg of diesel fuel emits 200 µg of Cry, i.e., 80 µg of B[a]A), the total production of Cry was 20.15 g and 8.06 g of B[a]A in 2020. In 2021, the total production of Cry was 21.39 g and 8.56 g. of B[a]A.

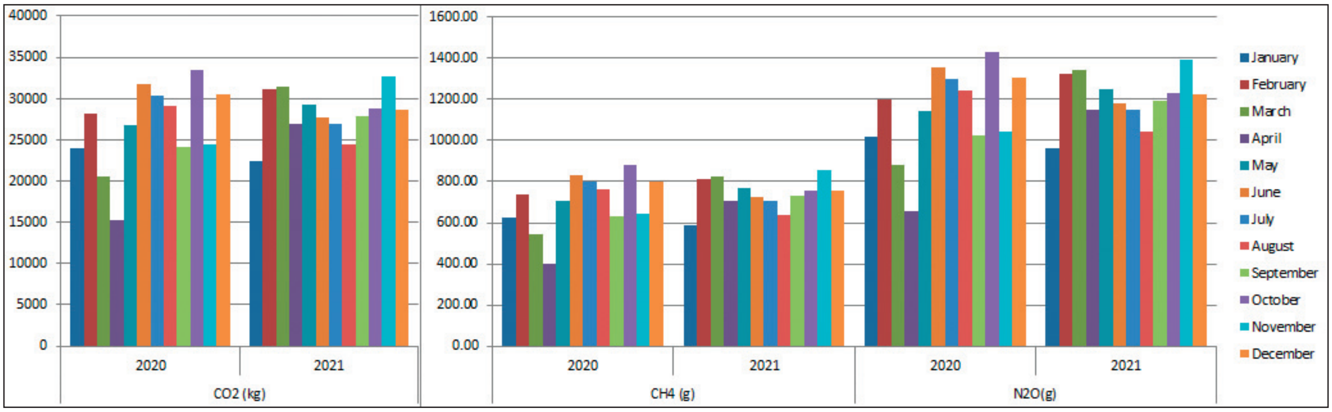

Figure 2. Air emissions of CO2, CH4 and N2O from NRMM from the landfill in 2020 and 2021.

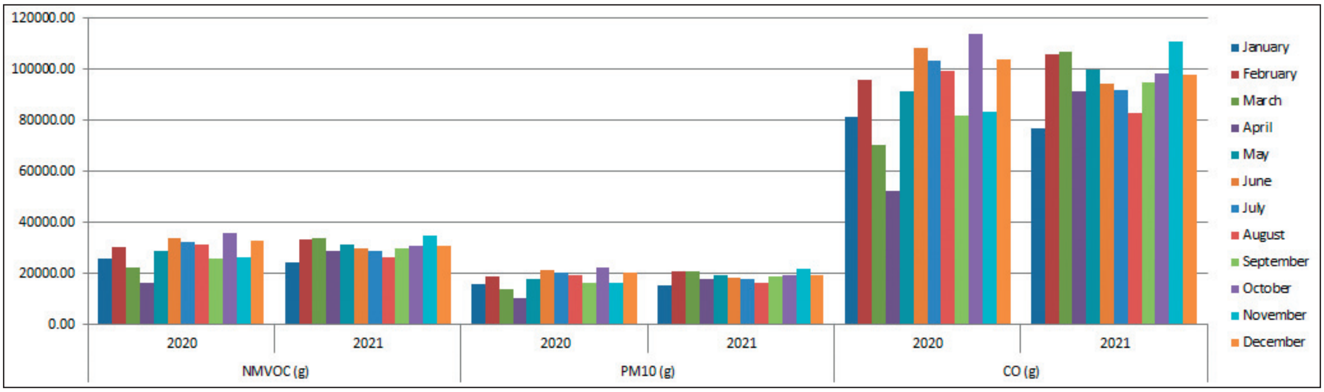

Figure 3. Air emissions of NMVOC, PM10 and CO from NRMM from the landfill in 2020 and 2021.

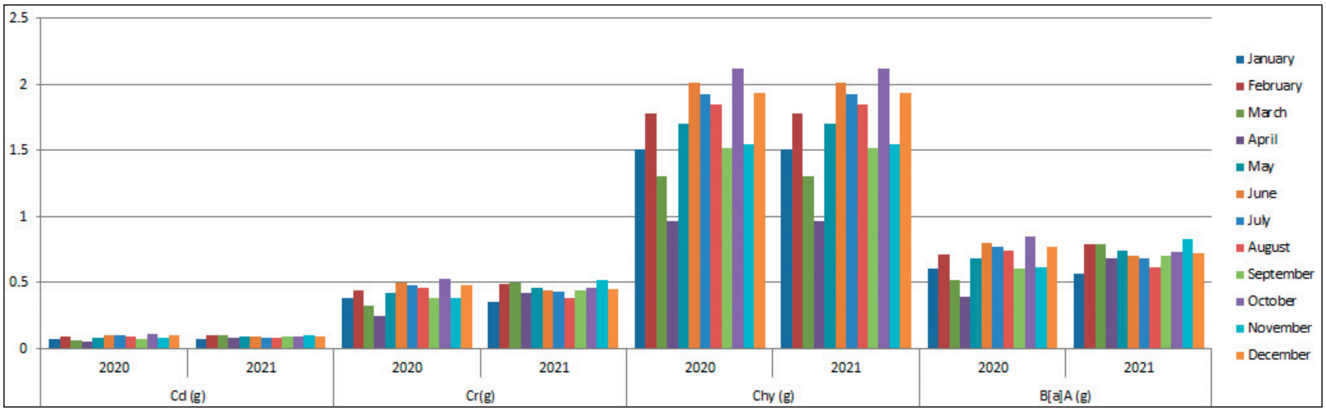

Figure 4. Air emissions of Cd, Cr, Chy and B[a]A from NRMM from the landfill in 2020 and 2021.

CONCLUSIONS

NRMM fuel consumption at the landfill location depends on the degree of waste compaction and the amount of soil that is excavated and/or moved for daily waste covering. The amount of fuel used by NRMM to dispose 1 ton of waste at the landfill is about 1.00 L/ton of waste. By disposing of solid waste, NRMM emits various pollutants into the air such as CO_2, CO, NMVOC, PM, PAHs, heavy metals, etc. The largest amounts of pollutants produced by these vehicles by burning diesel fuel are CO_2, NMVOC, PM10 and CO. NRMM produces much lower concentrations of Cd, Cr and PAHs (chrysene and benz[a]anthracene) with its activities at the landfill, but the harm and risk to human health and the environment of these substances is significant. To reduce emissions from NRMM, the recommendation is to implement innovations from the road vehicle engines into engines for NRMM, replacement of old NRMMs with new ones and establishing of sustainable waste management, which would reduce the amount of waste that is disposed of.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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