Fuel recovery from plastic and organic wastes with the help of mineralogical catalysts

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Abstract: Plastics are one of the most widely used materials, and, in most cases, they are designed to have long life spans. Since plastic and packaging waste pollute the environment for many years, their disposal is of great importance for the environment and human health. In this paper, a system was developed to store liquid fuel from plastic and organic waste mixes without solidification, which then can be used as fuel in motor vehicles and construction machinery. For this purpose, polyethylene terephthalate (PET), polyvinyl chloride (PVC), and organic wastes and clay, zeolite, and MCS23-code materials (50% magnetite-%25 calcium oxide-%25 sodium chloride) were heated in a closed medium at temperatures ranging from 300 to 400°C and subsequently re-condensed. The study conducted twenty tests, involving various types and rates of plastic and organic materials, as well as different rates of catalysts. Among these tests, the highest liquid fuel yield (67.47%) was achieved in Test 9, where 50% PVC-50% PET waste, 75 g of clinoptilolite, and 500 g of MCS23 waste were collectively used. Notably, Test 12 exhibited the highest density value (79.8 kg/m^3), while the best viscosity value (2.794 mm^2/s) was observed in Test 2. Across all samples, flash point values were found to be below 40°C. The most favorable yield point value was recorded in Test 2 (-6°C). The samples displayed ash content within the range of 0 to 0.01% (m/m)] and combustion heat values of 35.000> J/g which fall within the standard range. The incorporation of MCS23 with clinoptilolite additives is believed to have a significant impact on obtaining high-yield products with improved fuel properties.

Introduction

The disposal of plastic and packaging waste is critical for human health and the environment due to the long-standing damage they have inflicted. Furthermore, the separate storage and disposal of organic waste contribute to environmental pollution. Nowadays, a multitude of methods (such as landfilling, combustion, and composting) are employed for solid waste disposal. These methods pose environmental risks, are expensive, and do not promote recycling (Liu et al, 2022; Vinti et al, 2023).

The Integrated Waste Management Hierarchy (IWMH) serves the purpose of evaluating the entire spectrum of waste management steps, ensuring sustainability from both environmental and economic standpoints. The effectiveness of waste management is contingent upon the harmonious integration of all methods. According to the IWMH, the initial step involves the prevention and reduction of waste at its (Zhang et al, 2022). Reuse and recycling are used when waste generation cannot be averted. In cases where recycling is not a feasible option, regular landfilling is employed. It is worth noting that a significant proportion of waste plastics become part of the mixed waste stream, rendering recycling unviable

(Saliba et al, 2023). Inadequately managed plastic waste often finds its way to landfills or open dumping sites. Conventional plastic polymers undergo degradation in the environment, a process that often spans decades. As they enter the ecosystem, they act as soil contaminants and marine debris, accumulating within food chains via agricultural and aquatic mediums. This accumulation poses threats to animals and human health through inhalation and ingestion.

Numerous recovery techniques and research efforts have been dedicated to the recycling of plastic wastes. These methods encompass a range of approaches, including recycling through the blending of wastes with original plastics to obtain plastics resembling the original polymer, processes geared toward producing secondary-grade plastic as opposed to the virgin material, chemical recycling methods, and combustion of waste plastics. Particularly noteworthy is the focus on pyrolysis as a means of addressing Waste Plastics. In a study conducted by Williams and Williams in 1999, the concept of pyrolysis was proposed as a recovery method for mixed plastic waste, aimed at generating a petrochemical feedstock. The investigation entailed the utilization of six types of plastics-high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl

chloride (PVC), and polyethylene terephthalate (PET), all commonly encountered in municipal solid waste streams. The process involved subjecting each variety of waste plastic to pyrolysis, accomplished by heating them in a fixed bed reactor until reaching a final temperature of 700°C. The heating rate was maintained at 25°C per minute. This study introduced an innovative approach to plastic recycling through plastic pyrolysis, with a focused examination of the six primary plastic types, each assessed individually. The findings derived from the pyrolysis of these plastics were shared, shedding light on the potential of this method of recycling. In 1999, Kaminsky and Kim conducted experiments involving a laboratory--scale pyrolysis reactor to obtain aromatic pyrolysis oil and gas from mixed plastics collected in Germany. The process encompassed four different experiments, varying the feed rate between 400 and 900 grams per minute and employing different temperatures ranging from 685 to738°C. The primary petroleum products obtained from these studies were identified as benzene, toluene xylenes, and styrene constituting a weight yield of 30–40%.

Miranda et al. carried out a study in 2001 involving the pyrosis of waste materials, specifically HDPE, DYPE, PP, and PS. These processes occurred under a final temperature of 500°C and a total pressure of 2 kPa, each according to their respective material types. Comparison of pyrolysis product compositions from each polymer was conducted against yields from the mixed plastics. Notably, at 520°C, 99.55% of total chlorine content was determined as HCl. Moreover, solid, liquid, and gas yields were ascertained as follows: 62.0% wax, 31.1% oil, 1.0% gas, and 1.2% coking.

Erşen and Pehlivan explored the pyrolysis of high-density polyethylene (HDPE) sourced from domestic plastic waste, along with pine wood powder serving as biomass, in their study in 2011. Optimal liquid product yield was obtained at a pyrolysis temperature of 700°C.

Özcan et al. investigated the potential product recovery from used tires via the pyrolysis process in a 2016 study. The calorific values of resulting liquid and solid pyrolysis products were determined as 9117 kcal m^{-3} and 8710 kcal kg^{-1}, respectively. In these experiments, the highest liquid yield emerged at a pyrolysis temperature of 700°C.

Williams and Williams, (1999) conducted research involving various types of solid waste and pyrolysis methods. Similarly, Kaminsky and Kim, 1999; Pinto et al., 1999; Miranda et al., 2001; Kaminsky et al., 2004; Erşen and Pehlivan, 2011; Sharma et al., 2014; Özcan et al. 2016; Kalargaris et al., 2017; Öngen et al. 2019; Lee, 2022, among others, have also contributed to the understanding of energy production and solid waste recovery through pyrolysis. A common thread running through these studies is the consistent observation that the highest product yields are achieved through pyrolysis at temperatures exceeding 700°C.

Pyrolysis research has undergone significant development, mirroring advancements in the field of pyrolysis research, emerging technologies, and applications. The origins of academic exploration into pyrolysis trace back to the early 20th century, with initial articles concentrating on foundational pyrolysis principles and the formulation of analytical methodologies to investigate the process itself (Schafer 1979; Krishnamurthy et al., 1980).

Notable progress in pyrolysis technology emerged during the 1960s and 1970s, spurred by the advent of novel pyrolysis techniques such as fluidized bed reactors and vacuum pyrolysis (Kirov and Peck, 1970; Bhupendra et al.1973). This led to an increase in the number of academic articles on pyrolysis and a deeper understanding of the process. As a result, the focus shifted towards practical applications, resulting in a rise in the number of scholarly works concerning these topics. Notably, a growing interest has emerged in the applications of pyrolysis, particularly within the realms of biomass conversion (Qunqun et al., 2023; Varank et al., 2022; Öngen et al., 2016), waste management (Pan et al., 2023; Ma et al., 2022; Zhang et al., 2020), and energy production (Allende et al., 2022; Öngen et al., 2019) in recent years. From a broader perspective, academic literature on pyrolysis has evolved over time to mirror shifts in the field and an increased emphasis on practical applications and environmental concerns.

In this study, a new method was introduced, utilizing clinoptilolite, kaolin, and MCS23 catalysts (a material designed to maintain the fuel in liquid form), in comparison to other studies in the field of pyrolysis. The objective was to achieve liquid yields at a low temperature of 300°C, as well as at 400°C.

Materıal and methods

This study presents a system designed to produce liquid fuel from a combination of organic household waste and PVC and PET waste, all without using pressure. The system avoids product freezing through the utilization of additives and catalysts, eliminating the immediate requirement for energy conversion, and enabling the storage of liquid products. In pursuit of this goal, the study involved the heating of PVC, PET and organic wastes alongside clay, zeolite and MCS23-code materials (composed of 50% magnetite with an average particle size of 2mm, 25% calcium oxide with an average particle size of 0.6mm), and 25% sodium chloride with an average particle size of 2mm) with a pyrolysis reactor. This process was carried out within a temperature range of 300–400°C, followed by re-condensation and subsequent determination of the chemical characteristics of the resulting liquid products. Finally, the study examined the compatibility of these liquids with the TS EN and ISO fuel standards regulations, as well as their suitability for use in motor vehicles and heavy equipment.

Reactor Design
The liquid product samples were produced using a lab-scale reactor (Fig. 1) especially designed for this purpose. This reactor consists of a chromium chamber measuring 30 cm in diameter, 60 cm in height, and 1 cm in thickness, accompanied by three attached gas coolers. In order to attain the desired temperatures, a diesel fuel burner was used with a heating rate of 10°C/min. The system's temperature was monitored using an electronic thermometer. In the pyrolysis experiments dry air was used as a carrier gas flowing at a rate of 0.01 l/min

The waste materials, including PVC, PET and OM along with additives such as kaolin, clinoptilolite, and MCS23, were introduced into a chromium reactor. Utilizing a diesel burner, the reactor was heated to 400°C for 20–60 minutes, causing the waste materials within the chamber to transition into the

gaseous phase. The waste materials that underwent gasification during this process were subsequently converted into a liquid state. To facilitate the liquefaction process, three cooling units, all constructed from chromium, were used. These cooling units were interconnected at specific heights and angles and calibrated to ensure a gradual cooling rate. The condensation temperature of the resulting liquids ranged from 173°C and 325°C depending on the experimental conditions. Within the final cooling unit's lower segment, a liquid fuel outlet was integrated, while a gas outlet unit capable of withstanding pressure was positioned in the upper section. The gasified materials traversed through these cooling units, and the deliberate slow cooling process culminated in the production of a synthetic liquid fuel within the ultimate unit.

Analytical Procedure

A total of 20 tests were conducted, varying the rates and quantities of the afore mentioned waste materials and additives. In these tests, liquid fuel samples were generated using PVC, PET, and organic household waste (OM). Following the production of liquid fuel samples, additives including kaolin (ka), clinoptilolite (kl), and MCS23 were used to maintain the samples in a liquid state. The inclusion of MCS23 prevented the products from undergoing gelation gelling, thus enabling the storage of liquid products without immediate conversion into energy.

The chemical analysis of liquid fuel products was carried out at the Karadeniz Technical University (KTÜ-YUAM) in accordance with Turkish Standards (TS), European Standards (EN), as well as the tests and methods outlined by the International Standard Organization (ISO).

Chemical analysis of the samples and the subsequent assessment of results were conducted, taking into account the key fuel characteristics. The physicochemical parameters and corresponding tests undertaken are detailed as follows: density at 15°C analyzed using the TS EN ISO 12185 test (TS EN ISO 12185, 2007); viscosity at 40°C analyzed using the TS 1451 EN ISO 3104 test (TS 1451 EN ISO 3104, 1999), flash point analysis, performed via the TS EN ISO 2719 test (TS EN ISO 2719, 2016), yield point analysis, as determined by the TS 1233 ISO 3016 test (TS 1233 ISO 3016, 1997), water content analysis, carried out using the TS 6147 EN ISO 12937 method (TS 6147 EN ISO 12937, 2002), ash content analysis, executed according to the TS EN ISO 6245 test (TS EN ISO 6245, 2006), and combustion heat analysis (upper heating value), assessed by means of the DIN 51900-2 test (DIN 51900-2, 2003).

Results And Dıscussıon

The types and quantities of wastes and additives used in the tests and the temperature range for the formation of liquid and gas fuel products are shown in Table 1. The liquid product samples obtained were classified based on their test numbers and assigned a JLJ pre-code (Fig. 2).

Liquid product and solid residue values were measured, while gas values representing the remaining percentile were determined through calculations. Gas products were not retained, and the liquid product yield percentages were taken into consideration. As a result of Test 1, the liquid product yield and solid residue were determined to be 42.66% and 41.93%, respectively (Table 2). However, the liquid product obtained from this test solidified over time and lost its liquid form.

As a result of Test 2, the liquid product and solid residue were found to be 58.30% and 12.95%, respectively. The corresponding values from Test 3 were calculated as 52.24% and 37.69%. The product obtained from this test underwent a transition from its liquid state to a gel-like form after a while. In Test 4, the liquid product rate indicated to be 45.98%, while the solid residue rate was 19.73%. For Test 5, the respective rates were calculated as 29.30% for the liquid product and 56.78% for the solid residue. The liquid product obtained from
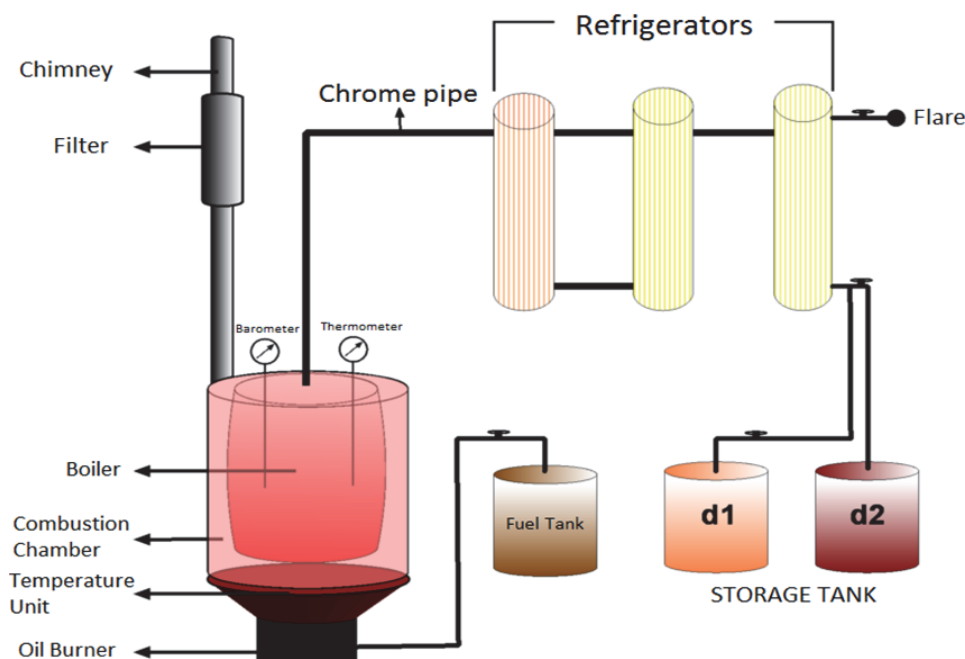

Fig. 1. Scheme of pyrolysis reactor used in the study

Table 1. Wastes and additives used in the tests and liquid outlet and final values

Test No	Waste (g)				Additives (g)			Temperature (°C)	
	PVC	PET	OHW	MHW	ka	kl	MCS23	Liquid start	Liquid finish
1	–	2000	–	–	250	250	500	325	378
2	2510	–	–	–	–	50	150	273	338
3	–	2480	–	–	–	50	150	301	348
4	–	2210	–	–	–	50	350	310	373
5	–	2080	–	–	–	50	600	270	327
6	–	1080	–	–	–	50	800	235	304
7	1050	1050	–	–	–	50	800	199	273
8	400	400	–	–	–	50	400	201	278
9	750	750	–	–	–	75	500	225	353
10	–	–	800	–	–	75	250	287	354
11	400	400	400	–	–	75	400	177	248
12	250	250	500	–	–	75	250	212	277
13	–	400	400	–	–	75	250	237	303
14	400	–	400	–	–	75	250	244	314
15	–	400	400	–	–	75	500	278	347
16	–	500	750	–	–	75	250	201	277
17	500	–	750	–	–	75	250	244	343
18	–	–	–	800	–	75	200	201	277
19	–	–	–	750	–	75	250	173	302
20	–	–	–	750	–	75	250	207	316
PVC: Polivinilklorür, PET: Polietilen Tereftalat, OHW: Organic Household Waste, MHW: Mixed Household Waste, ka: kaolin, kl:klinoptilolit									

Test 5 could not maintain its liquid state and exhibited a waxy appearance. However, when the product was heated to 40°C, it returned to its liquid form. As a result of Test 6, the liquid product yield and solid residue were determined to be 36.27% and 44.04%, respectively (Table 2). The liquid product rates for Tests 7 and 8 were 50.85% and 40%, respectively, while the solid residue rates for the respective tests were 45.93% and 44.24%. The results of Test 9 revealed a liquid product rate of 67.47% and a solid residue rate of 27.71%.

Liquid product rates from Tests 10 and 11 were determined to be 53.33% and 49.55%, respectively, with corresponding solid residue rates of 41.33% and 35.82%. In Test 12, the liquid product rate was 46.04%, while the solid residue rate was 42.26%. For Tests 13, 14, and 15, the liquid product rates were 53.33%, 48.89%, and 49.10%, and the respective solid residue rates were 33.33%, 36.27%, and 44.73%. In the case of Tests 16, 17, 18, 19, and 20, the liquid product rates were 46.35%, 50.16%, 61.40%, 50.23%, and 59.53%, while the corresponding solid residue rates were 30.41%, 27.05%, 28.37%, 38.60%, and 34.23% (Table 2). Previous studies have indicated that mixed plastic wastes yielded 80% in tests (Damodharan et al., 2019), and a yield of 95% was achieved using the slow pyrolysis technique (Papari et al., 2021).

The highest liquid product rate was observed in Test 9, while the lowest rate was recorded in Test 5 (Fig. 3). The liquid products obtained in Test 1, Test 3, and Test 5 underwent gell

formation soon after their production due to a temperature decrease.

100% PET was utilized as the waste material, and liquid yields and solid residual percentages were evaluated by varying additive rates in tests 1, 3, 4, 5, and 6. The highest values of liquid product yield (45.98%) and solid residue (19.73%) were recorded in Test 4. Test 2 exclusively employed 100% PVC waste (Table 1). In tests 7, 8, and 9, a mixture of 50% PVC and 50% PET waste was utilized, with varying additive rates resulting in liquid yield percentages of 50.85, 40.00, 67.47, and 45.93, 44.24 and solid residue percentages of 45.93, 44.24, and 27.71, respectively. Among the tests utilizing equal shares of PVC and PET waste, the most favorable outcome in terms of liquid yield and solid residue was achieved in test 9 (27.71%). Test 10 involved the use of 100% organic household waste (OHW) along with additives consisting of 75 g clinoptilolite and 250 g MCS23. In test 11, equal amounts of PVC, PET, and OHW were used, accompanied by additives of 75 g clinoptilolite and 400 g MCS23. Test 12 utilized a blend of 25% PVC, 25%PET, and 50% OHW, along with additives of 75 g clinoptilolite and 250 g MCS23.

In tests 10, 11, and 12, the liquid yields were determined as 53.33%, 49.55, and 46.04, while the solid residual amounts were measured at 41.33%, 35.82, and 42.26, respectively. Tests 13 and 15 employed a combination of 50% PET and 50% OHW, varying additive rates resulting in liquid yields of

53.33% and 49.10%, and estimated solid residual percentages of 33.33 and 44.73, respectively. Among the tests using equal shares of PVC and PET waste, the optimal outcome in terms of liquid yield (53.33%) and solid residual (33.33%) was achieved in test 13. In test 16, a mixture of 40% PET and 60% OHW was utilized, along with additives of 75 g clinoptilolite and 250 g MCS23, yielding a liquid yield of 46.35% and a solid residual of 30.41%. Test 14yielded a liquid yield of 48.89% and solid residual of 36.27% by using 50% PVC and 50% OHW with the addition of 75 g clinoptilolite and 250 g MCS23. For Test 17, a blend of 40% PVC and 60% OHW was employed, incorporating additives of 75 g clinoptilolite and 250 g MCS23, resulting in a liquid yield of 50.16% and

solid residual of 27.05%. In tests 18, 19, and 20, 100% mixed household waste (MHW) was used, and by adjusting additive rates, liquid yields of 61.40%, 50.23, and 59.53 and solid residuals of 28.37%, 38.60, and 34.23 were achieved. Among the tests involving mixed household wastes, the best results for both liquid yield and solid residual were observed in test 18.

The liquid product density analysis revealed that among the samples, the density of JLJ-12 (797.8 kg/m^3) closely approximated the standard (TS EN ISO 12185, 2007). Conversely, the lowest density (769.4 kg/m^3) was observed in sample JLJ-6 (Table 3). Sample JLJ-12, exhibiting the highest density,was derived from a composition of 250 g PVC, 250 g PET and 500 g OHW, alongside additives comprising 75 g

Fig. 2. Liquid product samples obtained from the tests

of clinoptilolite and 250 g of MCS23. In contrast, the sample JLJ-6, with the lowest density, resulted from combining 1080 g PET with 50 g of clinoptilolite and an additive of 800 gr MCS23.

The viscosity values of samples were compared with standards of TS, EN and ISO (TS 1451 EN ISO 3104, 1999). It was recognized that the viscosity values of samples JLJ-4, 6, 8, 9, 15, 17, 18, 19 and 20 were below the range of 2–4.5 mm^2/s (Fig. 4). The viscosity values of samples JLJ-2, 7, 10, 11, 12, 13, 14 and 16 were within this range. The viscosity of samples JLJ-2, JLJ-13 and JLJ-16 (2.794, 2.315 and

2.432 mm^2/s) yielded the closest value to the standards, and the lowest viscosity was measured in sample JLJ-8 (1.199 mm^2/s).

The flash point values of samples were measured to be below 40°C; therefore, they could not be compared with the standards (TS EN ISO 2719, 2016). Considering the flash point characteristics of these samples, they are not suitable for use as fuel in motor vehicles and construction machinery without undergoing improvements.

In the yield point analysis (TS 1233 ISO 3016, 1997), the best results were obtained from samples JLJ-2, JLJ-9 and

Table 2. List of liquid products, solid residual (char) and gas values obtained

| Test No	Additives (%)			Product (gr)		Product (%)		
	ka	kl	MCS23	Liquid Fuel	Char	Liquid Fuel	Char	Gas
1	8.33	8.33	16.66	1280	1258	42.66	41.93	15.41
2	–	1.85	5.54	1580	351	58.30	12.95	28.75
3	–	1.87	5.60	1400	1010	52.24	37.69	10.07
4	–	1.92	13.41	1200	515	45.98	19.73	34.29
5	–	1.83	21.98	800	1550	29.30	56.78	13.92
6	–	2.59	41.45	700	850	36.27	44.04	19,69
7	–	1.69	27.12	1500	1355	50.85	45,93	3.22
8	–	4.00	32.00	500	553	40.00	44.24	15.76
9	–	3.61	24.10	1400	575	67.47	27,71	4.82
10	–	6.67	22.22	600	465	53.33	41.33	5.34
11	–	4.48	23,88	830	600	49,55	35.82	14.63
12	–	5.66	18,87	610	560	46,04	42.26	11.7
13	–	6.67	22.22	600	375	53.33	33.33	13.34
14	–	6.67	22.22	550	408	48.89	36.27	14.84
15	–	4,45	36.36	675	615	49.10	44.73	6.17
16	–	4,76	15.87	730	479	46.35	30.41	23.24
17	–	4,76	15.87	790	426	50.16	27.05	22.79
18	–	6.98	18.60	660	305	61.40	28.37	10.23
19	–	6.98	23.26	540	415	50.23	38.60	11.17
20	–	6.98	23.26	640	368	59.53	34.23	6.24
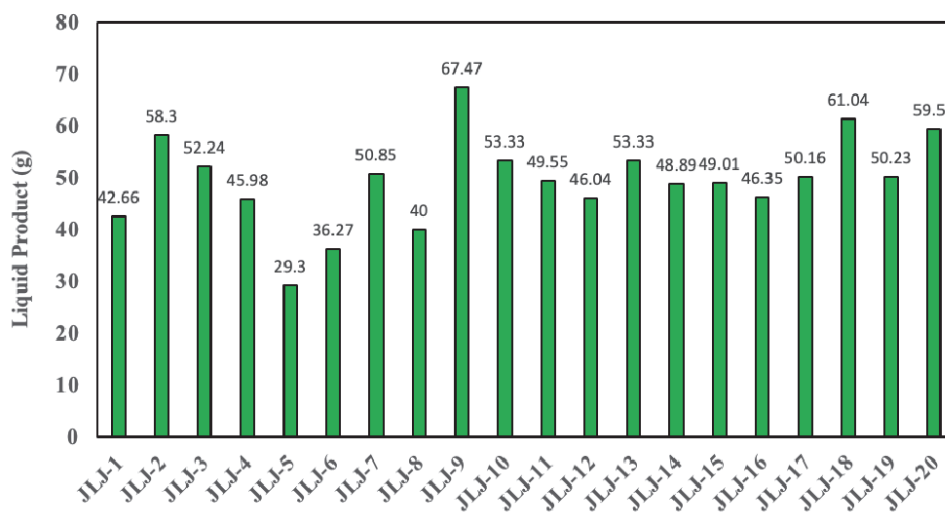
Fig. 3. Amount of liquid products obtained from experiments

JLJ-20, with values of -6, -3, and -3°C, respectively. The lowest value was measured in sample JLJ-13 (18°C).

Water content was determined only for samples JLJ-2, JLJ-6, and JLJ-7, and no water was detected in the other samples. Sample JLJ-2 was produced using only PVC, sample JLJ-6 was produced using only PET, and sample JLJ-7 was produced using a combination of PVC and PET. The water contents of samples JLJ-2, JLJ-6 and JLJ-7 are less than 0.1% (m/m), 0.1% (m/m), and 0.15% (m/m) respectively, according to TS 6147 EN ISO 12937 (2002). Considering the low water content, these samples could be used as fuel in motor vehicles and construction machinery.

The sample with the highest ash content (0.006%, m/m) was JLJ-20, according to TS EN ISO 6245 (2006). On the other hand, samples JLJ-7, 8, 9, 10, and 14 exhibited the lowest ash content (0.001%, m/m). Notably, all samples demonstrated ash content lower than the standard value of 0.01% (m/m) (Fig. 5).

All samples exhibited combustion heat values (upper heat values) measured above the lower limit stipulated by TS, EN and ISO standards (35.000 J/g). . Among the samples, the highest combustion heat value was recorded in sample JLJ-2 (46.500 J/g), while the lowest was in JLJ-6 (44.900 J/g). These results underline that the combustion heat values of all samples surpassed the standard value of 35.000 J/g (Fig. 5).

The experimental results, depicted in Table 1 as a function of time and temperature, unequivocally showcase the occurrence of an efficient reaction. The pyrolysis experiments yielded liquid products of approximately 42%. The outcomes of this study are consistent with prior research findings (Pan and Debenest 2022; Pan et al. 2022; Öngen et al. 2019; Sogancioglu 2017). Table 3 shows the condensation times of the liquid products resulting from the experimental processes. Upon examining the table, it becomes evident that the earliest liquid product was obtained at the 17th minute (173°C), while the latest was acquired at 33rd minutes (325°C).

The highest liquid product yield (67.47%; additives are not included in the calculation) was obtained from test 9, which was carried out with equal proportions of PVC and PET wastes and additives of 75 g clinoptilolite and 500 g MCS23. In this test, a solid residue of 27.71% was found, and 4.82% was expelled as gas and water vapor. Up to test 9, varying rates of clinoptilolite and MCS23 additives were used, and even when MCS23 was added in quantities exceeding 500 g, the yield decreased. In this study, the highest yield (67.47%) was achieved during test 9, which was conducted with 50% PVC, 50% PET, 5% clinoptilolite, and 34% MCS23. When considering studies involving the use of organic household waste (OHW), PVC, and PET, the highest yield (49.55%) was obtained from test 11. The highest yield was achieved when all wastes (OHW, PVC, PET) were added in equal amounts, along with additives consisting of 34% MCS23 and 6.25% clinoptilolite. For studies conducted with mixed household waste (MHW), the yield was mostly above 50%. The peak yield (61.40%) was recorded in test 18. Detailed results of the chemical analysis of liquid products are provided in Table 4.

The highest yield was obtained when additives of 34% MCS23 and 10% clinoptilolite were used. It was shown that the highest yield was achieved in tests conducted with mixed wastes. In experiments involving PET and OHW, the peak yield (53.33%) was recorded in test 13. Furthermore, it was

observed that as the OHW amount increases, the liquid product yield decreases. The highest yield was recognized when utilizing a mixture of 50% PET and 50% OHW, combined with additives of 31% MCS23 and 9% clinoptilolite. Similarly, in experiments involving PVC and OHW, the highest yield (50.16%) was observed in test 17. Just like in the PET and OHW experiments, an increase in OHW content led to a decrease in liquid product yield. The highest yield was observed when employing a blend of 50% PVC and 50% OHW, along with additives of 31% MCS23 and 9% clinoptilolite. When estimaying the liquid product yield percentage, the highest yield was achieved in tests in which PVC and PET wastes were added in equal amounts. In contrast, experiments that exclusively used PVC, PET, and OHW as individual waste sources resulted in a decreased liquid product yield., The most favorable yields were attained in experiments that used mixed household wastes.

Conclusion

The highest yield (67.47%) was achieved in Test 9, where PVC and PET wastes were utilized in equal proportions along with additives of 75 g clinoptilolite and 500 g MCS23. Throughout the experiment, a solid residue of 27.71% was observed, while 4.82% was expelled as gas and water vapor. When examining experiments involving PVC and PET wastes utilized in equal proportions, the best results were obtained from Test 13, yielding a liquid product yield of 53.33% and a solid residue yield of 3.33%. Meanwhile, experiments involving mixed

Table 3. Liquid products condensing time and temperatures

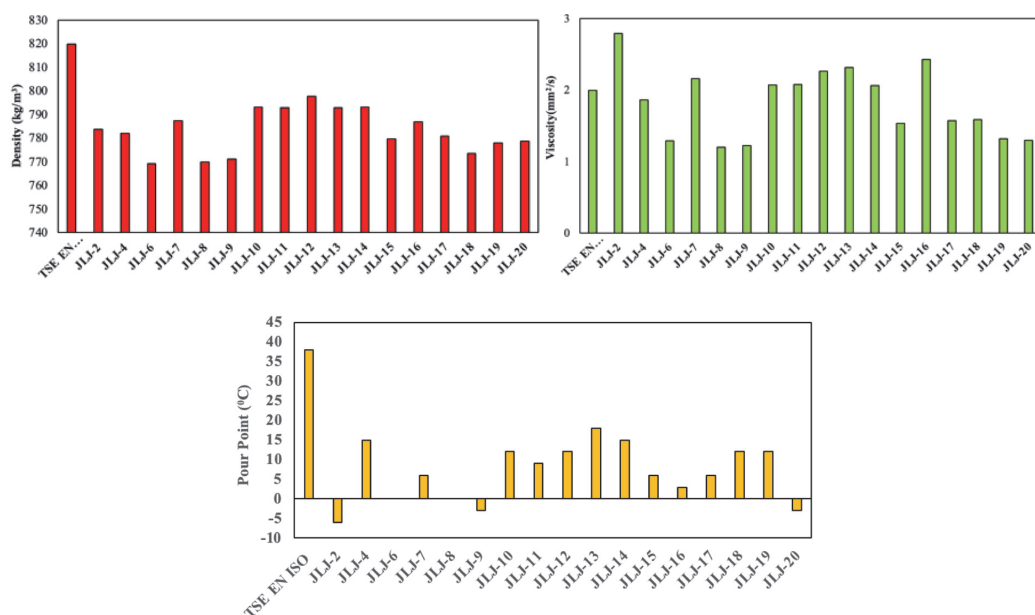| Test No	Condensing Time (min.)	Condensing Temperature (°C)	
		Start	Finish
1	33	325	378
2	27	273	338
3	29	301	348
4	30	310	373
5	28	270	327
6	22	235	304
7	20	199	273
8	20	201	278
9	23	225	353
10	29	287	354
11	18	177	248
12	23	212	277
13	24	237	303
14	24	244	314
15	28	278	347
16	20	201	277
17	25	244	343
18	20	201	277
19	17	173	302
20	21	207	316

Fig. 4. Density, viscosity and pour point properties of liquid samples obtained from experiments
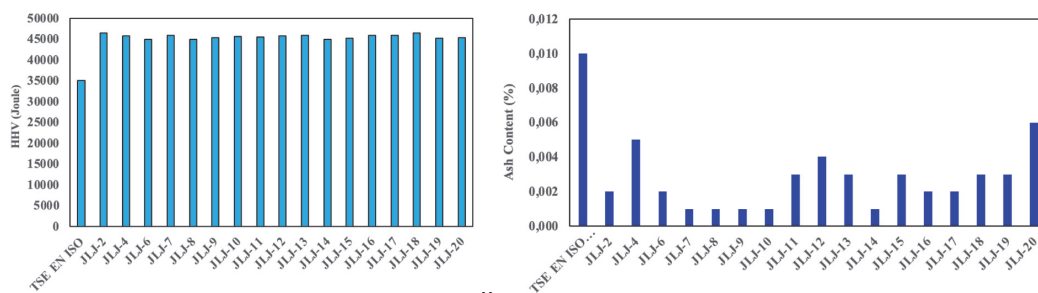

Fig. 5. Ash Content and Calorific Value properties of liquid samples obtained from experiments

Table 4. Summary of physico-chemical results of fuels obtained from the tests

Fuel Properties		Test Number (JLJ-)																	
Properties	Standard Volume	2	4	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Density (kg/m³) 15°C (TS EN ISO 12185)	820–845	783.7	782.0	769.4	787.4	769.9	771.1	793.1	793.0	797.8	793.0	793.1	779.7	786.9	780.8	773.6	777.9	778.8
Viskosity 40°C (mm²/s) (TS 1451 EN ISO 3104)	2–4.5	2.794	1.864	1.292	2.159	1.199	1.223	2.075	2.077	2.265	2.315	2.063	1.538	2.432	1.576	1.588	1.322	1.302
Pour Point °C (TS 1233 ISO 3016)	Max. +38	-6	15	0	6	0	-3	12	9	12	18	15	6	3	6	12	12	-3
Moisture (%(m/m)) (TS 6147 EN ISO 12937)	<0.2	<0,1	--	0.1	0.15	--	--	--	--	--	--	--	--	--	--	--	--	--
Ash (%(m/m)) (TS EN ISO 6245)	<0.01	0.002	0.005	0.002	0.001	0.001	0.001	0.001	0.003	0.004	0.003	0.001	0.003	0.002	0.002	0.003	0.003	0.006
Flash Point (°C) TS EN ISO 2719	>55	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40
Heat of combustion (upper calorific value) (J/g) (DIN 51900-2)	35.000>	46.500	45.710	44.900	45.890	44.940	45.370	45.690	45.530	45.770	45.940	44.920	45.200	45.910	45.860	46.430	45.230	45.380

household waste, showcased the most favorable in Test 18, yielding a liquid product yield of 61.40% and a solid residue yield of 28.37%. Notably, the yields could potentially increase if the gas products are appropriately stored.

Sample JLJ-12, with a density of 797.8 kg/m^3, exhibited a value closest to the standards., Additionally, samples JLJ-2, 13, and 16 displayed viscosities that closely approximated the standard values. The flash point of all samples was measured to be below 40°C, rendering them unsuitable for use as fuel in motor vehicles and construction machinery without necessary enhancements improvement.

In the yield point analysis, samples JLJ-2, JLJ-9, and JLJ-20, with temperatures of -6, -3, and -3°C, respectively, demonstrated values most akin to the standard. Regarding water content, samples JLJ-2, 6 and 7 aligned with the standard values, while no water was detected in the remaining samples. Consequently, all the samples could potentially be utilized as fuel for motor vehicles and construction machinery. Experimental findings indicated that the ash contents of all samples remained below the standard limit of 0.01% (m/m). Furthermore, the analysis results revealed that the combustion heat values of all samples exceeded the standard lower value of 35.000 J/g.

This paper demonstrates the significance of deriving products from both organic and plastic waste, wherein these contaminants are transformed into fuel, thereby yielding economic benefits. Damodharan et al., (2019) achieved an 80% pyrolytic oil yield using catalytic pyrolysis technique with a batch reactor and catalysts such as silica, alumina, ZSM-5, and kaolin. In previous research, waste materials were processed using pyrolysis, vacuum pyrolysis, and catalytic crushing methods, resulting in varying yields influenced by pressure and temperature. Notably, these studies mainly focused on specific plastic waste types like PE, PP, YYPE, DYPE. Much of the plastic waste employed in these investigations is recyclable and can serve as valuable raw material. The development of MCS23 material aimed to address the solidification issue encountered with liquid fuel produced in preliminary tests prior to this study. The experiments showed that the combined application of MCS23 and clinoptilolite additives significantly contributes to increasing the liquid fuel yields, enhancing fuel characteristic values, and facilitating the storage of fuel in liquid form.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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