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Environmental risks of thermal waste management and prospects for sustainable remediation

Serhii Soboliev

Doctoral Student
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychova Str., Kharkiv, Ukraine
https://orcid.org/0009-0000-4013-1193

Inna Pitak*

PhD in Technical Sciences, Associate Professor
National Technical University "Kharkiv Polytechnic Institute"
61002, 2 Kyrpychova Str., Kharkiv, Ukraine
https://orcid.org/0000-0002-5073-2942

Abstract. The management of municipal solid waste remains one of the most urgent environmental challenges in Ukraine, particularly in the Kharkiv Region, where soil contamination and groundwater vulnerability intensify ecological risks. The study aimed to assess the environmental risks of thermal waste treatment technologies in the Kharkiv Region and evaluate their compatibility with ecosystem restoration strategies. The research applied a comparative analytical approach, integrating environmental impact assessment methods to analyse incineration, pyrolysis, and plasma gasification technologies. The assessment included estimation of pollutant emissions, energy efficiency, and secondary waste formation under regional conditions. It has been established that incineration, while effective at reducing waste volume, produces hazardous residues containing heavy metals and organic toxins. Pyrolysis demonstrates lower emissions and produces biochar capable of immobilising pollutants in soils, thereby enhancing its potential integration with phytoremediation practices. Plasma gasification provides nearly complete decomposition of complex waste streams, but it demands a high energy input and advanced technical infrastructure. The study identified that, under the post-conflict context of the Kharkiv Region, pyrolysis offers the best balance between environmental safety and resource efficiency. A framework for integrating thermal treatment residues into soil recovery strategies has been developed to support regional sustainability. The results can be applied by environmental engineers, municipal authorities, and policymakers to design sustainable waste-to-energy systems adapted to environmentally sensitive and post-conflict areas

Keywords: waste-to-energy technologies; pollutant emissions; soil and water protection; ecosystem restoration; resource efficiency; sustainable recovery

Introduction

The modern civilisational model of development is based on constant consumption growth, which inevitably leads to the accumulation of vast amounts of waste. Economic growth, urbanisation, and improvements in the standard of living are shaping a new ecological reality in which waste management is no longer only a technical but also a strategic task for states. The increase in the amount of solid household and industrial waste leads to soil, water, and atmospheric pollution, while traditional methods of disposal, particularly landfills, are reaching their limits. In this context, there is a need for technological solutions that strike a balance between processing efficiency and environmental safety. Thermal transformation of waste, including incineration, pyrolysis, and plasma gasification, is

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*Corresponding author

considered a promising direction; however, its application generates environmental risks associated with the formation of toxic emissions and ash. The issue of assessing these risks, as well as the possibilities of sustainable restoration of polluted ecosystems, is central to modern research and requires an integrated approach.

Y.A. Hajam *et al.* (2023) examined waste management through the lens of sustainable development, focusing on the environmental risks posed by traditional waste-disposal methods. Researchers demonstrated that environmental management strategies should be based on the principles of resource efficiency, specifically the transformation of organic waste into fertilisers or energy resources. The authors emphasised that without the development of closed waste management cycles, no management system can be considered sustainable. These findings emphasise the need to shift from the concept of "waste elimination" to "resource recovery". M. Bogusz *et al.* (2021) analysed the ideology of the concept of "zero waste" as a means of supporting the environmental awareness of consumers. They concluded that the environmental effectiveness of waste management policies largely depends on behavioural factors, including the willingness of the population to separate waste, reduce consumption, and recognise the value of resources. Although the authors worked in the context of European Union countries, their conclusions are of universal significance for Ukraine, where consumer culture is still in the process of formation.

In the national context, the monograph by N.S. Remez *et al.* (2023) made a significant contribution. The researchers developed a structural model of municipal waste management that takes into account technical, legal, and socio-economic factors. The authors emphasised that the lack of proper infrastructure and low level of control over waste movement create systemic environmental risks for Ukraine. They also noted that any utilisation technology should not be considered in isolation, but as an element of a holistic ecological cycle. Practical issues in implementing modern management strategies are discussed in the manual by M.O. Barinov *et al.* (2021), which investigated the mechanisms of separate collection, pre-sorting, and recycling of waste in Ukrainian communities. The authors highlighted the effectiveness of decentralised approaches but emphasised that, even with their implementation, a significant residual volume of waste remains, requiring additional thermal or biological treatment. Thus, these studies confirm the need to develop innovative thermal disposal technologies that minimise environmental impact.

From the standpoint of applied chemistry, the results of B.V. Korinenko *et al.* (2021), who studied the catalytic effect on low-temperature pyrolysis of polymer waste, are valuable. They proved that the use of catalysts allows for reducing the energy consumption of the process and improving the quality of the formed gas fractions, while reducing the formation of toxic residues. The authors also highlighted the potential for local implementation of such technologies in industrial regions, where polymer accumulation has become an environmental threat. Additionally, the Roadmap for the implementation of the Law of Ukraine "On Waste Management" (2022) summarises the strategic directions for implementing state policy in the field of waste management. The document emphasises the importance of integrating scientific developments into municipal management and of creating a system to monitor the impact of waste on environmental components. This allows consideration of the problem of waste management not only within the framework of technological processes, but also in terms of environmental safety and sustainable development of territories.

Despite the availability of modern research, a significant portion of scientific work focuses on individual aspects of the problem, such as the technological efficiency of thermal treatment, consumer behavioural factors, or phytoremediation processes. The relationship between thermal waste utilisation products and changes in soil ecosystems remains insufficiently studied, especially in post-conflict regions. There is also a lack of integrated research that combines environmental risk assessment with the development of mechanisms for the biological restoration of contaminated areas. Based on this, the purpose of the study was to analyse the ecological risks of thermal waste management and to determine the prospects for applying phytoremediation technologies for the sustainable restoration of degraded ecosystems.

Materials and Methods

The methodological basis of the study combines systemic, analytical, and comparative methods, which enabled the identification of logical connections between theoretical provisions of waste management and practical approaches to minimising their environmental impact. The search strategy was built on the principles of transparency, reproducibility and scientific validity. The information sample was compiled based on leading international databases, including Scopus, Web of Science, and Google Scholar, as well as national sources such as Scientific Periodicals of Ukraine (URAN) and the National Repository of Academic Texts. The time frame covered publications from 2020 to 2025, which ensures the relevance and modernity of the analysed results. Language restrictions applied to English- and Ukrainian-language works that contained empirical or conceptual data on the topic of environmental assessment of thermal waste management.

Search queries were formed by a combination of keywords: "municipal solid waste", "thermal treatment", "waste-to-energy", "incineration", "pyrolysis", "plasma gasification", "environmental impact", "phytoremediation", "soil restoration". For Ukrainian-language sources, the following queries were used: "thermal waste processing", "pyrolysis", "ecological risks", "phytoremediation". At the initial stage, more than 400 works were identified. After a phased selection based on thematic relevance, source reliability and methodological quality, the 31 most representative publications were included in the final analysis.

The inclusion criteria required that the study contained an analytical or experimental evaluation of the environmental impacts of thermal waste processing, provided a clear and explicit description of the applied technologies, such as combustion, pyrolysis, or plasma gasification, and demonstrated a direct link between energy recovery processes and ecosystem restoration. Review materials without scientific analysis, as well as outdated sources or publications lacking data on the environmental impact of technologies, were excluded.

The theoretical framework of the study was based on the concept of sustainable ecosystem restoration, combined with the principles of a circular economy and reducing carbon footprints. Within this paradigm, a logical analysis was conducted to assess the compatibility of thermal processing technologies with environmental protection strategies. To assess ecological risks, content analysis of publications was used, which enabled to identify key impact indicators. The method of systematisation and generalisation enabled the comparison of approaches from different authors, the identification of scientific gaps, and the detection of trends in the development of the direction. A separate analysis of official documents and statistical materials was conducted – in particular, the Roadmap for the implementation of the Law of Ukraine "On Waste Management" (2022), state reports on household waste generation, which allowed to assess the scale of the problem quantitatively. The results obtained formed the basis for further comparative analysis of risks and the potential of environmentally friendly solutions.

Graphical visualisation of comparative data was performed using analytical generalisation of literature and statistical sources, with figures constructed to illustrate technological process flows and cause-and-effect relationships between waste treatment stages and environmental impacts. Schematic diagrams of incineration, pyrolysis, and plasma gasification were developed as conceptual models based on published technological descriptions and engineering principles, with the aim of standardising process representation rather than simulating operational parameters. All visual materials were used as supporting analytical tools to improve the clarity and interpretability of the results and do not represent experimental modelling or primary numerical simulations.

Results and Discussion

Waste thermal processing technologies

Thermal treatment technologies, including incineration, pyrolysis, gasification, and plasma gasification, are key components in modern waste management strategies in Ukraine. Their environmental efficiency and energy potential vary significantly depending on process parameters, waste composition, and regional conditions. Waste incineration is the most common method, capable of reducing waste volume by 85-90% and generating heat or electricity. The process is presented in Figure 1.

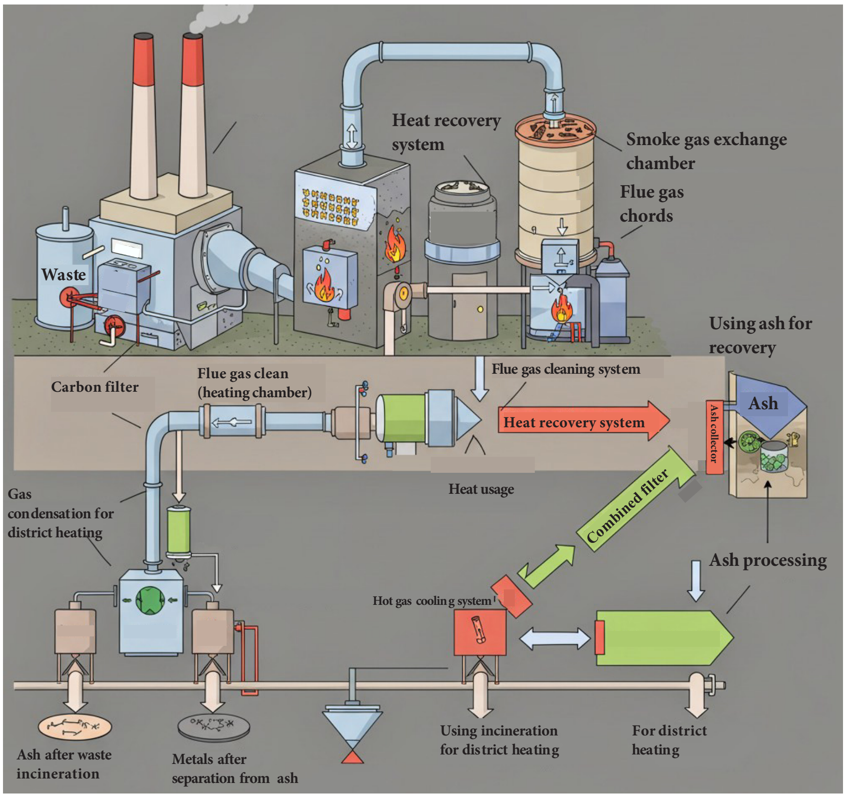

Figure 1. Incineration process

Source: made by the authors

The data indicate that while incineration provides the highest waste reduction, it generates the largest volume of hazardous residues. Pyrolysis offers a compromise between energy recovery and environmental safety. Gasification and plasma technologies ensure the lowest emissions but require a stable energy supply and advanced control systems (Table 1).

Table 1. Comparison of waste-to-energy technologies – efficiency, outputs, and environmental impact

Technology	Waste reduction (%)	Energy output	Major pollutants	Residue characteristics	Key advantages	Main limitations	References
Incineration	85-90	Heat, electricity	Dioxins, SO_x, NO_x, heavy metals	Toxic ash (10-15% of input)	Established technology; energy recovery	Toxic emissions; ash disposal risk	M. Niu *et al.* (2014), I. Cañete Vela *et al.* (2019)
Pyrolysis	70-80	Syngas, biochar, oil	VOCs, hydrocarbons	Biochar is suitable for soil application	Lower dioxin emissions; reuse potential	Energy-intensive; requires segregation	G. Özsin & A.E. Pütün (2022), J. Joo *et al.* (2022), C. Li *et al.* (2022)
Gasification	80-90	Syngas	CO, tar, trace metals	Inert slag	Efficient energy conversion; low emissions	Complex control; tar formation	S. Yasin *et al.* (2020), M. Dudyński *et al.* (2021)
Plasma gasification	90-95	High-quality syngas	Minimal (dioxins < 0.01 ng/m^3)	Glassy inert slag	Near-zero pollution; hazardous waste treatment	High cost; up to 1 MW/t energy need	V.Ya. Kozhukhar *et al.* (2021),V. Vashchenko *et al.* (2024), G. Cornelissen *et al.* (2025)

Source: compiled by the authors

The Kharkiv Region presents specific environmental conditions that strongly influence the mobility of contaminants. Soils are primarily chernozems with high humus content (4-6%), pH levels of 6.0-7.0, and shallow groundwater levels (2-10 m). These properties reduce the migration of Pb and As but promote accumulation in the upper soil horizon during atmospheric deposition. Annual precipitation ranges from 600 to 700 mm, with spring floods intensifying the leaching of nitrates and metals into groundwater, according to a statement by L. Di Stasio *et al.* (2025). Toxic ash from incineration poses a significant risk of secondary contamination under flood conditions. Pyrolysis and plasma gasification generate smaller, more stable residues; however, their reuse as construction materials requires detoxification, as stated in the National Report on the State of the Environment in Ukraine (Ministry of Environmental Protection and Natural Resources of Ukraine, 2018) and supported by data from R. Mallick & P. Vairakannu (2025). Regional adaptation of technologies must therefore include strict emission control, safe residue management, and integration with renewable energy. The pyrolysis process (Fig. 2), as explained by I. Zyma *et al.* (2024), which occurs at temperatures of 400-800°C in an oxygen-free environment, produces biochar, synthesis gas, and liquid fractions that can be used as fuel or to stabilise contaminants in soils.

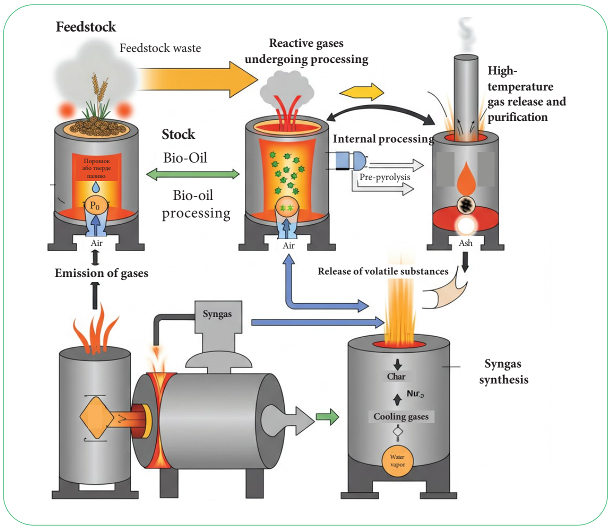

Figure 2. Pyrolysis process

Source: made by the authors

This technology reduces dioxin emissions compared to incineration, but its effectiveness depends on waste sorting and process stability. Studies show that pyrolysis biochar can bind Pb and Cd in chernozems (humus 4-6%), increasing the effectiveness of phytoremediation (*Brassica juncea* accumulates up to 1,000 mg/kg Pb). However, pyrolysis requires a significant energy input, which increases the carbon footprint if the energy is not renewable, and poses the risk of volatile organic compound formation during plastic recycling (Talwar *et al.*, 2025). Plasma gasification, which operates at temperatures ranging from 3,000 to 6,000°C, converts waste into synthesis gas and a glassy slag with minimal ash (Sanjaya & Abbas, 2023; Galaly *et al.*, 2024; Panwar *et al.*, 2025). This technology is effective for treating hazardous waste, such as medical or industrial waste, and reduces dioxin emissions to 0.01 ng/m^3 (Fig. 3).

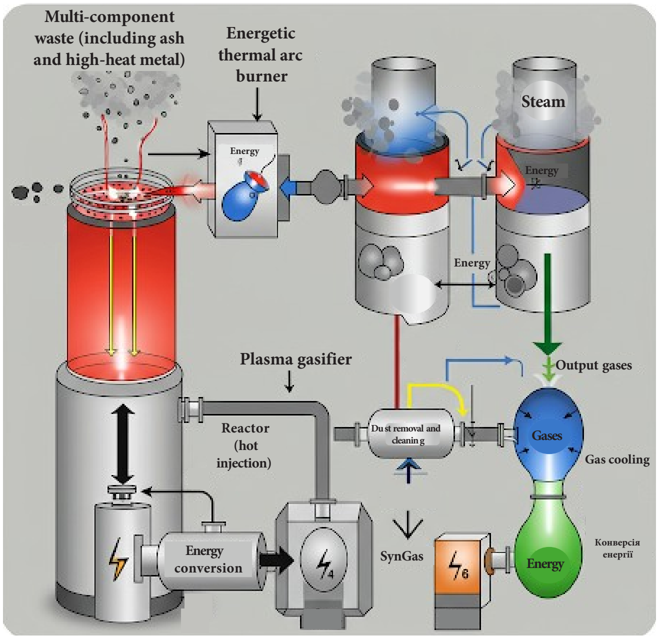

Figure 3. Schematic process of plasma gasification

Source: made by the authors

However, its high energy intensity, which can reach up to 1 MW per ton of waste, and the technological complexity of the equipment significantly limit its applicability in post-conflict regions such as the Kharkiv Region, where critical infrastructure remains constrained. Although the resulting slag is generally less toxic, the potential presence of heavy metal residues necessitates mandatory compliance with national regulatory requirements, in particular DSTU 7856:2015 (2015) and DSTU ISO 14001:2015 (2015), which governs its assessment prior to disposal. Overall, these factors indicate that plasma gasification in such conditions should be regarded as a technologically promising but currently constrained option that requires additional technical, economic, and environmental justification before large-scale implementation.

The environmental risks of thermal waste processing include air, soil and water pollution, which is especially relevant for the Kharkiv Region, where black soils with pH 6.0-7.0 and high humus content complicate the mobility of Pb and As, but increase the risk of their accumulation during the deposition of emissions (Solokha *et al.*, 2025). Emissions of dioxins and heavy metals from incineration can reduce the effectiveness of phytoremediation, as plants are sensitive to atmospheric pollution, which in turn reduces their ability to absorb nitrates (Di Stasio *et al.*, 2025). Studies show that protective strips of *Phalaris arundinacea* can retain up to 70% of atmospheric particles, but require regular monitoring, as specified in DSTU EN ISO 5667-1:2025 (2025). Toxic ash from incineration poses a threat to groundwater (2-10 m) in the Kharkiv Region, particularly during floods (600-700 mm of precipitation, with a peak in March-April), which can lead to secondary pollution as stated in the National Report on the State of the Environment in Ukraine (Ministry of Environmental Protection and Natural Resources of Ukraine, 2018). Pyrolysis and plasma gasification reduce the volume of ash, but its utilisation as a building material requires prior detoxification, which increases costs (Cornelissen *et al.*, 2025). The integration of thermal processing with phytoremediation requires spatial planning, as plants should be located at a distance from phytoremediation sites to prevent sedimentation of emissions.

Research gaps and regional context

The current literature primarily focuses on the industrial aspects of thermal processing, while its impact on agricultural regions, such as the Kharkiv Region, remains poorly understood. Most studies analyse the short-term effects of emissions, but the long-term impact on soil ecosystems, especially in combination with phytoremediation, remains poorly understood (Lackner & Besharati, 2025). For example, there is a lack of data on how Pb and Cd deposition from ash affects plants used for phytoremediation in conditions of high humus chernozems (4-6%). Additionally, limited studies have considered the energy intensity of technologies in post-conflict regions where access to renewable energy is challenging.

According to official statistical data and analytical reports, the scale of municipal solid waste generation in the Kharkiv Region is quantitatively significant and confirms the relevance of the problem stated in the methodology (Kharkiv Regional State Administration, 2024). In 2022, the total amount of waste generated in hazard classes I-IV in the Kharkiv Region was approximately 142,000 t, of which only 16.4 per cent was utilised, and approximately 13,875 t was treated by incineration or thermal recovery. At the same time, more than 27,000 t of municipal solid waste were disposed of in landfills, indicating a steady accumulation of waste and limited regional processing capacity. These figures reflect structural imbalances in the waste management system, in which disposal predominates over recovery and energy use. In addition, wartime conditions led to incomplete statistical reporting in 2022-2023, which constrains a full assessment of temporal dynamics but does not alter the overall conclusion about the critical scale of waste accumulation in the region. The regional data are consistent with national estimates, according to which Ukraine generates about 11-13 million tons of municipal solid waste annually, with more than 95% directed to landfills. This quantitative evidence substantiates the need to assess thermal waste treatment technologies in the Kharkiv Region not only from an environmental perspective but also in response to the objectively large and growing volume of municipal solid waste.

In the Kharkiv Region, where the climate (600-700 mm of precipitation) and hydrology (groundwater 2-10 m) favour nitrate leaching, thermal processing may complicate remediation due to secondary contamination. Studies recommend using renewable energy sources for pyrolysis and plasma gasification, as well as implementing remote monitoring (NDVI, drones) to assess the impact of emissions on phytoremediation sites (Ivanova & Kaverda, 2019; Petrushka & Volivach, 2024). However, the lack of standardised protocols for integrating these technologies with phytoremediation remains a challenge. Gasification, pyrolysis, and plasma gasification have significant potential for waste management, but are accompanied by environmental risks, including dioxin emissions, toxic ash formation, and high energy intensity. In the context of the Kharkiv Region, these risks may complicate phytoremediation, reducing the effectiveness of soil remediation for Pb, As, Cd, and nitrates. To minimise the impact, researchers Ya.H. Tsytsyura *et al.* (2022) suggested using modern filtration systems, buffer strips, monitoring, and renewable energy sources. However, gaps in the study of long-term effects and regional specificities indicate the need for further research that would combine thermal processing with phytoremediation in post-conflict settings.

The results obtained indicate that thermochemical waste processing methods, particularly pyrolysis, gasification, and plasma gasification, have significant potential for improving the efficiency of managing complex waste streams, such as textiles. The analysis confirms that the choice of temperature regime, the presence of catalysts and the design of the reactor determine the energy efficiency and yield of target products. Increasing the temperature leads to an increase in the yield of synthesis gas. At the same time, catalysts contribute to optimising the quality of liquid fractions, which is consistent with the results of modern research. In particular, N.L. Panwar *et al.* (2025) demonstrated that plasma gasification enables the reduction of CO_2 emissions and the complete elimination of dioxin formation, while maintaining a high calorific value in the resulting gas. Similar conclusions are presented in the work of E. Sanjaya & A. Abbas (2023), who emphasised that the introduction of plasma technologies into a closed-loop economy enables the combination of energy efficiency and environmental safety. A.R. Galaly *et al.* (2024) reported that plasma gasification of plastics provides minimal residual products and meets modern sustainability requirements. These results confirm the environmental advantage of the technology over classical combustion methods.

In the context of pyrolysis, the results are consistent with those of K. Sharma *et al.* (2022), G. Özsin & A.E. Pütün (2022), B.Y. Lamba (2025), who found that a temperature range of 600-800°C provides an optimal balance between the formation of gaseous and liquid fractions. I. Zyma *et al.* (2024) confirmed the importance of temperature control for stabilising the thermal decomposition of organic matter, while I. Petrushka & T. Volivach (2024) emphasised the role of catalysts in reducing the toxicity of the final products. Thus, an approach based on adapting the process parameters to the composition of the feedstock is crucial to achieve high energy performance and minimise harmful emissions.

Regarding gasification, analysis confirms the trends identified in V.V. Ivanova & L.O. Kaverda (2019), M. Lackner & M. Besharati (2025), and B. Hamidinasab & A. Nabavi-Pelesaraei (2025). The authors showed that at temperatures above 900°C, the content of CO and H_2 in the syngas increases significantly, while the formation of tars and ash decreases. However, as noted by N.L. Panwar *et al.* (2025), for the stable operation of such systems, preliminary preparation of the feedstock is necessary, in particular, the removal of flame retardants and impurities that reduce reactivity. Results of the current study confirm that differences in the composition of textile waste (cellulosic vs. synthetic) directly affect the gasification efficiency, which is consistent with the findings of A.R. Galaly *et al.* (2024) on the role of chemical heterogeneity in product formation.

A comparison of pyrolysis and gasification shows that both processes have the potential for fuel production, but gasification provides a cleaner energy product with lower residue content. However, as E. Sanjaya & A. Abbas (2023) point out, the formation of CO_2 and resins remains a problem, which reduces the efficiency of syngas use without additional purification. The results confirm these conclusions: even with optimisation of the temperature regime, a significant number of by-products is formed that require post-purification. Plasma gasification, on the other hand, demonstrates fundamentally different properties. As shown in the studies by N.L. Panwar *et al.* (2025) and A.R. Galaly *et al.* (2024), the use of plasma arc systems ensures the destruction of complex polymers and eliminates toxic emissions. Theoretical analysis confirms that extremely high temperatures (>2,000°C) contribute to the formation of clean syngas with high H_2 and CO content and virtually no tars, making the technology suitable for producing clean energy carriers. These results correlate with the conclusions of I. Zyma *et al.* (2024) on the need for innovative solutions in the field of emission control in high-temperature processes.

However, plasma technology has limitations, including high energy consumption and significant capital costs, as noted by E. Sanjaya & A. Abbas (2023) and N.L. Panwar *et al.* (2025). However, A.R. Galaly *et al.* (2024) and others believe that integrating plasma gasification with heat recovery and syngas reuse technologies can compensate for energy losses and improve overall profitability. A comparative analysis of literature sources reveals that over the past five years, there has been a noticeable increase in research interest in plasma technologies for waste management. This trend is observed in both domestic (Ivanova & Kaverda, 2019; Lackner & Besharati, 2025) and international publications (Sanjaya & Abbas, 2023; Galaly *et al.*, 2024; Panwar *et al.*, 2025), indicating the relevance of the topic. In general, it can be stated that plasma gasification is the most promising in terms of environmental safety and energy efficiency. At the same time, further research is needed to optimise balance, improve plasma burners, and scale the technology for industrial applications.

The assessment of thermal waste treatment technologies was refined with explicit consideration of the environmental conditions of the Kharkiv Region. Chernozem soils with high humus content and shallow groundwater increase the risk of secondary contamination from toxic residues generated during waste processing. Under these conditions, incineration poses a high environmental risk due to the formation of hazardous ash and its limited compatibility with ecosystem restoration measures. Pyrolysis demonstrates the highest regional suitability, as its biochar residues can reduce the mobility of heavy metals in soils and support phytoremediation practices. Plasma gasification provides low emission levels but is constrained by high energy demand and limited post-conflict infrastructure. Overall, the results indicate that pyrolysis is the most compatible thermal technology for the Kharkiv Region, combining waste treatment efficiency with practical integration into soil and ecosystem restoration strategies. Thus, the theoretical analysis conducted confirms that the transition from traditional incineration to high-temperature thermochemical conversion methods not only reduces environmental risks but also contributes to achieving sustainable development goals by converting waste into valuable energy sources.

Based on a comparative analysis of thermal waste treatment technologies, phytoremediation is not considered a stand-alone solution, but rather a complementary recovery stage following controlled thermal processing. In the conditions of the Kharkiv Region, the direct application of phytoremediation without prior stabilisation of pollutants is ineffective due to the presence of heavy metals and persistent toxic compounds in the soil. The results indicate that pyrolysis creates the most favourable conditions for subsequent phytoremediation. The application of pyrolysis-derived biochar reduces the bioavailability of Pb, Cd, and As, stabilises the upper soil horizon, and improves conditions for plant-based remediation. This allows phytoremediation to function as a targeted ecological recovery tool rather than a passive natural process. From an applied perspective, phytoremediation should be implemented in spatially separated zones, following residue characterisation and detoxification. Plant systems should be selected based on the type of contaminant and soil properties, and their performance must be supported by long-term monitoring. Under these conditions, phytoremediation becomes a practical component of an integrated waste management and ecosystem restoration strategy rather than an insufficiently explored concept.

Conclusions

The analysis revealed that thermal waste processing technologies, including incineration, pyrolysis, and plasma gasification, are key directions for transforming Ukraine's solid waste management system. Each of these methods has the potential to significantly reduce waste volumes and obtain secondary energy resources, but their implementation requires a balanced approach that considers potential environmental risks. Incineration remains the most common technology that significantly reduces waste volumes and energy generation. At the same time, its environmental safety is limited by the formation of toxic ash and emissions of harmful compounds, which requires highly efficient systems for cleaning, monitoring and disposal of by-products. Pyrolysis is a more environmentally balanced alternative, as it allows for the production of biochar, synthesis gas, and liquid fuel under conditions of limited oxygen access. The ability of biochar to fix heavy metals in the soil emphasises the dual effect of this process – energy and environmental protection. At the same time, the efficiency of pyrolysis largely depends on the quality of waste sorting and the stability of energy supply. Plasma gasification is the most technologically advanced method for processing hazardous or mixed waste streams. It provides the formation of synthesis gas and inert slag with minimal toxicity but requires significant energy resources and complex operational infrastructure.

The environmental consequences of thermal waste treatment are particularly important for the Kharkiv Region, where soil contamination with heavy metals and high groundwater vulnerability are observed. The success of such projects is possible only under the conditions of an integrated approach, which involves modern emission cleaning technologies, safe management of ash and slags, and the use of renewable energy sources to reduce the carbon footprint. For the Kharkiv Region, the study demonstrated that incineration and pyrolysis can significantly reduce waste volume and generate energy. At the same time, pyrolysis also provides additional heavy metal fixation in soils through the production of biochar. Plasma gasification is effective for mixed and hazardous waste, minimising the toxicity of slag, but it requires significant energy resources. The success of implementing these technologies in the region is possible only through an integrated approach, which includes modern emission treatment systems, safe management of residues, and the use of renewable energy. Further studies should assess the long-term impact of residues on soil and water ecosystems of the Kharkiv Region and determine the effectiveness of combining thermal technologies with phytosanitary measures. Such research will provide a scientific basis for combining technological innovations with ecological security and regional recovery objectives.

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Conflict of Interest

None.

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Екологічні ризики термічного управління відходами та перспективи сталого відновлення

Сергій Соболєв

Докторант
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0009-0000-4013-1193

Інна Пітак

Кандидат технічних наук, доцент
Національний технічний університет «Харківський політехнічний інститут»
61002, вул. Кирпичова, 2, м. Харків, Україна
https://orcid.org/0000-0002-5073-2942

Анотація. Управління твердими побутовими відходами залишається однією з найгостріших екологічних проблем в Україні, особливо в Харківській області, де забруднення ґрунтів і вразливість підземних вод посилюють екологічні ризики. Метою дослідження було оцінити екологічні ризики технологій термічної обробки відходів у Харківській області та визначити їхню сумісність зі стратегіями відновлення екосистем. У роботі застосовано порівняльний аналітичний підхід із інтеграцією методів оцінки впливу на довкілля для аналізу технологій спалювання, піролізу та плазмової газифікації. Оцінювання включало визначення викидів забруднювальних речовин, енергоефективності та утворення вторинних відходів з урахуванням регіональних умов. Встановлено, що спалювання, хоча й ефективно зменшує об'єм відходів, утворює небезпечні залишки, які містять важкі метали та органічні токсини. Піроліз характеризується нижчими рівнями викидів і утворенням біочару, здатного іммобілізувати забруднювачі в ґрунтах, що підвищує його потенціал інтеграції з практиками фіторемедіації. Плазмова газифікація забезпечує майже повне розкладання складних потоків відходів, однак потребує значних енергетичних витрат і розвиненої технічної інфраструктури. Дослідження показало, що в умовах післяконфліктного контексту Харківської області піроліз забезпечує найкращий баланс між екологічною безпекою та ресурсною ефективністю. Розроблено підхід до інтеграції залишків термічної обробки у стратегії відновлення ґрунтів з метою підтримки регіональної сталості. Отримані результати можуть бути використані інженерами-екологами, органами місцевого самоврядування та політиками для проєктування сталих систем перетворення відходів на енергію, адаптованих до екологічно чутливих і післяконфліктних територій

Ключові слова: технології перетворення відходів на енергію; викиди забруднювальних речовин; охорона ґрунтів і вод; відновлення екосистем; ресурсна ефективність; сталий розвиток