doi:10.14311/ppt.2026.2.56
Plasma Physics and Technology **13**(2):56–63, 2026

ATMOSPHERIC-PRESSURE OXYGEN PLASMA AS A SUSTAINABLE APPROACH FOR WASTE TIRE DISPOSAL AND EMISSION REDUCTION

R. Cakmak[a], H. Sahin Kol[a], F. Bozduman[b], N. Cakmak[c, d, *]

[a] *University of Karabük, Faculty of Engineering and Natural Sciences, Department of Environmental Engineering, 78050 Karabük, Türkiye*

[b] *University of Karabük, Faculty of Medicine, Department of Biophysics, 78050 Karabük, Türkiye*

[c] *University of Karabük, Faculty of Engineering and Natural Sciences, Department of Physics, 78050 Karabük, Türkiye*

[d] *University of Wah, Faculty of Science, Department of Physics, 47040 Wah-Cantt, Pakistan*

[*] neclac@karabuk.edu.tr

Abstract. The continuous increase in the number of land vehicles worldwide has resulted in the accumulation of large quantities of waste tires, posing serious environmental challenges. Conventional disposal methods, such as landfilling or use as fuel in cement kilns, contribute to greenhouse gas emissions and the formation of hazardous pollutants. In this study, atmospheric-pressure oxygen plasma technology is investigated as an alternative and sustainable method for waste tire treatment. The gaseous products generated during the plasma gasification process were analyzed and compared with those produced by conventional combustion. The results demonstrate that plasma treatment significantly reduces CO and CO_2 emissions relative to traditional combustion methods. Moreover, an enhanced production of methane was observed during the plasma process, indicating a potential opportunity for energy recovery and improved resource utilization. The relationship between material mass and gas emissions was also examined, revealing that gas emissions increase with increasing sample mass. In addition, plasma treatment was found to substantially reduce ash formation. Overall, the findings highlight that atmospheric-pressure oxygen plasma offers an efficient and environmentally friendly solution for waste tire disposal, combining emission reduction with potential energy recovery.

Keywords: Oxygen Plasma, Atmospheric Pressure, Waste Tires, Gas Emission, Disposal.

1. Introduction

The automotive industry has an important share of the world economy, so this sector directly affects tire production. In parallel with tire production, the disposal of end-of-life tires also emerges as an important problem. Considering a certain lifespan of tires, end-of-life waste tires tend to increase constantly every year. Herrera-Sosa *et al.* stated in their study that the final disposal of automotive tire waste is one of the biggest environmental problems in the world [1]. Durna *et al.* found in their study that when searching for a solution for the disposal of waste tires, situations such as the use of technology that does not harm nature, conversion into raw materials, being economical and suitable for widespread use, keeping the damage to established industries at a minimum level and the commercial value of the resulting product should be taken into consideration [2]. The use of atmospheric pressure plasma technology recommended within the scope of this research is a very clean and reliable application. This study aims to process end-of-life waste tires in a closed environment with atmospheric pressure plasma technology, to determine whether harmful components are formed in the environment, to analyze the components of the synthesis gas that will be formed during the plasma process, and to compare the heat released during decomposition with the plasma technique and the classical combustion technique. It is a comparison of the heat released. Thus, evaluating the data obtained aims to add a new alternative method to solid waste disposal methods. Tires have a composite structure consisting of rubber, cord fabric, steel wires, and many chemical components. Yakaboylu explained that the tire consists of five basic components: tread, shoulder, sidewall, bead, and carcass, and that steel, fabric belts, liner, and inner liner are also included in the tire structure [3]. Andrew reported that a car tire contains 47 % rubber, 21.5 % carbon black, 16.5 % metal, 5.5 % textile, 1 % zinc oxide, 1 % sulfur, and 7.5 % additives [4]. In their study, Anne and Russ listed the raw materials used in tire production as follows: fillers such as natural and synthetic artificial rubber, silica, phenolic resin, zinc oxide, titanium dioxide, aromatic, naphthenic and paraffinic oil, sulfur, and sulfur compounds, carbon black, fatty acids and steel wire [5]. Zhang *et al.* defined a tire as a three-dimensional polymer structure that comprises various additives such as natural or synthetic rubber, a vulcanization agent, carbon black as filler, aramid fibre as an explosion-proof rubber agent, and zinc oxide as a vulcanization activator. These components are crucial for tire functionality [6].

Reshner's study found that tire fires are difficult to control due to the large number of tires in storage areas [7]. He also stated that many harmful compounds are released into the atmosphere due to combustion, with the high heat released and the dense smoke produced. These compounds include sulfur and nitrogen oxides, volatile organic compounds (VOC), carbon black, polycyclic aromatic hydrocarbons (PAH), nitrosamines, and volatile particles.

Polycyclic aromatic hydrocarbons, phenols, zinc, and iron-containing compounds can leak into groundwater and rivers. Rainwater or water used to control fire causes these chemical compounds to pass into the soil and flow into other nearby water sources. The water used to control the fire cuts off the tires' contact with oxygen and causes pyrolysis. As it is known, there is a risk of hydrocarbons forming due to pyrolysis leaking into the soil. In other words, post-fire residues also potentially contaminate the soil. Mui *et al.* examined the pyrolysis of waste tire particles under various heating rate conditions, and the Coats-Redfern model and Runge-Kutta algorithm were applied to model the pyrolysis conditions. The models that have been developed are expected to facilitate improved design of the pyrolysis reactor, as well as a comprehensive understanding of heat and mass transfer events during the thermal degradation of the tire [8]. The carbonization process is the oldest known thermal decomposition process. It was stated in the report on developing bioenergy technologies published by the Risoe National Laboratory team that the carbonization process of waste tires is carried out by pyrolysis at various temperatures [9].

Plasma technologies use electricity as a heat source instead of thermal energy released from combustion, which makes the heat source independent of the substances being processed. This offers greater options in process chemistry, including system flexibility, rapid process control, and the possibility of producing valuable products, making plasma technology an interesting waste treatment option in advanced solid waste mining [10]. Plasma gasification and vitrification are considered a recovery process instead of a disposal technology. For a specific analysis of the arc plasma produced by a plasma pen, the length and diameter of the plasma jet can be measured based on current values by photographic technique during stable plasma formation. Generally, in the current range of 50 to 300 A, the length of the plasma jet formed at the tip of the pen is between 1 and 9 cm. Here, the flow rate of argon gas was determined as 20 liters/min. The plasma pen is a very effective heating device. Arc plasma heating technology is a very suitable and necessary technique for waste treatment and improvement and protection of the environment [11]. Compared with traditional pyrolysis, plasma pyrolysis has many unique advantages. For example, it provides a high temperature and high energy state for the reaction. Thus, the reaction sample is quickly heated to a high temperature, the reaction rate is quite fast, and some reactions that are not visible in conventional pyrolysis occur [12]. Lyubina and Suris examined the thermodynamic model of plasma gasification of organic solid waste and conducted a study on how the basic properties of municipal solid waste are affected by the power required by the plasmotron, the calorific value of the gas and other gasification products, and the unit yield [13]. To investigate the characteristics of rubber powder gasification, the rubber powder gasification process using a laboratory-scale fluidized bed gasifier was reported by [14]. In this study on granular rubber powders gasified with air in the temperature range of 350–900°C, the equivalence ratio, tire feeding rate, the rubber particle size, the bed temperature, the secondary reaction temperature, the product gas composition, the gas yield, the gas heating value, product (*i.e.*, gas, tar). The various parameters such as (*e.g.*, coal) distribution, volatile release rate, fixed carbon conversion rate, and energy recovery rate have significantly affected gasification results. Especially, the use of thermal plasmas in melting and cutting solid materials is gaining significant importance today. Thanks to its advantage in melting solid materials, it plays an effective role in solid waste disposal methods.

The solid waste can be processed using high-energy plasma pens. Plasma can process all types of waste. The plasma pen technology is relatively safe and is the best-known method of producing plasma at temperatures above 5000°C at atmospheric pressure [15]. In addition, the plasma technique is a suitable method for polymer pyrolysis. Especially old tires that have completed their service life as raw materials can be used in producing synthesis gas by thermal plasma pyrolysis. During heat treatments, sulfur additives from the tire-making process are transferred to vapor or liquid phases. Since heat treatment or pyrolysis is a common step in various disposal processes, understanding the physical and chemical transformation of sulfur in tires during heat treatment is crucial for the rational use of used old tires [16].

The rest of this paper is organized as follows. The information about the experimental system and apparatus are presented in Section 2. In Section 3, the experimental results are provided and discussed. Finally, a brief conclusion is given in Section 4.

2. Experimental procedure

Firstly, an end-of-life automobile tire was used in the experimental study. The experimental studies were carried out by cutting pieces with a mass of 2.5 g and 3 g from this tire with the help of a tire saw. The samples were cut in approximately rectangular shapes, and the geometry was kept consistent between the two masses. Figure 1 shows the experimental scheme of the study. The sensors and data acquisition card used to measure carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and toluene (C_7H_8) gases accumulated in the process chamber are shown in

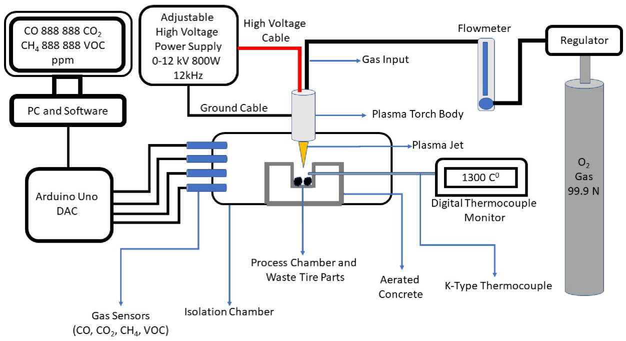

Figure 1. The experimental setup.

Figure 2. The data acquisition card has a USB connection and four analogue inputs. The measurement ranges of gas sensors are 0–500 ppm, 400–16,000 ppm, 0–300 ppm, and 0–300 ppm for CO, CO_2, CH_4, toluene gases, respectively. 1 (parts per million) ppm values refer to one unit per million.

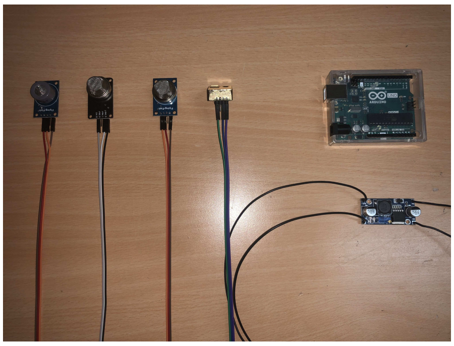

Figure 2. The gas sensors and DAC.

The active image of the plasma pen used to burn waste tires and the plasma formation is given in Figure 3. The plasma pen body is made of SS304 stainless steel, and the electrode distance is adjustable. The diameter of the nozzle hole of the plasma pen is 5 mm. The power supply unit used to create the plasma is shown in Figure 4. This power supply has a voltage of 12 kV and an output power of 800 W, and the frequency is 12 kHz.

Figure 3. View of the plasma pen in active state and plasma formation.

The design of the process room, which holds the gas sensors together and allows the gas to accumulate, is as shown in Figure 5. It contains a ceramic blanket

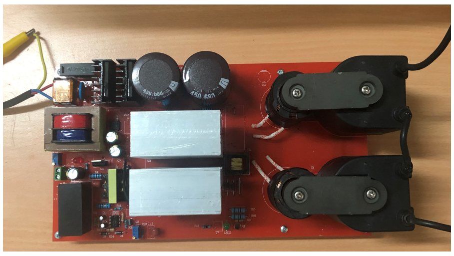

Figure 4. The power supply unit used to create the plasma.

and aerated concrete. Aerated concrete is used as a combustion chamber. The ceramic blanket prevents the process room, the gas isolation chamber, from being damaged due to the high temperature. The experimental setup was designed as a laboratory-scale system, with both the processing chamber and the aerated concrete combustion chamber constructed accordingly. The approximate dimensions of the system are as follows: the processing chamber ($L \times W \times H$) is approximately $30 \times 25 \times 20$ cm, while the aerated concrete combustion chamber measures approximately $10 \times 10 \times 5$ cm. Oxygen gas with 99.9 % purity created atmospheric pressure oxygen plasma. A digital precision scale was used to measure the masses of the cut tire pieces. CEM DT613K model with K-type thermocouple input and a digital display to measure the temperature of the existing process chamber in the first installation; A temperature measuring device with a temperature measurement range of -200°C to $+1372$°C, a temperature sensitivity of $+/-1$°C and a resolution of 0.1°C was used. The cut tire pieces were placed in the combustion chamber made of aerated concrete inside the process chamber and the process chamber was covered with an aluminum composite plate. The plasma pen is placed in the hole opened on the aluminum composite plate so that it can see the combustion chamber. After the gas sensors and data acquisition card were placed in the process room, they were connected to a computer for data analysis transfer.

Figure 5. The process chamber.

The image of the experimental setup before the plasma process is started is shown in Figure 6. After the oxygen plasma at atmospheric pressure was activated, the plasma combustion process was continued for one minute. Then the power of the plasma pen was disabled, that is, the plasma power was turned off. After this process, gas sensors collected data from the process room for five minutes and transferred them to the computer with the student version LabView signal processing program.

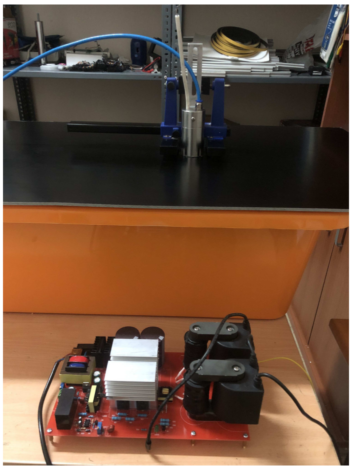

Figure 6. The image of the mechanism before the plasma process is started.

The normal combustion process results were used to evaluate the data obtained from combustion with the plasma process. The normal combustion process was carried out at approximately 500°C in Figure 7. For this process, the high-purity oxygen was released into the environment of the experimental setup at a flow rate of 5 lt/min.

Figure 7. The normal combustion process.

The summary of the experimental stages related to the detection and analysis of harmful components that may cause environmental pollution using atmospheric pressure plasma technology can be summarized as follows: Firstly, end-of-life waste tyre parts were collected. Then, the plasma pen was designed based on the available power supply parameters. High purity oxygen of 99 % and above was used as discharge gas. Discharge was carried out with atmospheric air using an air compressor. An analogue flow meter was used to control the oxygen flow rate. The power supply parameters were calibrated regularly to ensure stable plasma. These parameters are 500 mA and 220 V values. Then, the process room was designed for the analysis of environmentally harmful solid, liquid and gas products that may occur during the plasma process. The necessary gas sensors were added to this room and computer-aided measurements were taken during the process. The temperature of the process chamber was determined with a thermocouple probe. After the process, the gases accumulated in the sample chamber were analysed with gas sensors. Finally, the results obtained were compared with the classical method.

3. Results and Discussion

The emission values of gases released as a result of processing waste tires, which are included in the solid waste group, with atmospheric pressure plasma technology, are given in detail in this section. At the same time, the emission values of gases released from waste tires through the normal combustion process are also presented. With plasma technology, the sample was completely burned and gasified in one minute, while in the normal combustion process, this time was approximately five minutes. In both the plasma and normal combustion processes, high-purity oxygen gas was sent to the process room at a flow rate of 5 lt/min. The main reasons for using high-purity oxygen as the discharge gas in the plasma process can be listed as being harmless, economical, and having caustic properties. This oxygen gas was transmitted to the combustion chamber as oxygen plasma through the plasma pen. For the normal combustion to occur, this oxygen gas was released directly into the process room. With a thermometer probe that directly reads the temperature of the combustion chamber, it was observed that the atmospheric thermal plasma process was at a temperature of 1300°C, while the normal combustion process was at a temperature of 500°C. Since it was determined in the experimental studies that the average time for the gas sensors to reach saturation was 5 minutes, the data collection time for both the plasma process and the normal combustion process was over 5 minutes. The gas sensors collected data and transferred them to the computer with the LabView signal processing program. All data obtained are presented as ppm value per minute. The experimental parameters and their relevant values in the atmospheric pressure oxygen plasma process are presented in Table 1.

In this study, the detection of basic gasification gas products through gas sensors was repeated 40 times for waste pieces with a mass of 2.5 g and 3 g. The same processes were repeated with normal combustion for a 3 g mass waste piece. In addition, crystallized soot particles accumulated in the combustion chamber as a result of the gasification process of solid waste with

Parameter	Value
Power	120 W
Voltage	12 kV
Frequency	12 kHz
Gas Flow Rate	5 lt/min
Discharge Gas Type	99.99% High-purity O
Process Chamber Temperature	~1300°C

Table 1. The experimental parameters and values.

atmospheric pressure oxygen plasma were detected and imaged.

CO gas emission data obtained at 1300°C combustion temperature with 99.99% high purity oxygen gas of 2.5 g and 3 g mass tyre pieces by plasma process, and at 500°C combustion temperature of a 3 g mass tyre piece by normal process are shown as ppm per minute in Figure 8.

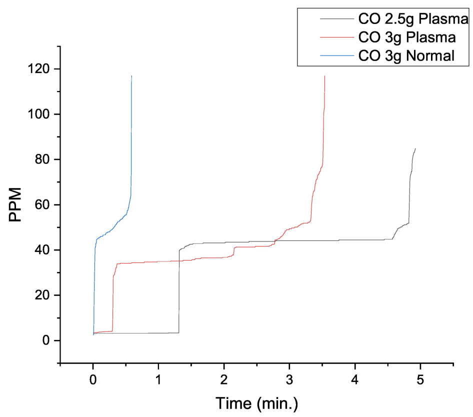

Figure 8. CO gas released from a 2.5 g and 3 g mass waste tire by plasma and normal processes.

CO gas at 40 ppm was measured immediately after the combustion process was initiated using the plasma pen for an average of 1.2 min for 2.5 g tire piece, and the gas sensors that reached saturation for 5 min measured CO gas emission at 84 ppm. For 3 g tire piece, CO gas was measured at 38 ppm immediately after the combustion process was started through the plasma pen for 0.5 min on average, and the gas sensors that reached saturation for 5 min measured CO gas emission at 117 ppm. CO gas at a value of 42 ppm was measured immediately after the normal combustion process was started for 0.2 min on average, and the gas sensors that reached saturation for 5 min measured CO gas emission at a value of 120 ppm.

CO_2 gas emission data obtained at 1300°C combustion temperature with 99.99% high purity oxygen gas of 2.5 g and 3 g mass tyre piece are shown in Figure 9 as ppm per minute. Immediately after the combustion process was started by means of the plasma pen, CO_2 gas was measured at a value of 500 ppm, and the gas sensors that reached saturation for 5 minutes measured CO_2 gas emission at a value of 2730 ppm. CO_2 gas emission data obtained at 1300°C combustion temperature with 99.99 % high purity oxygen gas of a 3 g mass tyre piece are shown in Figure 9 as ppm per minute.

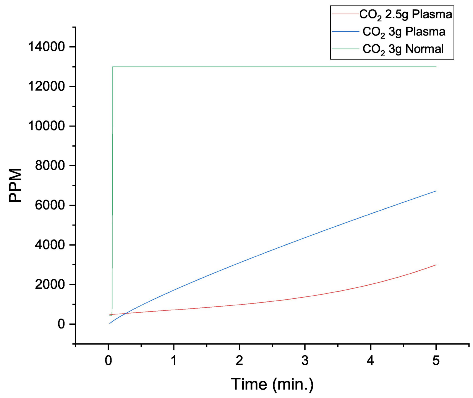

Figure 9. CO_2 gas released from a 2.5 g and 3 g mass waste tire by plasma and normal processes.

Immediately after the combustion process was started by means of the plasma pen, the gas sensors saturated for 5 minutes and measured CO_2 gas emission of approximately 6725 ppm. The fact that the amount of CO_2 gas emission in a 3 g piece of tire is measured more than in a 2.5 g piece of tire indicates that there is a gas emission proportional to the amount of mass. It is expected that the detection time of the gas sensors used in the plasma gasification process will vary. The CO_2 gas emission data obtained at the combustion temperature of 500°C of a tire piece with a mass of 3 grams is shown in Figure 9 as ppm per minute. Just after the normal combustion process was started, CO_2 gas was measured at a value of 13000 ppm, and the gas sensors, which reached saturation for 5 minutes, remained constant at this value. When the gas emission values measured by plasma treatment and normal combustion of tire parts with a mass of 3 grams are compared, it is seen how convenient the disposal of waste tires is with the plasma gasification process.

The methane gas emission data obtained at 1300°C combustion temperature with 99.99 % high purity oxygen gas of 2.5 g and 3 g mass tire piece are presented in Figure 10 as ppm per minute. Just after the combustion process was started through the plasma pen, methane gas was measured at 22 ppm and this value remained constant for 3 minutes. After saturating for 5 min, the gas sensors measured methane gas emission of approximately 133 ppm. In the gasification of 2.5 g and 3 g mass tire pieces with plasma process, it was observed that the gas emission value was proportional to the increase in mass.

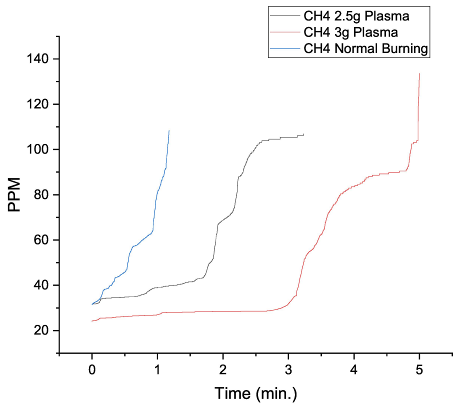

Figure 10. Methane gas released from a 2.5 and 3 grams mass waste tire by plasma and normal processes.

The methane gas emission data obtained at 500°C combustion temperature of a tire piece with a mass of 3 gram is shown in Figure 10 as ppm per minute. Immediately after the normal combustion process was initiated, methane gas emissions of 30 ppm were measured, and the gas sensors, which reached saturation for 5 minutes with an approximately linear increase, measured 108 ppm. When the gas emission values measured by plasma treatment and normal combustion of a tire piece with a mass of 3 grams are compared, it is seen that the methane gas emission value is slightly higher in the plasma gasification process, that is, less hydrocarbon is produced in the normal combustion process due to oxidation. The reason for the increase in ppm values in the specified gases is that combustion occurs rapidly after a certain period. After a certain period, the gas amounts stabilize. The burning effect of oxygen plasma is the main reason for this. In this study, gas measurements were limited to CO, CO_2, CH_4, and toluene (C_7H_8); other species, although present, could not be quantified. Occasional carbon-containing soot was observed in the combustion chamber, particularly after plasma treatment, due to incomplete conversion of carbonaceous material. Nonetheless, the strong oxidizing environment provided by high-purity oxygen ensured that most carbon was converted to gaseous products, limiting solid residue accumulation. No significant liquid-phase products were detected. The presence of soot indicates that complete oxidation of all carbonaceous material was not achieved within the 5-minute treatment period.

The toluene gas emission data obtained at 1300°C combustion temperature with 99.99 % high purity oxygen gas of a 2.5 g and 3 g mass tire piece are presented in Figure 11 as ppm per minute. Immediately after starting the combustion process through the plasma pen, toluene gas was measured at 180 ppm and it was observed that the gas sensors reached saturation at 234 ppm for 5 minutes. Immediately after starting the combustion process through the plasma pen, toluene

	CO	CO_2	CH_4	C_7H_8
2.5 g tire + Plasma	84.85	2730.55	106.87	234
3 g tire + Plasma	117	6725.27	133.50	235
3 g tire + Normal	120	13000	108.42	229

Table 2. The ppm values per minute of gases formed in plasma and normal combustion processes.

gas was measured at 170 ppm and the gas sensors saturated for 5 minutes and measured toluene gas emission at approximately 235 ppm. The toluen gas emission data obtained at 500°C combustion temperature of a 3 g mass tire piece is shown in Figure 11 as ppm per minute. Just after the normal combustion process was started, toluene gas emission was measured at 220 ppm and the gas sensors that reached saturation for 5 minutes measured toluene gas at 229 ppm. The toluene gas emission values remained approximately the same for both plasma gasification of 2.5 and 3 grams mass tire pieces and normal combustion.

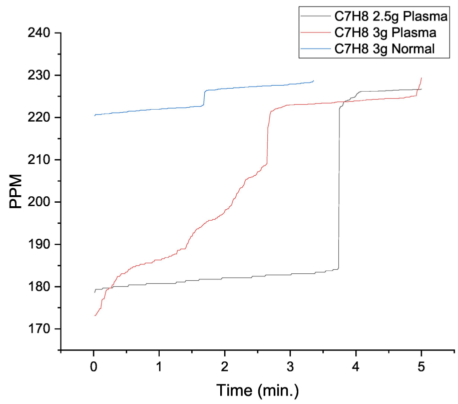

Figure 11. Toluen gas released from a 2.5 and 3 grams mass waste tire by plasma and normal processes.

The ppm emission values per minute of CO, CO_2, CH_4, and C_7H_8 gases released in mass amounts determined as a result of the atmospheric thermal plasma process and normal combustion process are summarized in Table 2. As seen in Table 2, when the data obtained accordingly the plasma treatment of the end-of-life waste tire piece with a mass of 3 g is evaluated according to the normal combustion process, it is seen that the value of CO gas emission is approximately close to each other.

A significant difference was observed in CO_2 gas emission values. The CO_2 gas emission value released from the plasma process is approximately 1.94 times of the data in the normal combustion process. As it is known, CO_2 emissions have the highest share of greenhouse gas emissions, which are released due to the ability of greenhouse gas compounds to retain heat in the atmosphere and increase the temperature in the atmosphere. We were not able to study gases other than those we studied during the experiments, such as oxides of sulphur, because due to the limitations of the project supporting our experimental work, we could not provide sensors to measure these gases. Our experimental study shows how useful the oxygen plasma process is in reducing the CO_2 gas emissions released by the current disposal of waste tires. According to the basic principles of thermodynamics, energy is always conserved. For this reason, we can express that the reason for the formation of more methane gas in the data obtained with the plasma process compared to the normal combustion process is that CO_2 gas emission is less than the normal combustion process, that is, the carbon atoms in the mass turn into methane gas. The plasma process has an increasing effect on the speed of the combustion reaction. The waste tire is suddenly exposed to high temperatures in the plasma process and quickly turns into a volatile organic compound. Plasma treatment increases the reaction kinetics and has a catalyzing effect.

4. Conclusion

There are many classical disposal methods in solid waste management. However, plasma technology, which is one of the sustainable solutions that does not harm nature and does not pose a problem for human health, is one of the most suitable methods in recent years for the disposal of end-of-life waste tires. Plasma pyrolysis and plasma gasification techniques can dispose of tire waste and produce flammable gases that can be used as fuel and prevent the formation of higher molecular aromatic compounds. Research shows that plasma pyrolysis and plasma gasification techniques are effective methods to dispose of tire waste and produce gases that can be used as fuel. The use of plasma technology, especially under atmospheric pressure, reveals that this method provides cleaner and faster waste disposal. The study analyzed gas emission values by comparing the plasma gasification process with the normal combustion process. The main objective of our study is not toincrease the gas emission depending on the mass. Our main goal is to achieve a higher level of recyclable gasesbetween normal combustion and plasma combustion. The plasma gasification process reduced CO_2 emissions while increasing methane gas production. Additionally, it has been determined that the synthesis gas during the plasma gasification process has a higher energy value and is advantageous compared to the normal combustion process. The study also examined the differences between the gas compositions obtained because of the plasma gasification process and the plasma pyrolysis process, coal yield, and process efficiency. It has been observed that plasma gasification reduces harmful gas emissions into the atmosphere and controls ash formation. This method also allows the recovery of scrap metals. As a result, disposal of waste tires with plasma technology offers an environmentally friendly and economical solution. Using this technology on a larger scale could increase the energy production and recycling potential of waste tires, contributing to environmental and economic sustainability.

This study was carried out in Karabuek University, Department of Physics, Plasma Physics Research Laboratory with limited facilities and the processing of end-of-life tyres, which are included in the solid waste group, with plasma technology has been carried out by us for the first time in our country. Thus, a technique that is cleaner and can be processed in a shorter time compared to the existing disposal methods has been introduced to the scientific community of our country.

Acknowledgements

N. Cakmak and F. Bozduman would like to acknowledge the support of the Karabük University, Scientific Research Projects Unit with Project Number: KBÜBAP-21-DS-008.

Authorship contribution statement

R. Cakmak and F. Bozduman: Methodology, Investigation, Formal analysis, Data curation. H. Sahinkol: Methodology, Investigation. N. Cakmak: Supervision, Writing-original draft, review & editing, Conceptualization.

References

[1] E. Herrera-Sosa, G. Martinez-Barrera, C. Barrera-Diaz, et al. Recovery and modification of waste tire particles and their use as reinforcements of concrete. *International Journal of Polymer Science*, 2015:234690, 2015. doi:10.1155/2015/234690.

[2] E. Durna, G. Koz, and N. Genc. Determination of the most suitable disposal option in the management of end of life tires in Turkey by PROMETHEE and fuzzy PROMETHEE method. *Politeknik Dergisi*, 23(4):915–927, 2020. doi:10.2339/politeknik.591100.

[3] O. Yakaboylu. Waste tire management and feasibility study for a model waste tire pyrolysis plant. MSc Thesis. Istanbul Technical University, Istanbul, Türkiye, 2010.

[4] A. Ciesielski. *An introduction to rubber technology.* Rapra Technology Limited. Shawbury, Shrewsbury, Shropshire, U.K, 1999.

[5] A. Evans and R. Evans. The composition of a tyre: Typical components. In *Waste Resources Action Programme*. Banbury, U.K, 2006.

[6] X. Zhang, H. Li, Q. Cao, et al. Upgrading pyrolytic residue from waste tires to commercial carbon black. *Waste Management & Research*, 36:436–444, 2018. doi:10.1177/0734242X18764292.

[7] K. Reschner. Scrap tire recycling: A summary of prevalent disposal and recycling methods. In *STR Consulting Tire and Rubber Recycling Report*. Berlin, Germany, 2008.

[8] E. Mui, V. Lee, W. Cheung, and G. McKay. Kinetic modeling of waste tire carbonization. *Energy & Fuels*, 22(3):1650–1657, 2008. doi:10.1021/ef700601g.

[9] H. Larsen, J. Kossmann, and L. Petersen. *Risoe Energy Report 2: New and emerging bioenergy technologies*. RISO-R-1430(EN). Risoe National Laboratory, Roskilde, 2003.

[10] G. Van Oost, M. Hrabovsky, V. Kopecky, et al. Pyrolysis of waste using a hybrid argon-water stabilized torch. *Vacuum*, 80(11-12):1132–1137, 2006. doi:10.1016/j.vacuum.2006.01.04610.1063/1.49010.

[11] R. Szente. Industrial applications of thermal plasmas. *AIP Conference Proceedings*, 345:487–494, 1995. doi:10.1063/1.49010.

[12] J. Chang, B. W. Gu, P. Looy, et al. Thermal plasma pyrolysis of used old tires for production of syngas. *Journal of Environmental Science and Health Part A: Environmental Science and Engineering and Toxicology*, 31(7):1781–1799, 1996. doi:10.1080/10934529609376456.

[13] Y. Lyubina and A. Suris. Thermodynamic model of the plasma gasification of organic solid wastes. *Chemical and Petroleum Engineering*, 35(7):403–406, 1999. doi:10.1007/BF02364351.

[14] D. Leung and C. Wang. Fluidized-bed gasification of waste tire powders. *Fuel Processing Technology*, 84(1-3):175–196, 2003. doi:10.1016/S0378-3820(03)00054-7.

[15] E. Leal-Quiros. Plasma processing of municipal solid waste. *Brazilian Journal of Physics*, 34(4b):1587–1593, 2004.

[16] L. Tang and H. Huang. An investigation of sulfur distribution during thermal plasma pyrolysis of used tires. *Journal of Analytical and Applied Pyrolysis*, 72(1):35–40, 2004. doi:10.1016/j.jaap.2004.02.001.