IRSTI 31.25.15 https://doi.org/10.26577/IJBCh202619110

T.R. Saidnazarov[1*], Kh.Kh. Turaev[1], P.I. Urkimbayeva[2], Z.A. Kenessova[2], M.U. Karimov[3], Kh.E. Eshmurodov[1], S.M. Samatov[1]

[1]Faculty of Chemistry, Termez State University, Termez, Uzbekistan
[2]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[3]Tashkent Research Institute of Chemical Technology, Tashkent, Uzbekistan
*e-mail: tohirsaidnazarov@gmail.com

EFFICIENT SYNTHESIS OF P-PHENYLENEDIAMINE FROM PET WASTE VIA ENERGY-EFFICIENT DEPOLYMERIZATION AND GREEN HOFMANN REARRANGEMENT

Abstract: The continuous use of post-consumer polyethylene terephthalate (PET) waste remains a major challenge due to its environmental properties and the high energy requirements of traditional recycling methods. In this study, an energy-efficient and environmentally friendly route for the synthesis of p-phenylenediamine (PPD) from secondary PET waste was developed. Terephthalic acid was obtained from PET waste under simple conditions and then terephthalamide was obtained through a catalytic high-pressure ammonolysis process. The main part of the process involved the Hofmann rearrangement reaction, for which an environmentally friendly chlorinating agent was selected based on research.

Various hypochlorite and dichloroisocyanurate salts were analyzed based on their active chlorine equivalents, reaction efficiency, safety, and waste profile. Among the tested reagents, sodium dichloroisocyanurate chlorinated amides to a high degree under alkaline conditions, reduced hazardous waste, and produced harmless by-products. As a result, p-phenylenediamine was obtained in 84% yield. The structure and properties of the synthesized product were confirmed by IR, NMR, TG, and DTA analyses.

This research work demonstrates a green and efficient method for converting PET waste into valuable aromatic diamines. However, it also highlights the importance of choosing an environmentally friendly reagent for the Hofmann rearrangement reaction.

Keywords: Polyethylene terephthalate (PET), ammonilysis, glycerin, sodium urea, dichloroisocyanurate salt, reactor autoclave, amination, terephthalamide.

Introduction

Some types of plastic materials are biodegradable, but PET waste is not. Therefore, it is an environmental hazard if it is thrown into a landfill (Wojnowska-Baryła et al., 2022). Therefore, the only way to solve the problem of PET waste from industry and social consumption is to recycle it (Coelho et al., 2011). Recycling can be used as a raw material for the chemical industry, in the social sector, or as a variety of materials or products (Sasse, Emig, 1998). In addition, the service life of any non-biodegradable plastic waste can be extended by recycling it (Mohanaprasadh et al., 2022). The good thing about PET is that it can be completely recycled as secondary waste (Raheem et al., 2019).

Nowadays, extensive research is being conducted on the creation and development of various chemical degradation reactions of PET (Khoonkari et al., 2015). For the effective recycling of PET waste, mainly mechanical and chemical methods are used (Shaikh et al., 2024). Most chemical recycling includes alcoholysis, hydrolysis, and ammonolysis (Lu et al., 2018). Chemical recycling methods allow the synthesis of initial monomers or various chemicals (Shadravan, Amani, 2012). These methods require high pressure, temperature, and a lot of time (Bohre et al., 2023).

When chemically recycling PET waste, terephthalic acid is often first synthesized, and various chemicals are obtained from it, such as benzene, dichlorobenzene, terephthaldiamide, and p-phenylenediamine (Cataldo, 1996).

P-phenylenediamine is an important raw material in the chemical industry, and its application is very wide (Heintz et al., 2014). However, the method used to produce it in chemical enterprises today does not meet modern environmental requirements (Patra et al., 2022). In fact, the main raw material for the synthesis of p-phenylenediamine in the chemical industry is

aromatic nitro compounds or aniline, and during the process, a lot of toxic gases are released into the environment (Amer, Brandt, 2018). Therefore, scientists are conducting research to develop an environmentally friendly method for the synthesis of p-phenylenediamine on an industrial scale (Al-Sabagh, 2016). Therefore, the extraction of p-phenylenediamine from PET waste is considered to have economic and environmental advantages (Yulchieva et al., 2023).

Currently, there are several chemical methods for synthesizing p-phenylenediamine from PET waste; for example, the obtained terephthalate is first chlorinated using thionyl chloride, after which the obtained p-phthaloyl chloride undergoes an amination reaction with sodium azide, and p-phenylenediamine is obtained as the final product (Jiyanova et al., 2024). This method is very efficient and does not require much energy, and the reaction yield is also high, but the prices of the substances used for chlorination and amination are expensive, and a large amount of SO_2 gas is released into the environment during the process, so it is not recommended for industrial use (Toshtemirov et al., 2024b).

In this work (Olzhabay et al., 2022), a technology for the chemical recycling of polyethylene terephthalate (PET) waste obtained from used plastic bottles was developed to produce a valuable monomeric product, bis(2-hydroxyethyl) terephthalate (BHET), suitable for the subsequent synthesis of biodegradable polymer films. The PET glycolysis process in the presence of zinc acetate as a catalyst was investigated. The effect of the temperature range of 140–190°C on the degree of PET conversion was studied. It was established that an increase in temperature leads to an increase in the rate and completeness of glycolysis. Optimal process conditions ensuring a high BHET yield of 77% were determined. The obtained results confirm the prospects of chemical recycling of PET waste as an efficient and environmentally sound approach for producing secondary raw materials for the manufacture of biodegradable polymer materials. And again, terephthalic acid obtained from PET waste through glycolysis, alkali, and ammonolysis is amidated at high pressure using ammonia gas, and in the next step, the terephthaldiamide obtained is mixed with water, and chlorine gas is passed through. In the next step, the N, N'-dichlorodiamide obtained is placed in an alkaline solution at low temperature, and p-phenylenediamine is obtained (Toshtemirov et al., 2024a). The substances used in this method are quite cheap and convenient, but the methods used to obtain terephthalic acid from PET waste require a lot of time and energy (Cosimbescu et al., 2021). At the same time, the chlorination process also takes a long time, and the reaction yield is not high. Sometimes sodium hypochlorite is used for chlorination (Tashkulov et al., 2025). Sodium hypochlorite is not suitable for chlorination, and its instability increases over time, which causes many inconveniences.

Taking into account the above shortcomings in the production of p-phenylenediamine, we have developed an economically and environmentally effective method. That is, we have used an energy-saving method to obtain terephthalic acid from PET waste. We have used an effective catalyst to synthesize terephthaldiamide from the obtained terephthalic acid and have significantly increased the reaction yield. At the same time, special attention was paid to the selection of an environmentally friendly chlorinating agent for the Hofmann rearrangement reaction used to obtain p-phenylenediamine from terephthaldiamide.

Materials and methods

Reagents and equipment

For the study, crushed and cleaned pieces of secondary PET bottles and articles, sodium hydroxide solution, urea, sodium hypochlorite, potassium hypochlorite, sodium dichloroisocyanurate salt and trichloroisocyanuric acid, and organic solvents acetone, toluene, and benzene were used. HNZXIB brand reactor autoclave made of stainless steel with a volume of 5 L, suitable for high pressure. SHIMADZU IR spectrophotometer, NMR spectrometer, and TGA-50/TG series thermogravimetric analyzer for determining deformation and valence changes with chemical bonds of the resulting product.

Obtaining terephthalic acid through an energy-efficient method

First, PET waste is thoroughly washed, excess parts are removed (emblem, cap, etc.), and it is crushed. Then 500 g of sulfuric acid is placed in a 1 L glass beaker, and 350 g of ready-made crushed PET pieces are mixed with it. The process is carried out at room temperature on a special magnetic stirring plate. Sulfuric acid reacts with the long chains of PET, causing them to break down and form small monomers. The reaction lasts 2.5 hours and results in a white sticky mixture. The resulting mixture is transferred to a 2 L glass beaker, 1.5 L of water is added, and alkali is added until completely neutralized. As a result, terephthalic acid precipitates in the beaker, which is then filtered and dried. At the end of the process, white terephthalic acid is obtained with a reaction yield of 95%, and its purity is checked by IR spectroscopy (Saidnazarov et al., 2024; Samatov et al., 2024).

Synthesis of terephthaldiamide using a convenient catalyst

100 g of synthesized terephthalic acid was measured and mixed thoroughly with 150 g of urea. At the same time, Fe_2O_3 was taken as a catalyst in an amount equal to 0.01% of the mass of terephthalic acid obtained for the reaction and mixed into the mixture. The mixture was placed in a reactor autoclave, and the parameters were adjusted to 10 kg/cm² pressure, 180ºC temperature, and 3 hours time. After the process was completed, a light brown or orange powder was obtained. After the process was completed, a light brown or orange powder was obtained. The resulting colored powder was washed in 80°C water and dried at 40°C, resulting in 89 g of terephthaldiamide with a yield of 90%.

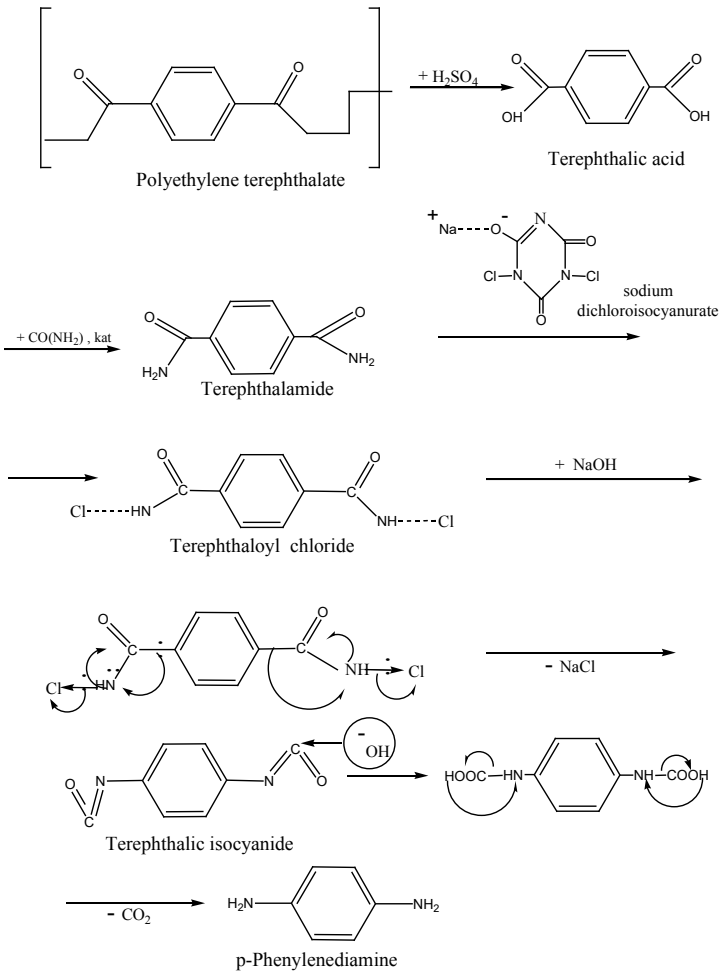
Synthesis of p-phenylenediamine

First, to start the process, 900 g of 10% alkali solution was prepared and placed in a 2-liter glass beaker. The temperature of the solution was cooled to +5ºC, and 89 g of synthesized terephthaldiamide were added to it. After that, the solution was stirred, and 90 g of sodium dichloroisocyanurate salt was added to the solution. The mixture was kept at +5ºC for 20 minutes, then stirred at room temperature for 1 hour using a magnetic stirrer. In the next step, the reaction temperature was raised to 60ºC and stirred at this temperature for 1 hour. After the specified time, the temperature of the mixture was lowered again to +5ºC and filtered. The resulting filtrate was extracted at room temperature using organic solvents to obtain p-phenylenediamine with a yield of 84%.

Reaction Mechanisms

The reaction mechanism and pathway for producing p-phenylenediamine from PET waste are shown in Figure 1. To produce terephthalic acid, PET pieces are chemically treated with sulfuric acid, which results in the destruction of long polymer chains and the formation of monomers.

Figure 1
Reaction mechanism and pathway



In the next step, the terephthalic acid obtained was aminated under high pressure and in the presence of a catalyst to obtain terephthaldiamide. The catalyst accelerates the amidation process with the -OH in the carboxyl group. Then, sodium dichloroisocyanurate salt was used to chlorinate terephthaldiamide. This salt, when dissolved in water, forms hypochlorite and chlorinates terephthaldiamide to form N,N'-Dichloroterephthalamide. N,N'-Dichloroterephthalamide rapidly undergoes a Hofmann rearrangement reaction under the influence of an alkaline medium, resulting in deprotonation, removing the hydrogen in –CO−NHCl and the formation of a negative charge on the nitrogen, leading to the formation of the chloramide anion $–CO–N^- – Cl$. The anion is unstable and eventually releases chlorine, resulting in isocyanate. Since the process takes place in an aqueous medium, the nucleophilic effect of water on the isocyanate leads to the formation of a primary amine. The resulting primary amine is unstable, so decarboxylation occurs, releasing carbonic anhydride gas, and the final product is p-phenylenediamine.

Results and discussion

Effect of catalyst on terephthaldiamide synthesis

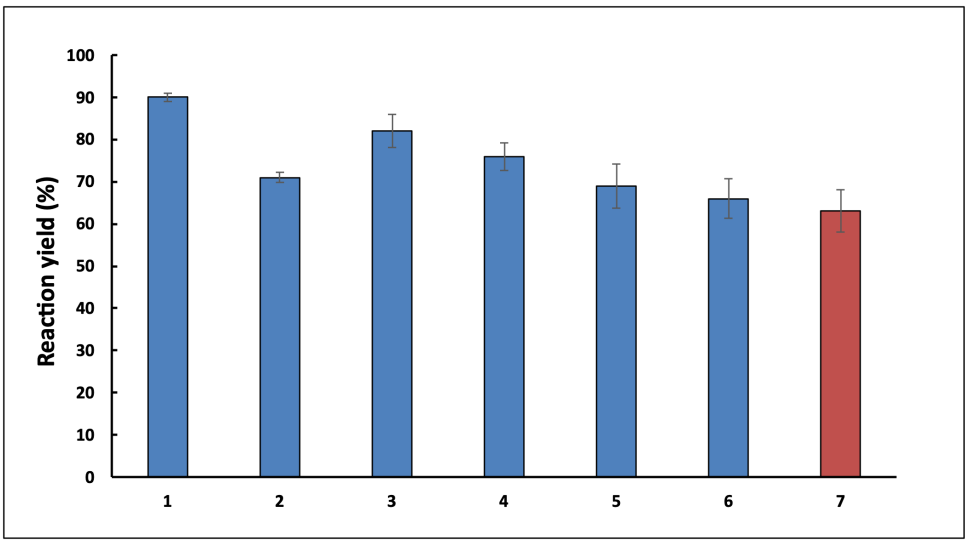
In order to significantly increase the reaction yield in the synthesis of terephthaldiamine, various inorganic substances have been used as catalysts. Since organic substances lose their state under the influence of pressure and temperature and increase the activity of the reaction, their studies as catalysts have not yielded the expected results. Figure 2 shows the results of studying the effect of inorganic salts and oxides used as catalysts on the reaction yield. The effect of many different inorganic compounds as catalysts on the reaction was studied, and the results of the best ones are included in the diagram. Also, when choosing a catalyst, attention was paid to the possibility of recovery after the reaction and its economic efficiency. The reaction efficiency increased when Fe_2O_3, CaO, $CuCl_2$, NaCl, $Ca(OH)_2$, and $MgSO_4$ were used as catalysts. Among these, the highest results were observed when using Fe_2O_3. Fe_2O_3 as a catalyst increased the degree of reaction of the carboxyl functional group in terephthalic acid with ammonia and increased the reaction yield. Based on the obtained research results, Fe_2O_3 was selected as the catalyst.

Choosing an environmentally friendly chlorinating reagent for the Hofmann reaction

A study was conducted to identify a more environmentally friendly chlorinating agent for the Hofmann reaction to produce p-phenylenediamine. The selection of this chlorinating reagent was based on its selective chlorination of amides under alkaline conditions, the absence of hazardous chemical waste, and the formation of harmless by-products.

Figure 2

Results of applying a catalyst to the reaction yield of terephthaldiamide. 1. Fe_2O_3; 2. CaO; 3. $CuCl_2$; 4. NaCl; 5. $Ca(OH)_2$; 6. $MgSO_4$; 7. Reaction yield without catalyst. All values are based on the mean (±) standard deviation of three parallel experiments.



A number of hypochlorite salts and dichloroisocyanurate derivatives were studied, and the reaction efficiency of active chlorine was compared. Hypochlorite-based reagents (NaOCl and KOCl) are widely used for the Hofmann reaction; however, their reaction efficiency and stability are very low. In contrast, dichloroisocyanurate salts provide long-term release of active chlorine, which contributes to the high formation of the chloramide intermediate under stable reaction conditions. Importantly, their main by-product, cyanuric acid (or cyanurate salts under basic conditions), is non-volatile and readily separated from solution.

The results of the study conducted under the same experimental conditions are summarized in Table 1, and sodium dichloroisocyanurate was selected as the most suitable chlorinating reagent in terms of reaction efficiency and environmental performance.

Table 1
Research results for selecting a suitable chlorinating reagent for the Hofmann reaction

No.	Chlorinating agent	Chemical formula	Reaction yield (%)	Gas emission risk	Major by-products	Toxicity / hazard level	Green assessment
1	Sodium hypochlorite (aq)	NaOCl	70 ± 3	Medium	Cl^-, ClO_3^- (trace)	Moderate	Acceptable
2	Potassium hypochlorite (aq)	KOCl	68 ± 4	Medium	Cl^-, ClO_3^- (trace)	Moderate	Acceptable
3	Sodium dichloroisocyanurate (NaDCC)	$NaC_3N_3O_3Cl_2$	84 ± 2	Low	Cyanuric acid / cyanurate salts	Low–moderate	Preferred (green)
4	Trichloroisocyanuric acid (TCCA)	$C_3N_3O_3Cl_3$	80 ± 3	Low	Cyanuric acid / cyanurate salts	Moderate	Good
5	Calcium hypochlorite	$Ca(OCl)_2$	72 ± 3	Medium	$CaCl_2$, Cl^-, ClO_3^- (trace)	Moderate	Acceptable
6	Potassium dichloroisocyanurate (KDCC)	$KC_3N_3O_3Cl_2$	75 ± 3	Low	Cyanuric acid / cyanurate salts	Low–moderate	Good / green
7	Calcium dichloroisocyanurate (CaDCC)	$Ca(C_3N_3O_3Cl_2)_2$	60 ± 3	Low	Cyanuric acid / cyanurate salts	Low–moderate	Good / green

IR Spectrum of Analysis. The IR spectrum of the synthesized p-phenylenediamine confirms that it is compatible with an aromatic diamine. The absorption band observed at 3354 cm^{-1} corresponds to the asymmetric and symmetric stretching vibrations of the $–NH_2$ groups, which is typical for primary aromatic amines. The deformation vibrations of the amino groups at 1602 cm^{-1} and 1510 cm^{-1} further confirm the presence of free amine functional groups.

The peaks at 1263 cm^{-1} are due to C–N stretching vibrations, indicating the formation of amine bonds after the Hofmann reaction. The peaks observed in the region of 2920–2850 cm^{-1} correspond to aromatic C–H bonds, while the lines at 1381 cm^{-1} and 1290 cm^{-1} are related to the benzene ring. Importantly, the absence of carbonyl absorption bands in the region of 1650–1700 cm^{-1} confirms the complete conversion of the amide groups to amine groups. (Figure 3).

NMR analysis. The structure of the synthesized p-phenylenediamine was confirmed by ^1H and ^{13}C NMR spectroscopy. The singlet peak observed at δ 6.517 ppm in the ^1H NMR spectrum corresponds to the aromatic protons of the benzene ring, indicating a symmetrical para structure. The signal at δ 3.258 ppm is associated with the protons of the amino ($–NH_2$) groups, which is consistent with the values reported for p-phenylenediamine in the literature (Figure 4).

The ^{13}C NMR spectrum at δ 138.7 ppm corresponds to carbon atoms bound to amino groups ($C–NH_2$), while the signal at δ 116.9 ppm is due to aromatic C–H carbons. The spectral results indicate high purity of the product and confirm the successful formation of p-phenylenediamine without significant by-products (Figure 5).

Figure 3
IR spectrum of the resulting p-phenylenediamine

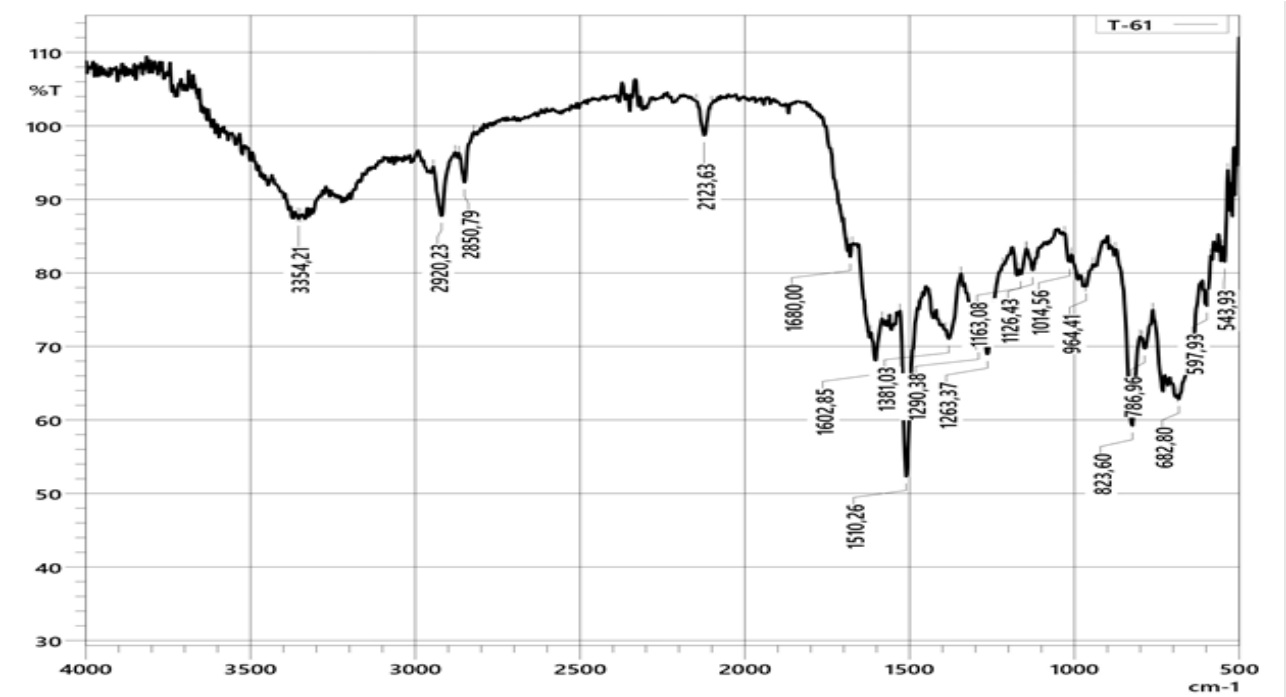


Figure 4
Result of ^{1}H NMR analysis of the obtained p-phenylenediamine

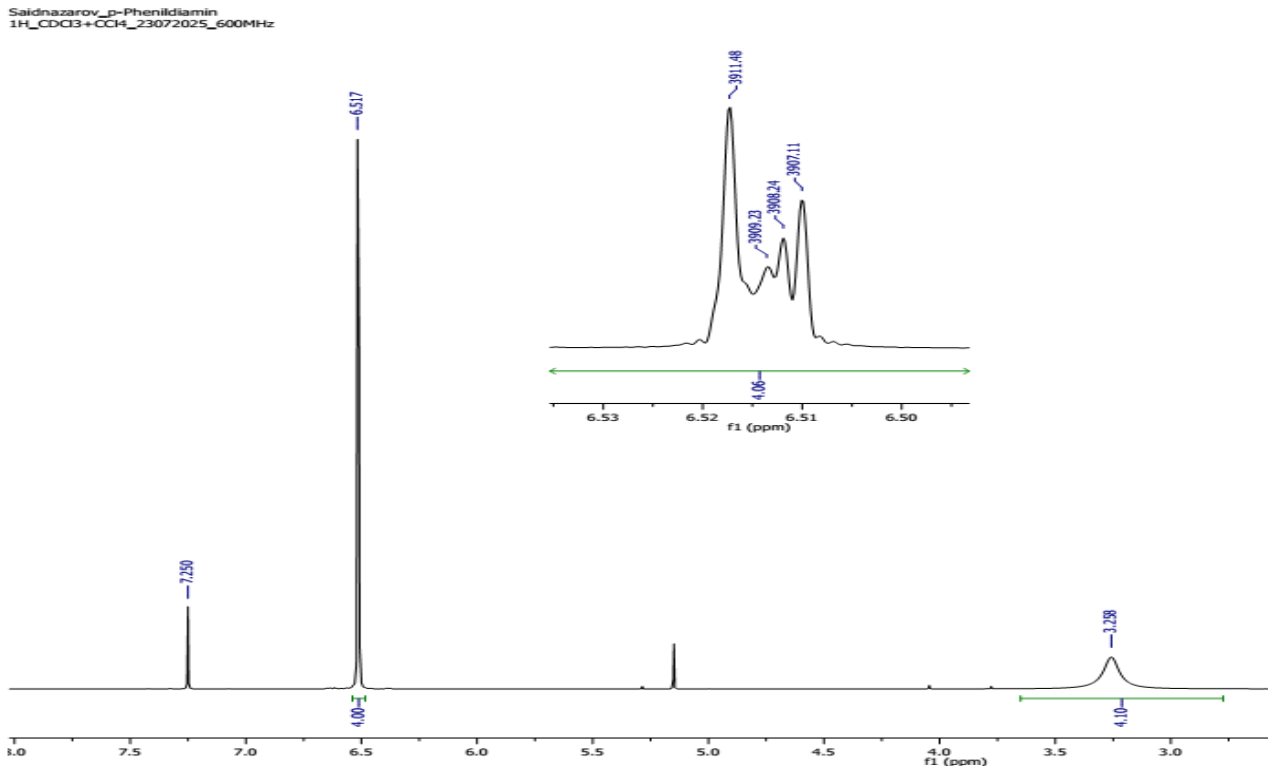
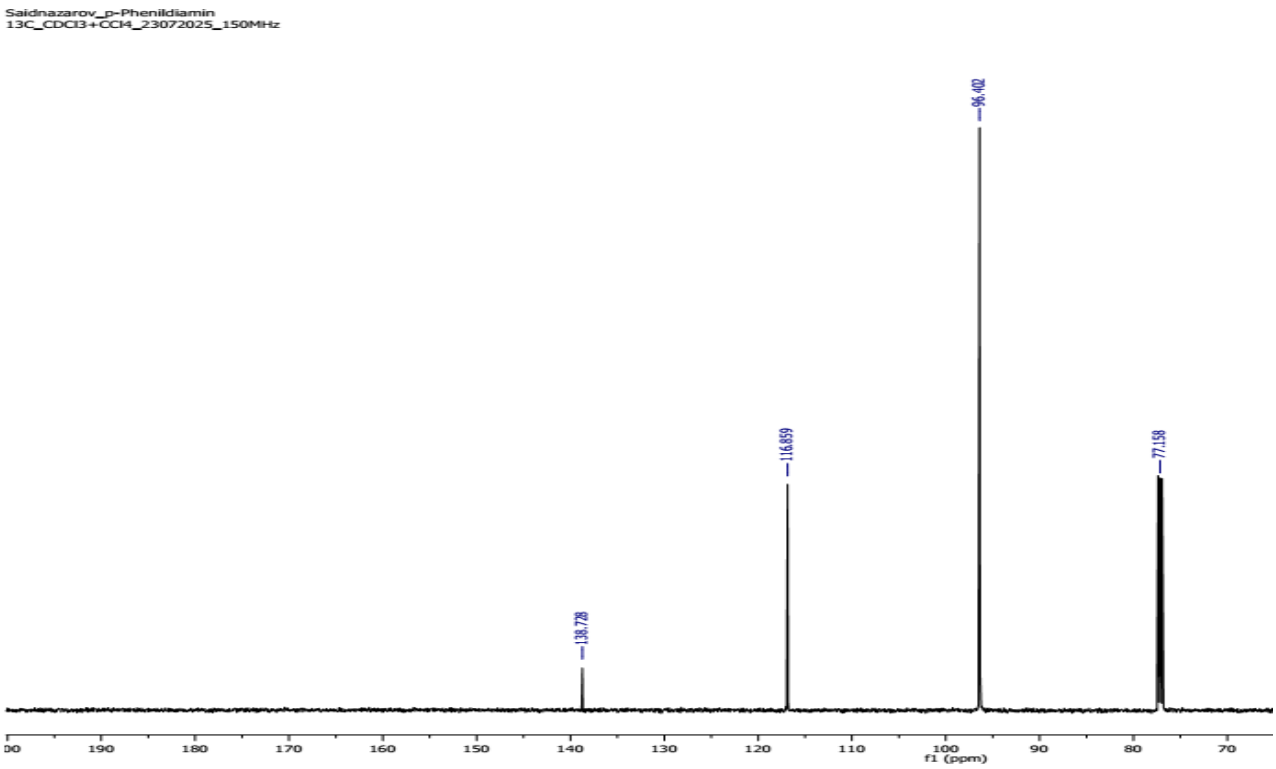


Figure 5
Result of ^{13}C NMR analysis of the obtained p-phenylenediamine



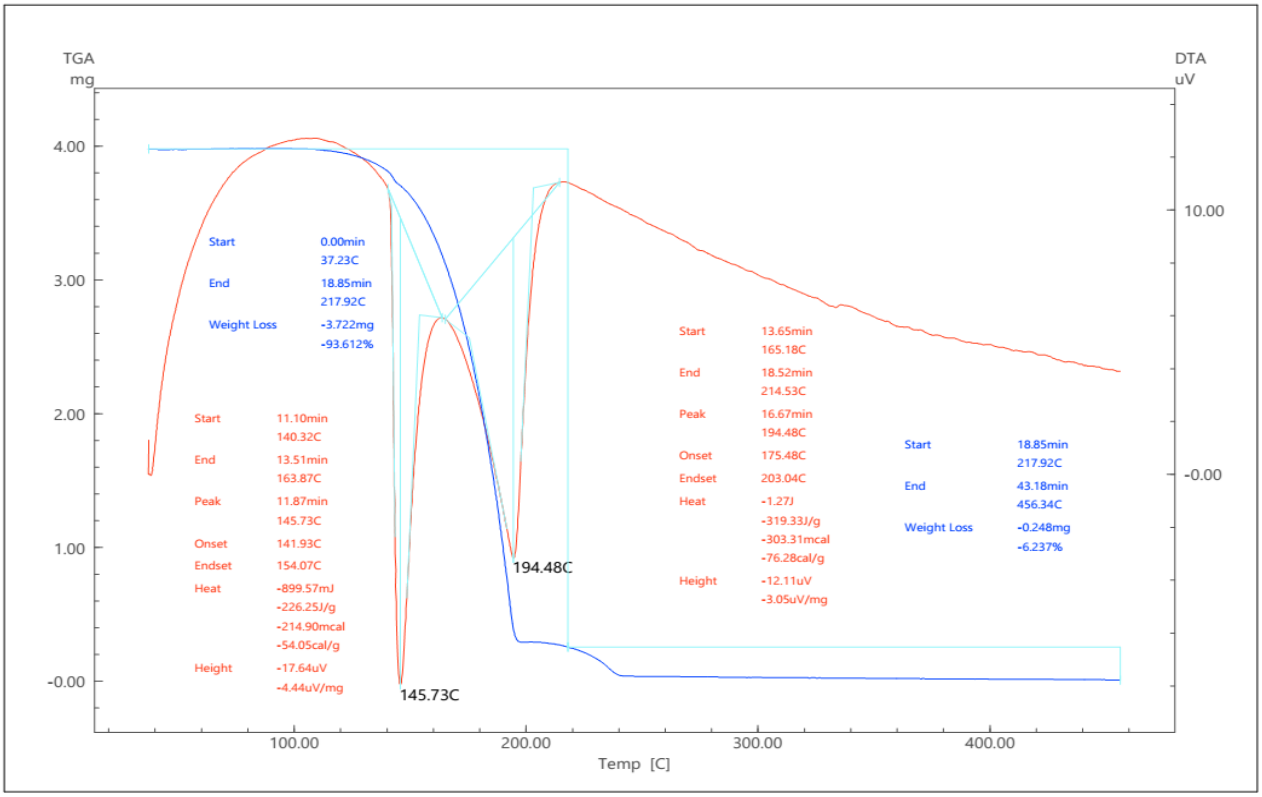
Differential-thermal and Thermogravimetric Analysis. According to the DTA analysis of the synthesized p-phenylenediamine, two endothermic peaks were observed at temperatures of 145.73°C and 194.48°C. No exothermic process was observed. The endothermic peaks appeared as a result of energy absorption due to the decomposition of amines (NH_2). The energy values of these endothermic processes were 214.9 mcal (899.57.16 mJ) and 303.31 mcal (1.27 J), respectively.

According to the TGA analysis results of the synthesized p-phenylenediamine, the substance lost mass in two stages. The first stage occurred between 37.23°C and 217.92°C and lost 93.6% (3.722 mg) of the total mass. The second stage of mass loss occurred between 217.92°C and 456.34°C and decomposed 6.2% (0.248 mg) of the total mass (Figure 6).

Table 2
TGA analysis of synthesized p-phenylenediamine

Reaction process	Reaction process duration (min)	Temperature range	Mass loss (%)
Stage 1	18.85	37.23°C-217.92°C	93.6%
Stage 2	24.33	217.92°C-456.3°C	6.2%

Figure 6
TG and DTA analysis results of synthesized p-phenylenediamine



Conclusion

Terephthalic acid was obtained from PET waste at room temperature in an energy-saving manner and amidated under pressure using a catalyst. The obtained terephthalamide was chlorinated using sodium dichloroisocyanurate salt and subjected to the Hofmann reaction in an alkaline medium to synthesize p-phenylenediamine.

A stepwise reaction mechanism for the overall process was developed. In order to identify an environmentally friendly and highly efficient chlorinating reagent, various chlorinating compounds were studied, and sodium dichloroisocyanurate salt was found to be the best among them.

Based on the results obtained, the proposed method was found to be an effective and reliable approach for the conversion of PET waste into p-phenylenediamine. Spectroscopic and thermal analyses clearly confirm the successful preparation, structural properties and high purity of the product. In particular, IR and NMR analyses showed the complete conversion of terephthaldiamide to p-phenylenediamine, while TG and DTA results revealed the thermal properties of the obtained compound.

This developed study showed that the process is not only chemically efficient but also suitable for further technological development.

Authors contribution

T.R. Saidnazarov: Original draft-writing, The organizational and editing of work. *Kh.Kh.Turaev*: the paper's proofreading and editing. *M.U. Karimov, P.I. Urkimbayeva, Z.A. Kenessova*: The provision and certification of software by. *Kh.E. Eshmurodov, S.M. Samatov*: The original manuscript, concept, investigation, and visualization of writing.

Acknowledgments

All analyses and studies were carried out using the equipment of the "Organic Chemistry" scientific laboratory of the Tashkent Chemical Technology Scientific Research Institute.

Conflict of interest

All authors are aware of the article's content and declare no conflict of interest.

References

1. Al-Sabagh, A. M., Yehia, F. Z., Eshaq, G., Rabie, A. M., & ElMetwally, A. E. (2016). Greener routes for recycling of polyethylene terephthalate. *Egyptian Journal of Petroleum*, *25*(1), 53–64. https://doi.org/10.1016/j.ejpe.2015.03.001
2. Amer, I., & Brandt, S. (2018). Synthesis and characterization of poly(p-phenylenediamine) and its derivatives using aluminium triflate as a co-catalyst. *Cogent Engineering*, *5*(1), Article 1499701. https://doi.org/10.1080/23311916.2018.1499701
3. Bohre, A., Darji, D., & Gogate, P. R. (2023). Chemical recycling processes of waste polyethylene terephthalate using solid catalysts. *ChemSusChem*, *16*(14), Article e202300142. https://doi.org/10.1002/cssc.202300142
4. Cataldo, F. (1996). On the polymerization of p-phenylenediamine. *European Polymer Journal*, *32*(1), 43–50. https://doi.org/10.1016/0014-3057(95)00118-2
5. Coelho, T. M., Castro, R., & Gobbo, J. A., Jr. (2011). PET containers in Brazil: Opportunities and challenges of a logistics model for post-consumer waste recycling. *Resources, Conservation and Recycling*, *55*(3), 291–299. https://doi.org/10.1016/j.resconrec.2010.10.010
6. Cosimbescu, L., Vasiliev, A., & Thiele, S. (2021). Simple but tricky: Investigations of terephthalic acid purity obtained from mixed PET waste. *Industrial & Engineering Chemistry Research*, *60*(35), 12792–12797. https://pubs.acs.org/doi/10.1021/acs.iecr.1c02604
7. Heintz, J., Belaud, J. P., & Gerbaud, V. (2014). Chemical enterprise model and decision-making framework for sustainable chemical product design. *Computers in Industry*, *65*(3), 505–520. https://doi.org/10.1016/j.compind.2014.01.010
8. Jiyanova, S. I., Turaev, K. K., Eshmurodov, K. E., Khamzaev, N. J., & Nabiev, D. A. (2024). Magniothermal methods of silicon extraction from quartz sands of "Jerdanak" mine. *International Journal of Engineering Trends and Technology*, *72*(10), 316–322. https://doi.org/10.14445/22315381/IJETT-V72I10P129
9. Khoonkari, M., Haghighi, A. H., Sefidbakht, Y., Shekoohi, K., & Ghaderian, A. (2015). Chemical recycling of PET wastes with different catalysts. *International Journal of Polymer Science*, Article 124524. https://doi.org/10.1155/2015/124524
10. Lu, X. B., Liu, Y., & Zhou, H. (2018). Learning nature: Recyclable monomers and polymers. *Chemistry – A European Journal*, *24*(44), 11255–11266. https://doi.org/10.1002/chem.201704461
11. Mohanaprasadh, S. V., Singh, P., & Bahukhandi, K. D. (2022). Disposal of non-biodegradable waste using eco-friendly methods. In *Environmental pollution and natural resource management* (pp. 345–363). Springer. https://doi.org/10.1098/rstb.2009.0053
12. Olzhabay, A. T., Urkimayeva, P. I., Yespenbetova, Sh. O., Kenessova, Z. A., & El-Sayed, N. (2022). Development of a technology for processing waste plastic bottles and bags to obtain various types of biodegradable polymer films. *International Journal of Biology and Chemistry*, *15*(1), 107–116. https://doi.org/10.26577/ijbch.2022.v15.i1.012
13. Patra, A. K., & Pariti, S. R. K. (2022). Restricted substances for textiles. *Textile Progress*, *54*(1), 1–101. https://doi.org/10.1080/00405167.2022.2101302
14. Raheem, A. B., Noor, Z. Z., Hassan, A., Hamid, M. K. A., Samsudin, S. A., & Sabeen, A. H. (2019). Current developments in chemical recycling of post-consumer polyethylene terephthalate wastes for new materials production: A review. *Journal of Cleaner Production*, *225*, 1052–1064. https://doi.org/10.1016/j.jclepro.2019.04.019
15. Saidnazarov, T. R., Turaev, K. K., Karimov, M. U., Kasimov, S. A., & Akhatov, A. A. (2024). High-quality synthesis of terephthalamide from secondary PET waste. *International Journal of Engineering Trends and Technology*, *73*(4). https://doi.org/10.14445/22315381/IJETT-V73I4P132
16. Samatov, S. M., Turaev, K. K., Kholnazarov, B. A., Toshkulov, A. K., & Shukurov, D. K. (2024). Synthesis of hydrogels based on starch-graft-acrylonitrile/bentonite. *International Journal of Engineering Trends and Technology*, *72*(11), 371–379. https://doi.org/10.14445/22315381/IJETT-V72I11P135
17. Sasse, F., & Emig, G. (1998). Chemical recycling of polymer materials. *Chemical Engineering & Technology*, *21*(10), 777–789. https://doi.org/10.1002/(SICI)1521-4125(199810)21:10<777::AID-CEAT777>3.0.CO;2-L
18. Shadravan, A., & Amani, M. (2012). HPHT 101: What petroleum engineers and geoscientists should know about high pressure high temperature wells environment. *Energy Science and Technology*, *4*(2), 36–60. https://doi.org10.3968/j.est.1923847920120402.635
19. Shaikh, T. M., Mubarak, N. M., Mazari, S. A., et al. (2024). Chemical recycling of polycarbonates via ammonolysis and polycaprolactones by KOH-catalyzed methanolysis. *European Journal of Organic Chemistry*, *27*(10), Article e202301308. https://doi.org/10.1002/ejoc.202301308
20. Tashkulov, A. K., Turaev, K. K., Eshmurodov, K. E., et al. (2025). Synthesis, crystal structure and Hirshfeld surface analysis of bis(benzene-1,2-diamine)-bis(2,4-dihydroxybenzoato)-nickel. *Journal of Chemical Crystallography*, *55*(2), 147–155. https://doi.org/10.1007/s10870-025-01046-5
21. Toshtemirov, A. E., Turaev, K. K., Ibragimov, A. B., et al. (2024a). A new mixed ligand copper(II) complex: Synthesis, crystal structure and Hirshfeld surface analysis. *International Journal of Engineering Trends and Technology*, *72*(11), 106–116. https://doi.org/10.14445/22315381/IJETT-V72I11P114
22. Toshtemirov, A. E., Turaev, K. K., Umbarov, I. A., et al. (2024b). Synthesis of copper(II) complex with 1,10-phenanthroline and nitrate anion in the presence of mandelic acid and crystalline structure. *Crystallography Reports*, *69*, 1087–1092. https://doi.org/10.1134/S1063774524602065
23. Wojnowska-Baryła, I., Bernat, K., & Zaborowska, M. (2022). Plastic waste degradation in landfill conditions: The problem with microplastics and their direct and indirect environmental effects. *International Journal of Environmental Research and Public Health*, *19*(20), Article 13223. https://doi.org/10.3390/ijerph192013223

24. Yulchieva, M. G., Turaev, K. K., Kasimov, S. A., Nabiev, D. A., & Chorieva, N. B. (2023). Research on the synthesis of nitrogen-containing sorbents. *International Journal of Engineering Trends and Technology*, *71*(8), 161–167. https://doi.org/10.14445/22315381/IJETT-V71I8P214

Information about the authors:

Toir Saidnazarov – 3-year PhD student, Faculty of Chemistry, Termez State University (Termez, Republic of Uzbekistan, e-mail: tohirsaidnazarov@gmail.com).

Khayit Turaev – Professor, Faculty of Chemistry, Termez State University (Termez, Republic of Uzbekistan, e-mail: hhturaev@rambler.ru).

Perizat Urkimbayeva – Candidate of Chemical Sciences, Acting Professor, Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: Urkimbayeva.perizat@gmail.com).

Zarina Kenessova – PhD, Associate Professor, Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: zarina.kenesova@gmail.com).

Masud Karimov – Professor, Tashkent Research Institute of Chemical Technology (Tashkent, Republic of Uzbekistan, e-mail: f_adm@ust.ac.kr).

Khurshid Eshmurodov – PhD, Faculty of Chemistry, Termez State University (Termez, Republic of Uzbekistan, e-mail: khurshideshmurodov@mail.com).

Sanjar Samatov – 3-year PhD student, Faculty of Chemistry, Termez State University (Termez, Republic of Uzbekistan, e-mail: sanjarsamatov888@gmail.com).

Received 10 February 2026;
received in revised form 26 May 2026;
accepted 9 June 2026