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PREPARING THE EMISSION INVENTORY OF AIR POLLUTANTS FROM ISFAHAN'S WASTE IN 2016

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ABSTRACT:

Introduction: Waste sources include municipal solid waste and municipal wastewater, as well as the air pollutants produced by human and animal digestion. The purpose of the present study was to investigate the level of air pollutants resulting from these waste sources.
Materials and methods: In order to conduct this study, emission factors defined by the European Environment Agency were used. First, the type and quantity of the municipal solid waste produced in Isfahan were studied. Next, the amount of municipal solid waste recycling and compost were determined. Then, using related emission factors, emission inventories of $PM_{2.5}$ and PM_{10} from municipal solid waste landfill, and ammonia from composting processes were determined. In the subsequent step, the volume from the municipal wastewater treatment facilities of Isfahan and selected nearby cities was specified, and by using the emission coefficient, the total emission of VOCs was determined. By specifying city population and predicting the population for the next 10 years, ammonia from human digestion was estimated.
Results: The results showed that annually, 20391 g of VOCs are produced by municipal wastewater treatment facilities in the Isfahan metropolitan area. In addition, it was specified that 675980 kg PM_{10} and 319740 kg $PM_{2.5}$ were emitted into the air from Isfahan's Gardane Zinal landfill each year. Annual amounts of carbon monoxide and ammonia produced by composting are estimated at 11191 and 13189 tons, respectively.
Conclusions: Investigating the contributions of various sources of pollutants in metropolitan Isfahan may lead to a suitable context in which the share of different sources of pollutants is understood, and therefore, air pollution management will be possible.

INTRODUCTION

Isfahan is among the cities in Iran with an air pollution problem. Air pollution is created by different sources, of which the most important include transportation systems and industries. In addition, a smaller subset of opportunities to address waste exist, known as waste resources. Waste resources include municipal solid waste, municipal wastewater as well as human and animal digestive systems.

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Each day, millions of tons of municipal solid waste are produced in Isfahan and contribute to air pollution. Sanitary landfilling of municipal solid waste is known as one of the best disposal methods, and has been used for several years in Isfahan. In 1958, the first composting facility was constructed in Isfahan [1]. By late 2012, with the development of technology and new methods for recycling municipal solid waste, recycling methods were used instead of landfilling. Isfahan's composting facility was closed in 1970 due to its failure to comply with health regulations; however; a new plant put into place in 1989 [2].
Disposing of solid waste by sanitary landfilling can produce some air pollutants, such as particulate matter (PM), carbon dioxide, methane, hydrogen sulfide, and non-methane volatile organic compounds [3]. During processes such as composting, air pollutants like ammonia and carbon dioxide are produced and emitted into the atmosphere. Therefore, investigating the portion of air pollution from landfills and composting facilities is very important to community wellbeing [4].
Wastewater treatment facilities are a source of air pollution in cities [5]. Wastewater is the water consumed in many aspects of human life that has lost its natural composition due to those uses [5]. Not only can wastewater not be used in sectors such as agriculture, but due to its level of pollutants, wastewater can be a serious threat to the health and activities of humans. Wastewater contains large quantities of organic chemical compounds, some of which have low molecular weight and low evaporation temperature [6]. Turbulence and aeration of these compounds cause their evaporation from the wastewater surface and their release into the atmosphere. These compounds are called volatile organic compounds (VOCs). Most VOCs are dangerous, with risks to human health.
In 1996, the European Environment Agency (EEA) mandated that all wastewater treatment facilities in the European Union annually report their VOCs from sewage treatment [3]. The EEA developed certain available methods for their covered industries. In Canada, the amount of VOCs emission from a municipal wastewater treatment facility in Ontario in 1993, was between 36 and 50 g for each 1000 m^3 of treated wastewater [7]. Unfortunately, no study has yet been conducted to investigate the emission inventory of municipal wastewater treatment facilities in Iran. Therefore, the emission inventory must be determined to evaluate the contribution of wastewater treatment to air pollution in Isfahan.
The digestive systems of humans and animals produce gases related to food consumption [8]. Since animal population in urban areas is much smaller than that of humans, for purposes of this study the effect of animals' digestive systems on air pollution can be ignored. The EEA has reported that ammonia is the primary pollutant generated by human digestion [3].
Ammonia is dissolved into the moisture available in the respiratory system, oral cavity, skin, eyes, etc., and in the body it forms ammonium hydroxide, a very caustic compound. "Ammonium hydroxide causes the necrosis of tissues through disruption of cell membrane lipids (saponification) leading to cellular destruction. As cell proteins break down, water is extracted, resulting in an inflammatory response that causes further damage" [9]. Given that hundreds of thousands or more people live in larger cities, the impact of the ammonia produced by human digestion must be evaluated.
Although Isfahan's air pollution has been studied, no research has yet determined the amount of pollutants resulting from waste resources. Therefore, this study seeks to determine the emission inventory of pollutants resulting from its municipal solid waste landfills, composting plants, wastewater treatment facilities, and human digestion in the Isfahan metropolitan area.

MATERIALS AND METHODS

According to the EEA, PM_{10} and $PM_{2.5}$ are the main pollutants from solid waste disposal in landfills [3]. PM_{10} is defined as air pollution particulate matter less than 10 μm in diameter. The term for even finer air pollution particulate matter is $PM_{2.5}$, for which 2.5 μm is the maximum diameter. In addition to PM_{10} and $PM_{2.5}$, other pollutants such as carbon dioxide, methane, and VOCs are produced in landfills during anaerobic solid waste decomposition. Since nearly all organic solid waste of Isfahan are separated and transferred to the composting factory and are not landfilled, the production of their carbon dioxide, methane, and VOCs are not taken into consideration in landfill-based pollution measurements. The pollutants produced during wastewater treatment are considered to be VOCs. According to the EEA, ammonia is the main pollutant from human digestion [3]. EEA standard methods are applied in all European countries to prepare their emission inventory every year. The better method to compile the emission inventory of waste resources is direct measurement of emission rates. Unfortunately, we were not able to perform direct measurement due to inadequate logistics. Therefore, EEA standard methods were applied in this study.

Estimating the VOCs produced in Isfahan's wastewater treatment facilities

In this study, total VOCs are the pollutants produced during wastewater treatment. According to EEA standards, for each cubic meter of wastewater treated, 15 mg of VOC are produced. Therefore, the first step in this study was to determine the volume of input wastewater to the wastewater treatment facilities of Isfahan Province. Then, using Eq. (1), daily and annual emissions of VOCs were specified.

$$E = EF \times Q_{wastewater} \quad (1)$$

Where *E* is the amount of VOCs emission in mg/day, *EF* is the emission factor of the VOCs in mg/m^3 of the treated wastewater, and is the volume in m^3 of wastewater that enters the facility.

Estimation of PM_{10} and $PM_{2.5}$ from landfills

Landfilling of solid waste was stopped in Isfahan in 2012 and recycling was instituted. Although the maximum potential and effort of the municipality has concentrated on recycling, some waste cannot be recycled and must be landfilled by the municipality. Non-recyclable waste includes construction waste. Landfilling this part of solid waste leads to the release of particles into the air. In Isfahan, 4000 tons of construction waste are landfilled daily; according to the standards of the EEA, for each ton of landfilled waste, 0.463 kg PM_{10} and 0.219 kg $PM_{2.5}$ are released into the air. Eq. (2) estimates the emission of particles from landfilling construction waste.

$$E = EF \times S \quad (2)$$

where *E* is the amount of PM_{10} or $PM_{2.5}$ emitted in kg/day, *EF* is the emission factor of the relevant particles in kg/ton of landfilled waste, and *S* is tons of landfilled solid waste.

Estimating ammonia and carbon monoxide released from compost processing

During the composting process, carbon monoxide and ammonia are the two important pollutants produced and released into the air. Each day, 1000 tons of solid waste are generated in Isfahan, including 600 tons of organic materials. These materials, after distinctions, are transferred to the composting company. Investigations show that for every 600 tons of solid waste transferred to the company, 150 tons of compost are produced. The amount of the moisture of the organic part of the waste transferred to the Isfahan composting plant is 68%. According to international reports, from each ton of compost produced, 0.56 kg carbon monoxide and 0.66 kg ammonia are produced. Eq. (3) is used to estimate the carbon monoxide and ammonia resulting from compost production.

$$E = EF \times S_{Compost} \quad (3)$$

Where *E* is the amount of emissions of carbon monoxide and ammonia in kg/day, *EF* is the emission factor of the produced compost in kg/ton, and $S_{Compost}$ is the amount of produced compost in tons/day.

Estimating ammonia produced by human digestion

Human and animal digestive systems produce gas which mainly contains ammonia. Since the number of animals in Isfahan is much less than humans and no relevant statistics are available for animals, the ammonia produced by animals has not been taken into consideration in this study. The EEA has determined that the ammonia produced by the human digestive system is 1.6 kg per kg of body weight per year. Eq. (4) provides the total emission rate of ammonia by human in Isfahan city.

$$E = (EF \times H \times B) + (EF \times F \times D) \quad (4)$$

Where *E* is the ammonia emission rate in kg/year, *EF* is the emission factor in kg ammonia produced per year per kg of body weight, *B* is the average weight of men, *D* is the average weight of women, *F* is the population of women, and *H* is the population of men. In this study, it has been assumed that the average body weight of women is 58 kg and the average body weight of men is 74 kg. The populations of men and women in Isfahan according to the 2016 national population and housing census were 1109803 and 1133446, respectively. Although using this methodology is a rough estimation, it was adopted in this study to be employed to make emission inventory because of inadequate logistics for direct measurement.

Modeling the emission of pollutants into the air

In this study, in order to investigate the emission of pollutants into the air, AERMOD View software was used. It estimates the concentration of pollutants at checkpoints based on a Gaussian equation. Each of the pollutants was modeled separately for landfills, compost fertilizer production, sewage treatment, and human digestion. Landfilled construction waste and wastewater treatment facilities were considered as point resources, while the compost production plant and the human digestive system were considered as nonpoint sources since they are the diffuse one. The space allocated to aerobic fermentation in the compost factory was considered to be the area producing carbon monoxide and ammonia and consequently was introduced to AERMOD View. Ammonia was defined as that produced within the city limits of the Isfahan municipality. To model the release of pollutants into the atmosphere, parameters such as wind direction, wind speed, ceiling height, hourly precipitation, global horizontal radiation, dry bulb temperature, relative humidity, station pressure, opaque cloud cover, topographical data of the region, and land use around pollutant resources were collected from organizations such as the Isfahan Meteorological Organization and the National Cartographic Center of Iran, located in Tehran.

Predicting future population

To estimate the amount of solid waste produced in the future, it is necessary to know the population of Isfahan. The Tehran-based Statistical Centre of Iran, provided the population of Isfahan for 2015-2016. Isfahan's population from 2016 to 2026 had to be estimated. According to the statistics of the Statistical Center of Iran, the population growth rate of Isfahan is 0.97% per annum. In this study, it has been assumed that during 2016-2026, the population growth rate will remain stable at 0.97% per annum. Eq. (5) predicts future population and determines the city's waste production.

$$P_n = P_0(1 + r)^n \quad (5)$$

Where P_n is population in year *n*, P_0 is population in the current year, *r* is the rate of population growth in percent, and *n* is the number of years. To estimate waste production in 2016, the total solid waste produced that year was divided by the population in the same year, yielding 477.5 g/day per person. In estimating future waste production, the future solid waste production rate was assumed to be stable. By multiplying the above solid waste production rate by the estimated population, the solid waste production for each year was projected.

RESULTS AND DISCUSSION

Meteorological situation

The speed and direction of predominant winds throughout the Isfahan metropolitan area are shown in a wind rose (Fig. 1). 43.5% of the winds fall within the category of very slow and the rest have noticeable speed. In Fig. 1, the wind rose shows that the predominant wind direction is east to west. Since Isfahan Airport and the main parts of the Isfahan railways are located east of the city, the wind transports their emitted pollutants toward Isfahan. A wind speed of 8.3 m/s is considered adequate to disperse the emitted pollutants [10].

Analysis of solid waste

Isfahan's coordinates are latitude 32.3830° N, longitude 51.3940° E. In the 2016 population census, the population was determined to be 2243249. Isfahan has always been one of the important urban centers on the central Iranian plateau. Isfahan has been a pioneer in dispensing with landfills and instead using recycling. Daily production of municipal solid waste in Isfahan is about 1000 tons, composed of 60% perishable organic materials and 40% non-perishable materials. Estimates show that municipal solid waste per capita is about 445.7 g/day. Isfahan discontinued landfills in 2012; now, all collected waste are used in different applications [11]. However, some waste, such as construction waste, cannot be recycled and is landfilled. Fig. 2 displays the non-perishable solid waste analysis for Isfahan.

Estimating VOCs produced in wastewater treatment facilities in Isfahan and modeling their emissions into the air

Several wastewater treatment facilities are located inside or around of Isfahan. The annual emission rate of volatile compounds produced in each of these facilities is presented in Fig. 3. As can be seen, the significant contribution belongs to the wastewater facility located in the north of Isfahan, which treats 179937 m³ wastewater per day and releases 9852 g VOCs into Isfahan's atmosphere each year. The treatment facility south of Isfahan treats 112641 m³ wastewater and releases 6167 g VOCs per year, and so it ranks second in

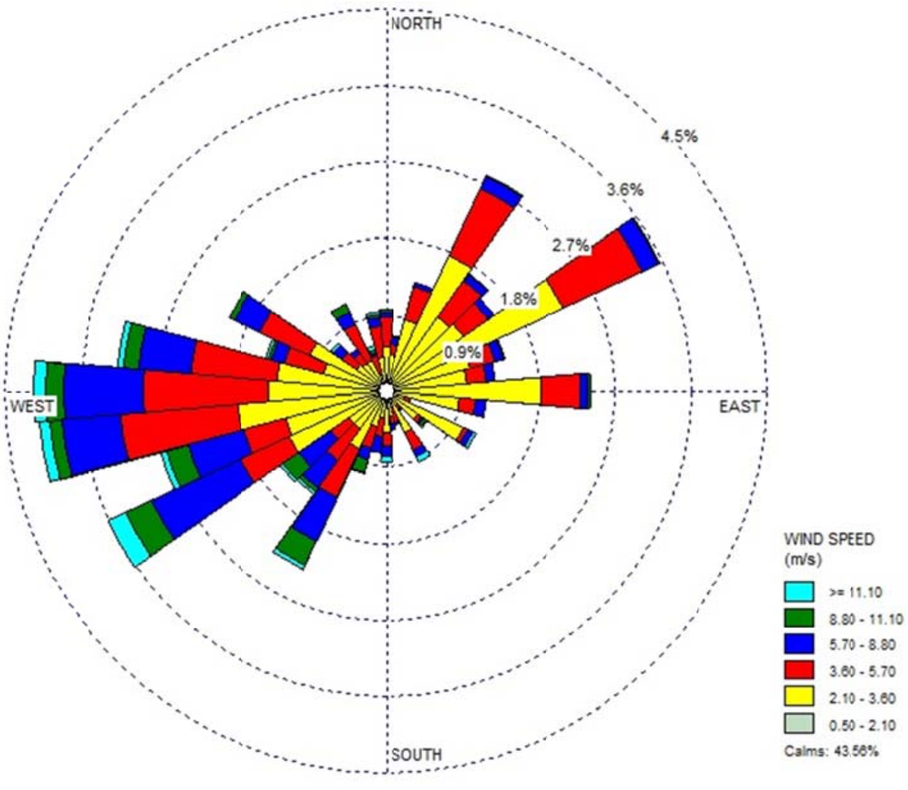

Fig. 1. Isfahan wind rose

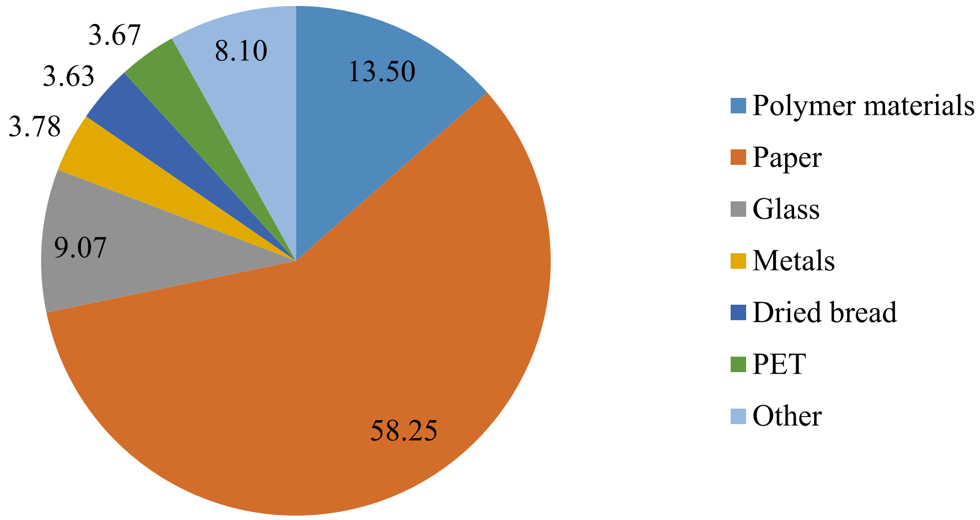

Fig. 2. The analysis of the non-perishable solid waste in Isfahan

Isfahan in compounds released. In third place is the Shahin Shahr wastewater facility, 15 km south of Isfahan. It treats 55613 m^3 of wastewater and releases 3045 g VOCs annually into the environment. However, the 34-km distance between Shahin Shahr wastewater treatment facilities and the city of Isfahan functions as a barrier against the pollutants penetrating Isfahan. Another wastewater treatment facility east of Isfahan treats 54023 m^3 wastewater per day and by releasing 2958 g VOCs annually ranks fourth. Fig. 3 shows that the amount of organic material produced by the remaining treatment facilities is not considerable in comparison to the four previously-mentioned treatment facilities. The results showed that, in sum, 20391 g VOCs are produced and released into the air each year by treatment facilities in Sepahan Shahr, in eastern and northern parts of Isfahan, and in the suburb of Baharestan, 27 miles south of Isfahan.

In Fig. 4, the results of modeling of VOCs' dispersion into the atmosphere of northern Isfahan, southern Isfahan, eastern Isfahan, and Sepahan Shahr are presented. The highest concentration of VOCs was observed around both the north and south wastewater treatment facilities, as much as 0.003 $\mu g/m^3$. It seems that the amount of VOCs emitted from wastewater treatment facilities is insignificant compared with other VOCs sources in Isfahan. Regardless, emissions in such facilities need to be controlled. Several methods have been suggested for the removal of VOCs from air, including biofiltration [12-16], adsorption [17, 18], and incineration [6, 19]; each has many advantages and disadvantages. Managers of wastewater treatment facilities can select one of the above-mentioned methods to control their VOCs emission based on their budget. Zeng Wu et al. reported that among VOCs emitted from wastewater treatment facilities, acetone, isopropanol, and dimethyl sulfide are the major emission types [20]. They mentioned that 87% of the VOCs emitted from wastewater treatment facilities are acetone; an estimate of the concentration of acetone around both the north and south wastewater treatment facilities should be nearly 0.0023 $\mu g/m^3$. Zeng Wu et al. also reported that that the maximum concentrations of acetone around the wastewater treatment facilities of Hsinchu, Taiwan equal 400.4 ppbv [20]. The permissible exposure limit for acetone has been found to be as much as 2400000 $\mu g/m^3$ over an 8-hour work shift. In the short term, this means that VOCs emitted from Isfahan's north and south wastewater treatment facilities have no negative effects on nearby residents.

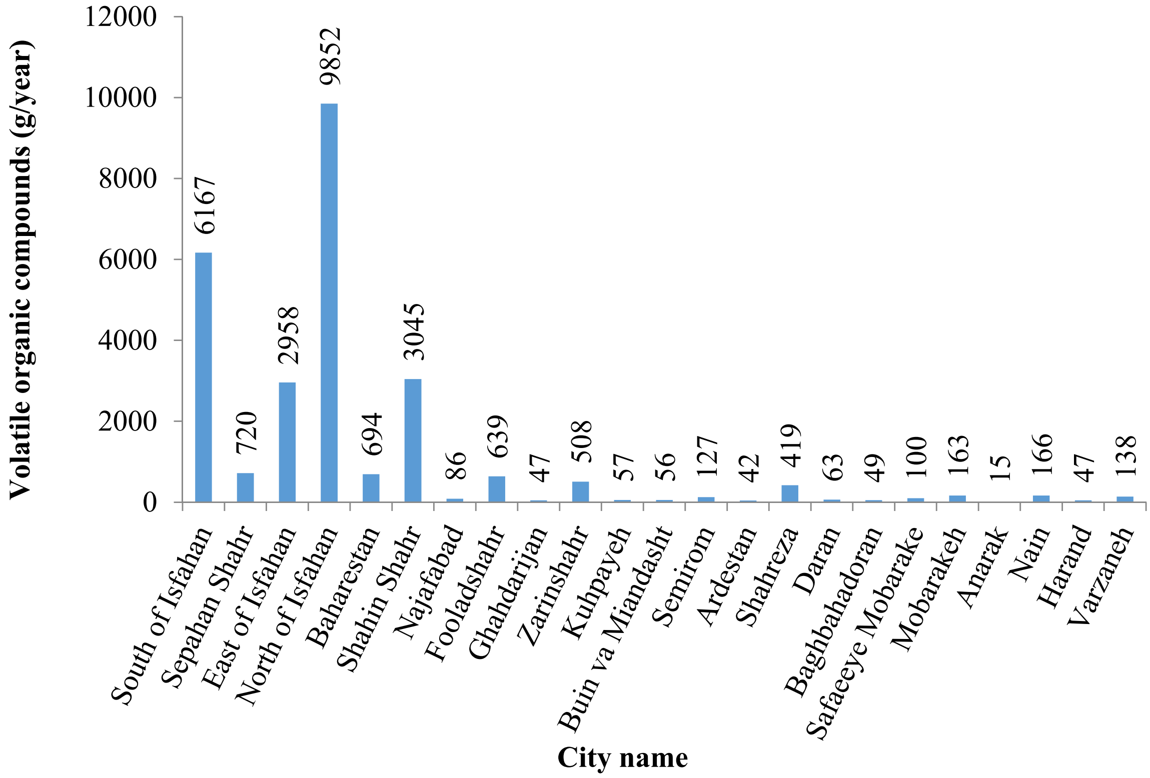

Fig. 3. Comparing the VOCs produced by wastewater treatment facilities in Isfahan and surrounding cities

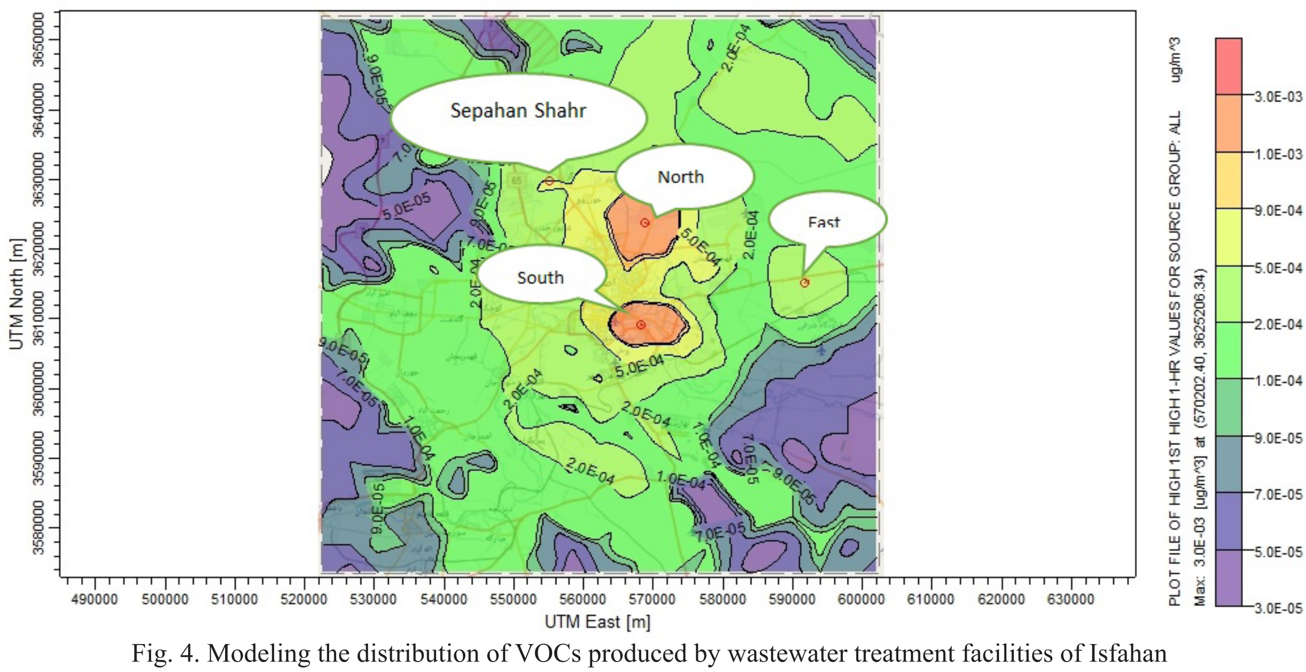

Fig. 4. Modeling the distribution of VOCs produced by wastewater treatment facilities of Isfahan

Estimating PM_{10} and $PM_{2.5}$ resulting from landfilling construction waste and modeling their emission into the air

Each year, a large amount of solid waste is produced in Isfahan. Part is recycled, but the rest cannot be. The non-recyclable part of solid waste is construction waste. Landfilling can lead to the release of particles into the air. Isfahan has two such facilities, the landfills of Sajzi and Gardane Zinal. The results of this study show that 67598 kg PM_{10} and 31974 kg $PM_{2.5}$ are released into the air from the Sajzi landfill in 2016. The amounts of PM_{10} and $PM_{2.5}$ produced by landfills are 675980 and 319740 kg/year, respectively (Fig. 5). Since all organic parts of solid waste are separated for composting, the landfilled solid waste in the Sajzi and Gardane Zinal landfills cannot produce carbon dioxide, methane, and non-methane volatile organic compounds. The landfills' particle emissions are illustrated in Figs. 6 and 7. These figures show that around the landfills the amounts of PM_{10} and $PM_{2.5}$ are 273 and 127 µg/m^3, respectively. In addition, they show that the concentrations of PM_{10} and $PM_{2.5}$ in residential areas of Isfahan are reduced to 3 and 1 µg/m^3, respectively.

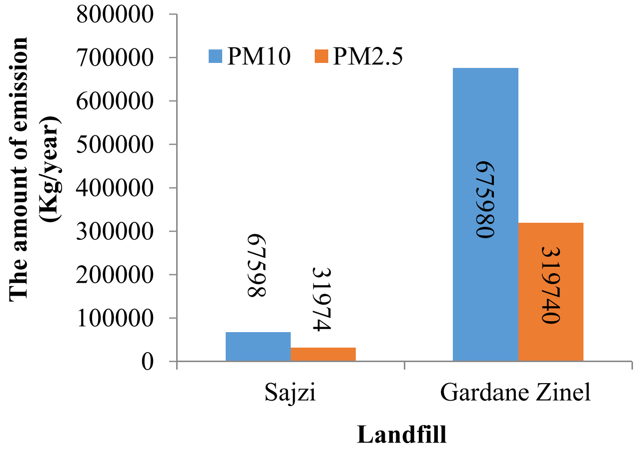

Fig. 5. The amounts of PM_{10} and $PM_{2.5}$ resulting from landfilling construction waste in two landfills

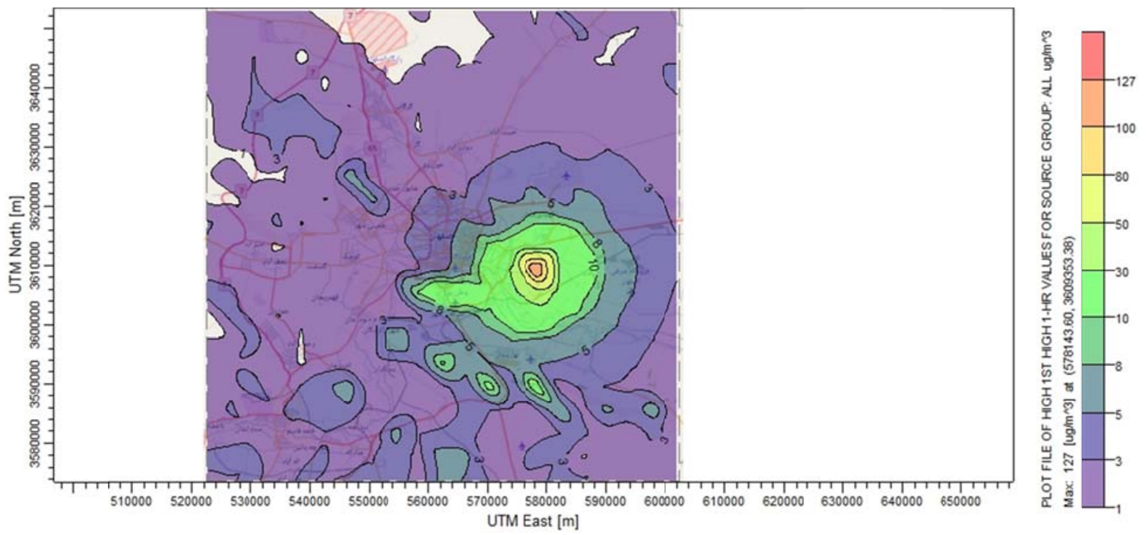

Fig. 6. Modeling the distribution of $PM_{2.5}$ resulting from the landfill of construction waste in Isfahan's landfill

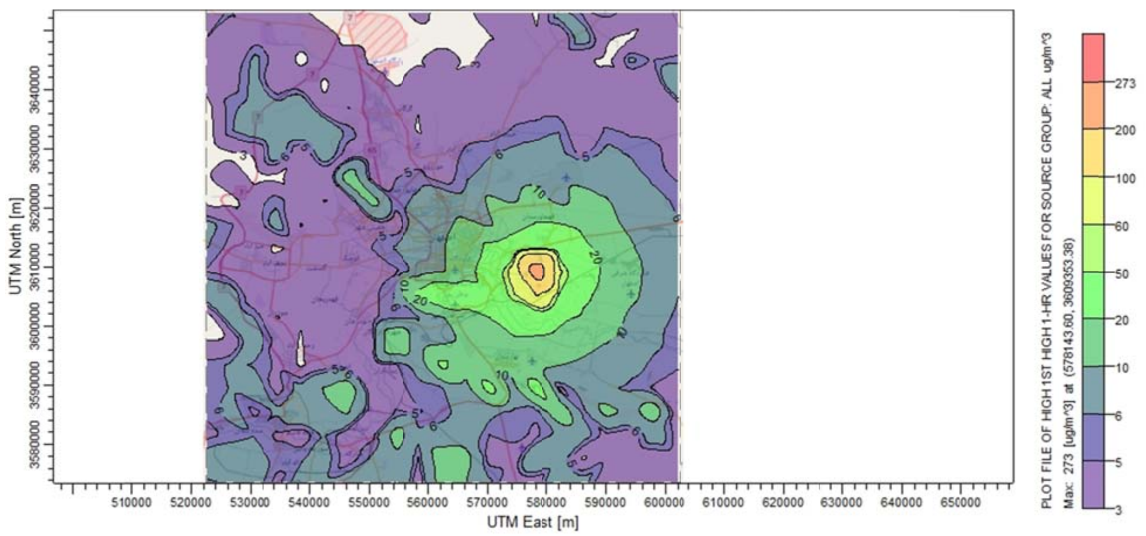

Fig. 7: Modeling the distribution of PM_{10} resulting from the landfill of construction waste in Isfahan's landfill

Estimating ammonia and carbon monoxide produced by composts and modeling their emission into the air

According to the EEA, during composting by aerobic processes, the main pollutants produced are ammonia and carbon monoxide. The results of this study show that each day in Isfahan, roughly 30660 kg carbon monoxide and 36135 kg ammonia are produced by composting and released into the atmosphere. The annual amount of carbon monoxide and ammonia produced during compost production in Isfahan is 11191 and 13189 tons, respectively.

Fig. 8 shows the predicted carbon monoxide and ammonia resulting from compost production, based on our modeling. By 2026, the emission rate of carbon monoxide and ammonia resulting from compost production are expected to be 32300 and 39950 kg/day, respectively. The results of the modeling of the emission of these pollutants into the air are presented in Figs. 9 and 10. The results of modeling carbon monoxide and ammonia around of the composting factory are 20.8 and 39.5 μg/m³, respectively in 2016. The concentration of carbon monoxide and ammonia in residential areas of Isfahan has been reduced to 0.2 and 0.4 μg/m³ due to dilution into the air.

Estimating the ammonia produced by human digestion

Human digestion while digesting food produces various gases. The major gas produced is ammonia. The results showed that in 2016, 237190 tons of ammonia were produced by human digestion and released into the Isfahan's atmosphere. The results of predicting the amount of ammonia to be produced by human digestive system during 2016-2026 are presented in Fig. 11. As can be seen, it is estimated that by 2026, 24459 tons

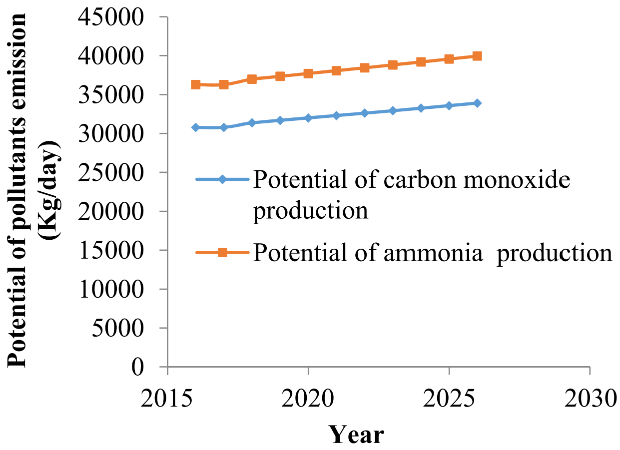

Fig. 8. Predicting the production of ammonia and carbon monoxide resulting from compost production between 2016 and 2026

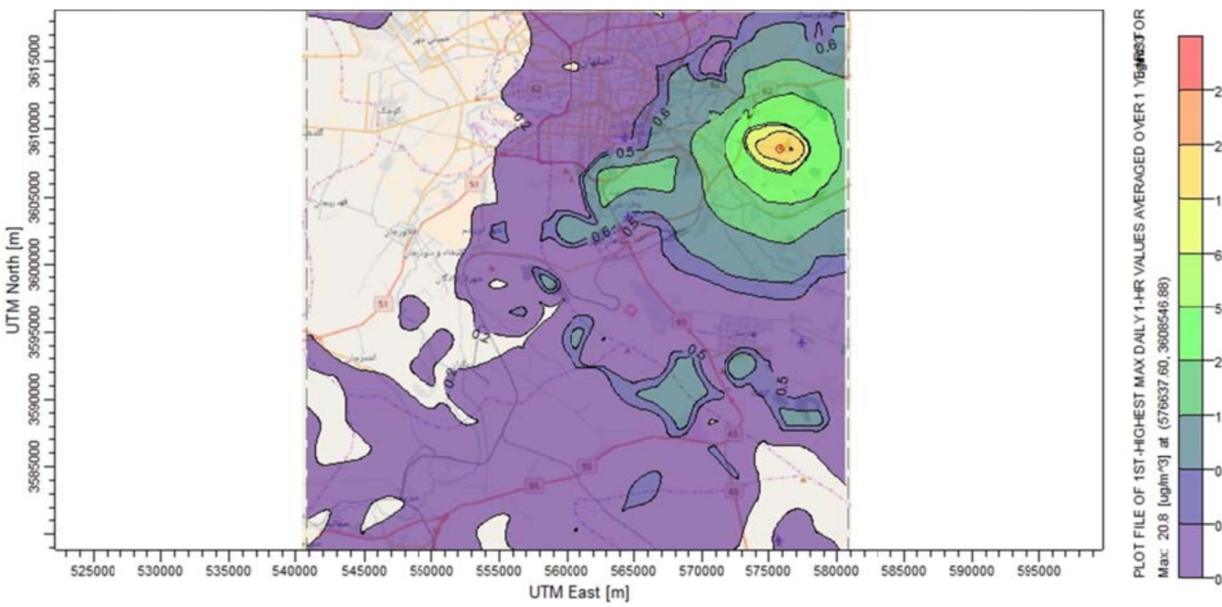

Fig. 9. Modeling the distribution of carbon monoxide produced by the Isfahan compost plant

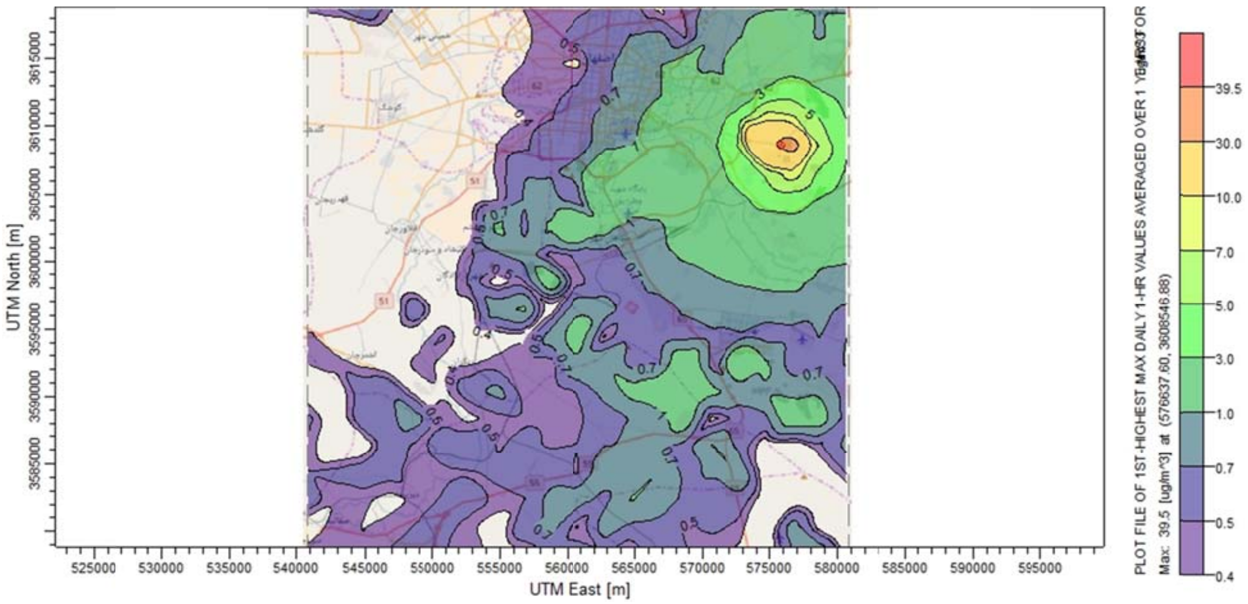

Fig. 10. Modeling the distribution of ammonia produced by the Isfahan compost plant

of ammonia annually will be released through human digestion into the Isfahan's air. Fig. 12 presents the results of this modeling. As can be seen, the concentration of ammonia produced by human digestive system can increase the concentration of this compound in Isfahan atmosphere between 100 and 1750 μg/m^3 in 2016, which is not a dangerous level. It has been reported that 22500 to 37500 μg/m^3 ammonia can cause to very low to moderate stimulation of respiratory system [21]. At a concentration of 97500 μg/m^3, the eyes are irritated and tears are produced. At a concentration of 375000 μg/m^3, the respiration rate in human changes [21]. The results showed that the concentration of the ammonia in Isfahan's atmosphere resulting from human digestion hasn't reached a dangerous level.

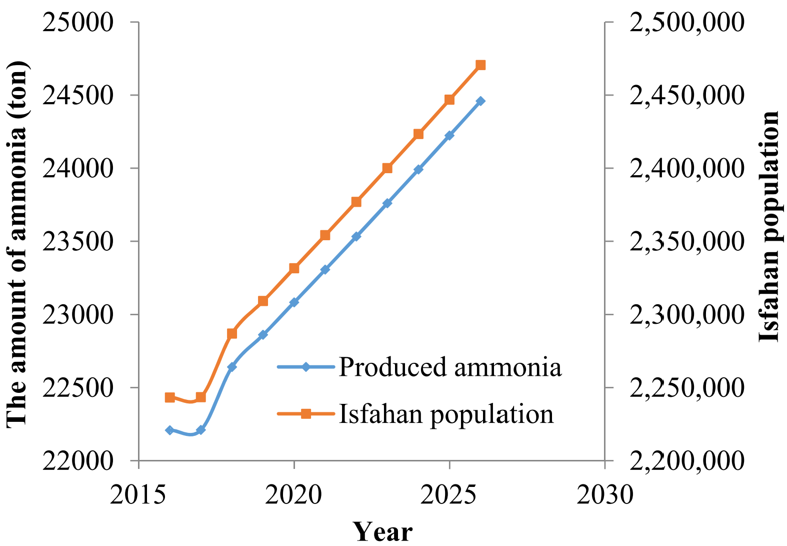

Fig. 11. Predicting the ammonia produced through human digestion annually2016-2026

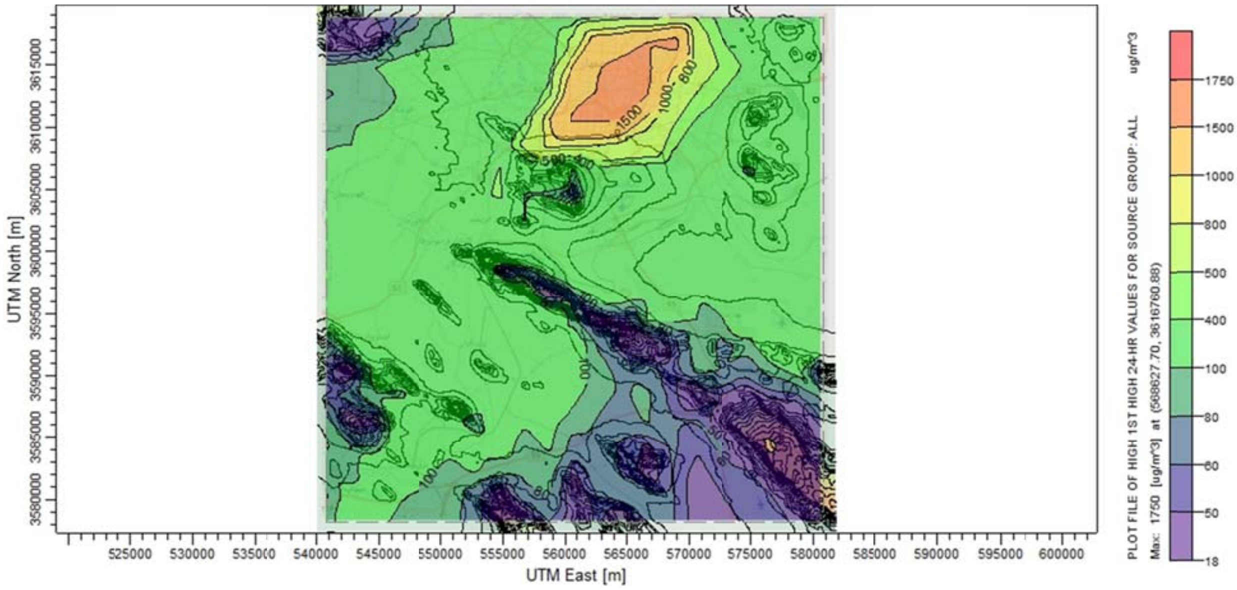

Fig. 12. Modeling the distribution of ammonia resulting from human digestion in Isfahan's atmosphere

CONCLUSIONS

In this study, the pollutants produced by waste resources were investigated in Isfahan, Iran, and nearby communities. Waste resources include wastewater treatment facilities, municipal solid waste, and human digestion. In this study, it was specified that annually, 20391 g VOCs are produced in wastewater facilities south of Isfahan, in the city of Sepahan Shahr, in the eastern and northern parts of Isfahan, and in the suburb of Baharestan, and are released into the air. It was specified that 67598 kg PM_{10} and 31974 kg $PM_{2.5}$ are released into the Isfahan atmosphere annually by the Sajzi landfill. The amounts of PM_{10} and $PM_{2.5}$ produced by the Gardane Zinal landfill are 675980 and 319740 kg/year, respectively. The amounts of carbon monoxide and ammonia produced annually during compost production process are 11191 and 13189 tons, respectively. In 2016, 237190 tons of ammonia were released into the Isfahan atmosphere by human digestion. Since the amount of ammonia produced from human digestive system is dependent on the population, in this study, the population between 2016 and 2026 was estimated and the produced ammonia in these years was predicted. It is estimated that by 2026, 24459 tons of ammonia annually will be released through human digestion into the Isfahan's air. The concentration of ammonia produced by human digestive system can increase the concentration of this compound in Isfahan atmosphere between 100 and 1750 μg/m^3 in 2016

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COMPETING INTERESTS

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

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ETHICAL CONSIDERATIONS

Authors are aware of, and comply with, best practice in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

AUTHOR CONTRIBUTION

It is certified that all the authors have made the same contribution in the experiments and manuscript writing.

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