Jurnal Ners Volume 10 Nomor 1 Tahun 2026 Halaman 1608 - 1615
JURNAL NERS
Research & Learning in Nursing Science
http://journal.universitaspahlawan.ac.id/index.php/ners

MEDICAL WASTE MANAGEMENT INNOVATION BASED ON THERMAL AND CHEMICAL DEGRADATION OF POLYMERS

Ilyu 'Ainun Najie'[1], Muhammad Dary Adhidrawa Margolang[2], Muhammad Diaz Supandi[3], Keysa Najmi Tsaqib[4], Niken Sylvia Puspitasari[5]
University of Darussalam Gontor
ian@unida.gontor.ac.id

Abstrak

Pertumbuhan layanan kesehatan yang masif, terutama pascapandemi COVID-19, telah meningkatkan volume limbah medis berbasis polimer berbahaya dan infeksius secara signifikan. Metode konvensional seperti insinerasi terbuka menimbulkan risiko lingkungan dan kesehatan akibat emisi toksik serta sterilisasi tidak sempurna, sehingga mendorong kebutuhan mendesak akan inovasi pengelolaan yang aman, efisien, dan berkelanjutan. Penelitian ini menganalisis efektivitas teknologi degradasi termal (pirolisis, gasifikasi) dan kimia (depolimerisasi, Advanced Oxidation Processes/AOPs) dalam menangani limbah medis melalui studi pustaka kualitatif. Data dikumpulkan dari sumber terpercaya (jurnal terindeks, laporan WHO/UNEP, kebijakan pemerintah; 2018–2025) dan dianalisis secara deskriptif-kritis serta komparatif. Hasil menunjukkan bahwa degradasi termal dalam reaktor terkontrol mengurangi volume limbah hingga 90%, menetralkan patogen pada suhu 400–800°C, dan menghasilkan produk bernilai (syngas, bio-oil), sementara pendekatan kimia (katalis, AOPs) mendegradasi polimer pada tingkat molekuler serta menetralkan logam berat dan kontaminan organik tanpa emisi dioksin. Integrasi kedua teknologi ini dalam strategi clustering berbasis kapasitas regional dan skema pendanaan blended finance terbukti layak secara teknis-ekonomi. Kontribusi penelitian mencakup: (1) Rekomendasi kebijakan bagi Kementerian Kesehatan/LHK untuk standarisasi teknologi hijau; (2) Model bisnis Technology-as-a-Service bagi fasilitas kesehatan; (3) Panduan implementasi kolaboratif pemerintah-swasta-akademisi mendukung target SDGs dan Indonesia Emas 2045 melalui pencegahan polusi, ekonomi sirkular, dan peningkatan kualitas kesehatan masyarakat.

Kata Kunci: *Limbah Medis; Degradasi Termal; Depolimerisasi; Teknologi Hijau; Indonesia Emas*

Abstract

The massive growth of healthcare services, particularly post-COVID-19, has significantly increased volumes of hazardous polymer-based and infectious medical waste. Conventional methods like open incineration pose environmental and health risks due to toxic emissions and incomplete sterilization, highlighting an urgent need for safer, efficient, and sustainable management innovations. This study analyzes the effectiveness of thermal (pyrolysis, gasification) and chemical (depolymerization, Advanced Oxidation Processes/AOPs) degradation technologies through qualitative library research. Data from credible sources (indexed journals, WHO/UNEP reports, government policies; 2018–2025) were descriptively-critically and comparatively analyzed. Results demonstrate that controlled thermal degradation reduces waste volume by 90%, neutralizes pathogens at 400–800°C, and converts waste into valuable products (syngas, bio-oil), while chemical approaches (catalysts, AOPs) decompose polymers at the molecular level and neutralize heavy metals/organic contaminants without dioxin emissions. Integrating both technologies via capacity-based regional clustering and blended finance schemes proved technically-economically feasible. Contributions include: (1) Policy recommendations for the Ministry of Health/Environment to standardize green technologies; (2) Technology-as-a-Service business models for healthcare facilities; (3) Collaborative implementation frameworks (government-private-academia) supporting SDGs and Indonesia's 2045 Golden Vision through pollution prevention, circular economy, and improved public health outcomes.

Keywords*: *Medical Waste; Thermal Degradation; Depolymerization; Green Technology; Indonesia 2045

* Corresponding author :
Address : University of Darussalam Gontor
Email : ian@unida.gontor.ac.id

INTRODUCTION

Hospitals and healthcare facilities are complex environments that connect individuals with diverse health status. The multidimensional interactions between patients, visitors, and medical personnel not only have the potential to transmit diseases, but also generate various types of hazardous waste (Ciawi et al., 2024). Every clinical and non-clinical activity in health facilities generates waste that requires special handling due to its characteristics that can endanger human health and damage the balance of the ecosystem (Ismayanti et al., 2020).

Medical waste can be categorized into solid, liquid, and gas, with specific subcategories including infectious, pathology, cytotoxic, pharmaceutical, sharps, chemical, and radioactive waste (Gałko & Sajdak, 2022). The waste generated includes needles, contaminated bandages, vaccine vials, blood, sputum, chemical reagents, and heavy metals from dental practices (Heriwati, Meliyanti and Budianto, 2023). Despite the presence of non-medical (domestic) waste such as plastics and food waste, Indonesian Health Profile data shows a significant composition of medical waste, for example in Cilegon hospitals reaching 23.2% of the total 3.25 kg of waste per bed per day (Giakoumakis et al., 2021).

Nationally, the volume of medical waste generated is enormous reaching an estimated 376,089 tons per day, emphasizing the urgency of a systematic and sustainable management system (Windfeld & Brooks, 2015). However, the reality on the ground is alarming, as data from the Data and Information Center of the Indonesian Ministry of Health (2015) revealed that only 64.6% of health centers properly separate medical and non-medical waste, and only 26.8% have incinerators(Aravind et al., 2021). The lack of infrastructure distribution is very evident, such as in Merangin Regency, Jambi Province, where none of the health centers have independent incineration facilities, thus relying on uneven cooperation with hospitals.

Suboptimal medical waste management poses serious health risks. Infectious waste and sharps, especially syringes, have the potential to become a medium for the transmission of dangerous diseases(Zhang et al., 2024). Chua Say Tiong (2012) stated that exposure to contaminated needles can transmit Hepatitis B and HIV. World Health Organization (2015) data reinforces this, showing that 32% of Hepatitis B cases and 5% of new HIV cases in health workers are related to sharps injuries. Hygienists, medical personnel, and the surrounding community face a high risk (Rochmawati & Syarifah Has, S.KM., M.Epid, 2023)

In addition to direct health risks, unmanaged medical waste has the potential to contaminate the environment at large air, soil and water (e.g. by heavy metals or chemicals from liquid waste or ash). The concept of environmental health according to WHO emphasizes ecological balance for healthy living. The Indonesian Association of Environmental Health Experts (HAKLI) emphasizes that sustainable waste management, including medical waste, is a crucial aspect (one of 17 scopes) in realizing an environment that supports optimal health and prevents pollution (Enny Mar’atus Sholihah, Nuriyati, Ari Kusdiana, 2024).

Response to complex challenges and data showing management gaps, technological innovation is an urgent need (Yong et al., 2009). Thermal degradation technologies (such as pyrolysis or controlled gasification) and chemical degradation of polymers offer potential solutions to destroy medical waste, especially infectious plastics, more effectively reducing volume and minimizing harmful emissions compared to conventional incineration (Qin et al., 2018). This innovation is in line with Indonesia's Golden Vision 2045 which emphasizes sustainable development, health system strengthening, and environmental preservation (Alfian and Wulamdari, 2023).

The research problem in this study is how the effectiveness and feasibility of applying polymer thermal and chemical degradation technologies can be implemented in medical waste management in Indonesia, and to what extent the results of this analysis can provide evidence-based policy recommendations that are relevant for hospitals, health centers, and policymakers in designing waste management strategies that are safer, more efficient, environmentally friendly, and supportive of achieving sustainable development targets and the Golden Indonesia 2045 vision.

METHODS

This study adopted a qualitative narrative review with a Systematic Literature Review (SLR) approach to examine innovations in medical waste management through thermal and chemical polymer degradation technologies. The review process involved several systematic stages, beginning with the formulation of research questions that explored the nature of technological innovations, their effectiveness compared to conventional incineration, and their applicability within Indonesia’s socio-economic and regulatory frameworks. Literature was collected from reputable academic databases (Scopus, Web of Science, PubMed), as well as policy documents and reports from global organizations such as

WHO, UNEP, and the World Bank. The inclusion of sources was determined by three main criteria: relevance to medical waste management, novelty of research (2018–2025), and credibility through peer review or institutional authority. Data extracted were categorized into primary technical findings (e.g., pyrolysis, gasification, depolymerization, and advanced oxidation processes) and secondary contextual information (e.g., regulations, policies, socio-economic factors). A thematic analysis was then applied to highlight recurring patterns concerning technological effectiveness, sustainability, and alignment with Indonesia's Golden Vision 2045.

The analysis followed a descriptive-critical framework, focusing on identifying challenges in medical waste management, evaluating the efficiency of thermal and chemical degradation technologies, and assessing their feasibility within Indonesia's context. Comparative analysis (SWOC) was also employed to map strengths, weaknesses, opportunities, and challenges of these innovative methods relative to existing practices. To ensure validity, the study applied source triangulation by cross-checking findings from academic publications with official reports and international standards. Both quantitative indicators (e.g., waste volume reduction rates, gas composition from pyrolysis, polymer degradation levels) and qualitative evidence (e.g., policy analysis, institutional reports) were integrated. The outcome of this review is a conceptual synthesis and strategic recommendations designed to guide policymakers, academics, and healthcare practitioners in adopting thermal and chemical degradation technologies effectively and sustainably, without aiming to propose a definitive technical solution but rather providing a strong foundation for future policy and practice.

RESULTS AND DISCUSSION

Thermal Degradation Innovation

Thermal degradation, particularly through controlled pyrolysis and gasification technologies, has emerged as a crucial innovation to overcome the critical weaknesses of traditional incinerators in managing medical waste. Unlike open burning, which produces toxic emissions (such as dioxins, furans, and particulates) and significant residual ash, thermal degradation operates in low-oxygen or oxygen-free environments (Qin et al., 2018). This process intelligently avoids direct combustion (oxidation) by replacing it with the thermochemical decomposition of organic materials and polymers (such as infectious plastics, bandages, and plastic syringes) at high temperatures (typically between 400°C and 800°C). The ingenuity of this innovation lies in its ability to trap harmful pollutants while simultaneously transforming waste into valuable products, rather than merely transferring the problem into smoke and ash (Ray & Cooney, 2018).

The key process of thermal degradation begins with the loading of solid medical waste—primarily polymer-based—into a sealed reactor. The waste is then intensively heated in the absence of, or with a very limited supply of, oxygen (Heriwati et al., 2023). Under these conditions, the long chemical bonds of polymers (such as polypropylene in syringes or polyethylene in infusion bottles) undergo thermal cracking. Large molecules break down into smaller fractions: synthetic gases (syngas, a mixture of H_2, CO, CH_4), liquids (bio-oil), and carbonaceous solids (char). An innovation in volume reduction of up to 90% is achieved through the mass transformation of low-density solid waste into gas, liquid, and highly concentrated solid residues (Vienken & Boccato, 2024). The volume of solid char produced is only about 10–15% of the original volume of plastic waste, while the rest is converted into usable energy or chemical materials (Barbu & Năstase, 2018).

The core wisdom of this innovation lies in its environmentally conscious destruction approach. The high temperatures within a sealed reactor ensure the complete neutralization of pathogens, viruses, and infectious agents, effectively breaking the chain of disease transmission. More importantly, the tightly controlled process design prevents the formation of persistent organic pollutants (POPs) such as dioxins and furans, which are major hazards in conventional incineration systems (Tamošiūnas et al., 2025). The synthetic gas produced can be purified and utilized as an energy source to power the system itself—making it more self-sustaining—or to meet other energy needs within healthcare facilities, thus enhancing energy efficiency. Bio-oil has potential as a fuel or chemical feedstock, while char can be further processed or safely stored with minimal environmental risk compared to the original waste. This process significantly reduces the carbon footprint of medical waste management. (See Figure 1.)

Figure 1. Illustration of Thermal Degradation Innovation

From an operational perspective, thermal degradation technology offers space efficiency and flexibility that are crucial for healthcare facilities in Indonesia. Medium-capacity modular units can be installed on-site at hospitals or within regional clusters, reducing dependence on risky waste transportationand centralized incinerators, which are often overloaded or unavailable (Montero-Calderón et al., 2023). Its ability to achieve nearly 90% volume reduction significantly lowers transportation costs and the need for final landfill space (Wang et al., 2023). This innovation is not merely a technical solution for waste destruction, but a partial circular economy approach that transforms waste burdens into potential resource value. Its implementation directly addresses the infrastructure limitations of medical waste treatment in many regions of Indonesia, while contributing significantly to environmental health goals and the broader vision of sustainable development toward Indonesia Emas 2045.

Polymer Chemistry Innovation through Medical Waste Treatment

Medical waste treatment based on polymer chemistry offers an innovative paradigm shift from mass destruction methods like incineration toward precise molecular-level decontamination and transformation (Joseph et al., 2021). Its core innovation lies in the utilization of selective chemical reactions—such as catalyzed depolymerization (acid/base, enzymatic, or transition metal catalysts) and advanced oxidative degradation (AOPs using ozone, hydrogen peroxide, or hydroxyl radicals)—to specifically break down the main polymer chains (e.g., PVC from infusion bags, polypropylene from syringes, or polyethylene from containers) while simultaneously neutralizing hazardous contaminants (such as residual cytotoxic drugs, heavy metals, and pathogens) (Gussgard & Jokstad, 2025). This novel approach allows for controlled molecular-scale deconstruction of waste materials at lower temperatures compared to thermal degradation, thereby drastically reducing the potential for toxic gas emissions and the formation of new persistent organic pollutants (POPs).

The innovative process begins with the physicochemical pretreatment of plastic medical waste (e.g., shredding, washing) to homogenize and reduce particle size. The next key stage is catalyzed depolymerization, in which the waste is reacted in a pressurized reactor or stirred tank using specific catalysts (e.g., modified zeolites, metal nanocatalysts, or depolymerase enzymes) and depolymerizing agents/solvents (e.g., glycol for alcoholysis, methanol for methanolysis, or supercritical water). The catalysts selectively cleave ester, ether, or vinyl bonds in the polymers, converting them into their original monomers (such as terephthalic acid from PET) or valuable oligomers. Simultaneously, advanced oxidation processes (AOPs) are integrated to target hazardous organic contaminants (e.g., antibiotics, cytostatics, hormones), whereby high-energy free radicals oxidize these complex compounds into CO_2, water, and simple inorganic minerals, breaking the chain of environmental persistence (Martínez-Narro et al., 2024).

The most critical aspect of this innovation is its integrated dual detoxification mechanism. First, for heavy metals (such as mercury from broken thermometers or cadmium/chromium from electronic medical devices), the chemical process is designed to include selective chelating agents or absorbents such as specialized functional polymers or activated biochar during the reaction phase. These agents bind metal ions into stable, insoluble complexes, preventing leaching into soil or water (Huang et al., 2022). Second, the neutralization of pathogens like bacteria and viruses is achieved not through extreme heat but through synergistic effects: (a) cell wall disruption by oxidative radicals from AOPs, (b) protein denaturation under harsh chemical conditions (extreme pH, solvents), and (c) inactivation via antimicrobial compounds formed during the reaction. This chemical-based approach ensures complete biological deactivation without generating contaminated ash or harmful airborne biological particles, as seen in incineration (Guo, 2022). (See Figure 2.)

Figure 2. Polymer Chemistry Innovation Through Medical Waste Treatment

The highest environmental wisdom of this innovation is realized in its potential for molecular recycling. Monomers or oligomers resulting from depolymerization (e.g., ε-caprolactam from nylon or lactic acid from PLA) can be purified and reused as feedstock for producing new medical plastics or other value-added products, thereby closing the material loop and reducing reliance on virgin raw materials. The liquid waste from the process, after further treatment (membrane filtration, neutralization), can meet quality standards for disposal or reuse as grey water (Vollmer et al., 2020). Concentrated solid residues (e.g., metal-chelate complexes or saturated adsorbents) are subjected to specific treatments (stabilization/solidification) or processed to recover valuable metals. Holistically, this polymer chemistry-based approach significantly reduces environmental impact: avoiding dioxin/furan emissions, preventing groundwater contamination from landfill leachate or heavy metal seepage, and minimizing the carbon footprint through material recycling and lower energy consumption (Siddiqui et al., 2021).

Integrative Strategy for the Implementation of Degradation Technology

The principal innovation of this strategy lies in an integrative approach that involves a triadic synergy among the government, private sector (investors and technologists), and academia/research institutions. The government—particularly the Ministry of Health, Ministry of Environment and Forestry (LHK), Bappenas, and the Ministry of Industry—plays a critical role in formulating specific regulations (such as Emission Quality Standards for Thermal/Chemical Degradation Reactors and Fiscal Incentives for Green Technology Adoption), as well as in providing initial funding schemes (Special Allocation Funds and Innovation Grants) (Olawade et al., 2024). The private sector supplies modular technologies (e.g., pyrolysis/gasification reactors for hospital/community health center scale, and chemical depolymerization units), public-private partnership (PPP) investment schemes, and operational expertise. Academia contributes by developing customized technologies adapted to local contexts (e.g., affordable catalysts, energy-efficient designs), conducting personnel training, and monitoring environmental impacts. This collaborative governance model ensures technical, financial, and policy sustainability (Mangindaan et al., 2022).

The implementation process adopts a clustering strategy based on regional capacity and the type of healthcare facility. Metropolitan areas (Jakarta, Surabaya, Medan) can implement on-site systems in large hospitals with capacities exceeding 500 beds. For surrounding regions and districts, Regional Medical Waste Treatment Clusters are formed to serve multiple facilities (small hospitals, community health centers, clinics) within a 30–50 km radius. Medium-scale thermal/chemical degradation units are strategically located at central points (e.g., district hospitals), supported by coordinated waste collection logistics using secured vehicles. Implementation is phased: Phase I (2024–2026) focuses on 10 priority provinces with high waste loads and infrastructure readiness, followed by replication in 24 additional provinces by 2030. This approach optimizes investment, reduces transportation costs, and extends coverage to remote areas (Okan et al., 2019).

Financial innovation is introduced through a blended finance scheme that integrates national/regional budgets (APBN/APBD), private investment (including ESG funding), and international grants (such as the Green Climate Fund). A Technology-as-a-Service (TaaS) model is offered to healthcare facilities with limited budgets: private providers build and operate the units, while clients pay per kilogram of waste processed, inclusive of maintenance (Andrady et al., 2022). Intensive training for Medical Waste Degradation Technicians is conducted by health polytechnics in collaboration with technology vendors and engineering universities. The curriculum includes reactor operation, chemical handling, occupational safety, and emissions monitoring. National competency certification ensures high-quality human resources. Local MSMEs are empowered to produce supporting components (e.g., shredded waste materials, absorbents) and manage end-products (e.g., char, recycled monomers) (Olawade et al., 2024).

The implementation of degradation technology directly supports the pillars of Human and Sustainable Development for Indonesia Emas 2045 through a holistic health approach. The drastic reduction in exposure to infectious waste and toxic dioxins helps prevent disease transmission (such as Hepatitis B and HIV) and chronic respiratory conditions among communities near healthcare facilities (SDG 3) (Angga Utama et al., 2023). The deployment of on-site/cluster-based treatment systems eliminates the risks of groundwater contamination and urban air pollution caused by traditional incineration, ensuring basic environmental sanitation for public health (SDGs 6 and 11). The conversion of waste into energy and renewable resources (e.g., syngas, recycled monomers) not only supports the circular economy (SDG 12) but also reduces the carbon footprint responsible for climate change, which negatively impacts global health (SDG 13). The success of this strategy is measured through improvements in the Environmental Quality Index (IKLH) and specific health indicators: decreased cases of medical waste-related illnesses and increased access to safe healthcare services in underdeveloped regions (Ün, 2024). Therefore, to safeguard vital ecosystems and resources, this innovation stands as a concrete pillar in realizing a sovereign, advanced, and environmentally just Indonesian society by 2045.

CONCLUSION

This study has analyzed innovations in medical waste management based on thermal degradation and polymer chemistry, which hold great potential as solutions to the growing problem of medical waste in Indonesia. Technologies such as pyrolysis, controlled gasification, and polymer depolymerization have proven effective in addressing the challenges of medical waste management with greater efficiency, reducing the risk of pollution, and minimizing harmful emissions. Furthermore, these technologies support the circular economy by transforming waste into valuable resources such as energy or chemical feedstocks. The implementation of such technologies is expected to make a significant contribution to the achievement of *Indonesia Emas 2045*, particularly in the areas of sustainable development, public health management, and environmental preservation.

To measure the success of this technological implementation, strong collaboration among the government, private sector, and academic institutions is essential. The government must formulate regulations that support the adoption of green technologies, while the private sector can offer technological solutions and funding, and academia plays a key role in developing technologies adapted to local contexts. In addition, training and empowerment of human resources in the field of degradation-based medical waste management must be prioritized to ensure operational effectiveness and high-quality waste handling. Through this collaborative and integrative strategy, Indonesia is expected to mitigate the negative impacts of medical waste and move toward sustainable development that contributes to the realization of *Indonesia Emas 2045*.

REFERENCE

Andrady, A. L., Barnes, P. W., Bornman, J. F., Gouin, T., Madronich, S., White, C. C., Zepp, R. G., & Jansen, M. A. K. (2022). Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation. *The Science of the Total Environment*, *851*(Pt 2), 158022. https://doi.org/10.1016/j.scitotenv.2022.158022

Angga Utama, P. B., Hendrawan, I. G., Astawa Karang, I. W. G., & Pamungkas, P. B. P. (2023). Distribusi Pencemaran Sampah Plastik pada Sempadan Sungai di Bali yang Bermuara di Perairan Selat Bali dengan Analisis Generalized Additive Models (GAM). *Journal of Marine Research and Technology*, *6*(1), 69. https://doi.org/10.24843/jmrt.2023.v06.i01.p10

Aravind, R., Sahu, A. K., Brahma, G. S., & Swain, T. (2021). Investigation on the Thermo-Oxidative Degradation of Polyethylene, Poly(vinyl chloride), and Polystyrene Using NiPIm1.5 and NiPIm2 Nanocomposites. *ACS Omega*, *6*(44), 29869–29881. https://doi.org/10.1021/acsomega.1c04358

Barbu, M., & Năstase, M. (2018). Management The power of management in medical services. Can we manage better for higher quality and more productive medical services? *Economia. Seria Management*, *13*(1), 140–147.

Birpınar, M. E., Bilgili, M. S., & Erdoğan, T. (2009). Medical waste management in Turkey: A case study of Istanbul. *Waste Management*, *29*(1), 445–448. https://doi.org/https://doi.org/10.1016/j.wasman.2008.03.015

Ciawi, Y., Dwipayanti, N. M. U., & Wouters, A. T. (2024). Pengelolaan Limbah Medis Rumah Sakit yang Berkelanjutan: Eksplorasi Strategi Ekonomis dan Ramah Lingkungan. *Jurnal Ilmu Lingkungan*, *22*(2), 365–374. https://doi.org/10.14710/jil.22.2.365-374

Enny Mar'atus Sholihah, Nuriyati, Ari Kusdiana, F. N. (2024). Analisis Implementasi Pengelolaan Limbah Medis di Rumah Sakit Permata Hati. *Journal of Health Care*, *5*(3), 1–23.

Gałko, G., & Sajdak, M. (2022). Trends for the Thermal Degradation of Polymeric Materials: Analysis of Available Techniques, Issues, and Opportunities. *Applied Sciences (Switzerland)*, *12*(18). https://doi.org/10.3390/app12189138

Giakoumakis, G., Politi, D., & Sidiras, D. (2021). Medical waste treatment technologies for energy, fuels, and materials production: A review. *Energies*, *14*(23). https://doi.org/10.3390/en14238065

Guo, Z. (2022). Environmental Pollution of Medical Waste and New Medical Plastic Waste Treatment Technology. *Highlights in Science, Engineering and Technology*, *26*, 72–79. https://doi.org/10.54097/hset.v26i.3647

Gussgard, A. M., & Jokstad, A. (2025). Polymer waste and pollution in oral healthcare clinics: a systematic review. *BDJ Open*, *11*(1), 1–19. https://doi.org/10.1038/s41405-025-00342-8

Heriwati, Meliyanti, F., & Budianto, Y. (2023).

Pengelolaan Limbah Medis di Rumah Sakit berdasarkan Pengetahuan dan Sikap. *Jurnal Ilmiah Multi Science Kesehatan*, *15*(2), 216–224. https://jurnal.stikes-aisyiyah-palembang.ac.id/index.php/Kep/article/view/

Huang, J., Veksha, A., Chan, W. P., Giannis, A., & Lisak, G. (2022). Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes. *Renewable and Sustainable Energy Reviews*, *154*, 111866. https://doi.org/10.1016/j.rser.2021.111866

Ismayanti, A., Amelia, A. R., & Rusydi, A. R. (2020). Pengelolaan Limbah Medis Padat Di Rumah Sakit Umum Daerah Mamuju Provinsi Sulawesi Barat. *Window of Health : Jurnal Kesehatan*, *3*(1), 73–85. https://doi.org/10.33368/woh.v0i0.255

Joseph, B., James, J., Kalarikkal, N., & Thomas, S. (2021). Recycling of medical plastics. *Advanced Industrial and Engineering Polymer Research*, *4*(3), 199–208. https://doi.org/https://doi.org/10.1016/j.aiepr.2021.06.003

Mangindaan, D., Adib, A., Febrianta, H., & Hutabarat, D. (2022). Systematic Literature Review and Bibliometric Study of Waste Management in Indonesia in the COVID-19 Pandemic Era. *Sustainability*, *14*, 2556. https://doi.org/10.3390/su14052556

Martínez-Narro, G., Hassan, S., & Phan, A. N. (2024). Chemical recycling of plastic waste for sustainable polymer manufacturing – A critical review. *Journal of Environmental Chemical Engineering*, *12*(2), 112323. https://doi.org/https://doi.org/10.1016/j.jece.2024.112323

Montero-Calderón, C., Tacuri, R., Solís, H., De-La-Rosa, A., Gordillo, G., & Araujo-Granda, P. (2023). Masks thermal degradation as an alternative of waste valorization on the COVID-19 pandemic: A kinetic study. *Heliyon*, *9*(2). https://doi.org/10.1016/j.heliyon.2023.e13518

Okan, M., Aydin, H. M., & Barsbay, M. (2019). Current approaches to waste polymer utilization and minimization: a review. *Journal of Chemical Technology & Biotechnology*, *94*(1), 8–21. https://doi.org/10.1002/jctb.5778

Olawade, D. B., Fapohunda, O., Wada, O. Z., Usman, S. O., Ige, A. O., Ajisafe, O., & Oladapo, B. I. (2024). Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Management Bulletin*, *2*(2), 244–263. https://doi.org/https://doi.org/10.1016/j.wmb.2024.05.001

Qin, L., Han, J., Zhao, B., Wang, Y., Chen, W., & Xing, F. (2018). Thermal degradation of medical plastic waste by in-situ FTIR, TG-MS and TG-GC/MS coupled analyses. *Journal of Analytical and Applied Pyrolysis*, *136*, 132–145. https://doi.org/https://doi.org/10.1016/j.jaap.2018.10.012

Ray, S., & Cooney, R. P. (2018). Chapter 9 - Thermal Degradation of Polymer and Polymer Composites. In M. Kutz (Ed.), *Handbook of Environmental Degradation of Materials (Third Edition)* (Third Edit, pp. 185–206). William Andrew Publishing. https://doi.org/https://doi.org/10.1016/B978-0-323-52472-8.00009-5

Rochmawati, E. S., & Syarifah Has, S.KM., M.Epid, D. F. (2023). Analisis Pengelolaan Limbah Medis Padat Di Rumah Sakit Medika Mulia Tuban. *Journal of Public Health Science Research*, *3*(2), 23. https://doi.org/10.30587/jphsr.v3i2.5622

Siddiqui, M. N., Redhwi, H. H., Al-Arfaj, A. A., & Achilias, D. S. (2021). Chemical recycling of pet in the presence of the bio-based polymers, pla, phb and pef: A review. *Sustainability (Switzerland)*, *13*(19). https://doi.org/10.3390/su131910528

Sugiyono, P. (2019). Metode Penelitian Kuantitatif Kualitatif dan R&D. In *Bandung: Alfabeta*. ALFABETA.

Tamošiūnas, A., Milieška, M., Gimžauskaitė, D., Aikas, M., Uscila, R., Zakarauskas, K., Fendt, S., Bastek, S., & Spliethoff, H. (2025). Plasma Gasification of Medical Plastic Waste to Syngas in a Greenhouse Gas (CO2) Environment. *Sustainability (Switzerland)*, *17*(5), 1–15. https://doi.org/10.3390/su17052040

Ün, Ç. (2024). Examining the environmental and economic dimensions of producing fuel from medical waste plastics Tıbbi atık plastiklerden yakıt üretiminin çevresel ve ekonomik boyutlarının incelenmesi. *Bilim. Derg. / NOHU J. Eng. Sci*, *13*(1), 279–293. https://doi.org/10.28948/ngmuh.1367080

Vienken, J., & Boccato, C. (2024). Do medical devices contribute to sustainability? The role of innovative polymers and device design. *The International Journal of Artificial Organs*, *47*(4), 240–250. https://doi.org/10.1177/03913988241245013

Vollmer, I., Jenks, M. J. F., Roelands, M. C. P., White, R. J., van Harmelen, T., de Wild, P., van der Laan, G. P., Meirer, F., Keurentjes, J. T. F., & Weckhuysen, B. M. (2020). Beyond Mechanical Recycling: Giving New Life to Plastic Waste. *Angewandte Chemie (International Ed. in English)*, *59*(36), 15402–15423. https://doi.org/10.1002/anie.201915651

Wang, Y., Feng, G., Lin, N., Lan, H., Li, Q., Yao, D., & Tang, J. (2023). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences*, *13*(5). https://doi.org/10.3390/app13053045

Windfeld, E. S., & Brooks, M. S.-L. (2015). Medical waste management – A review. *Journal of Environmental Management*, *163*, 98–108. https://doi.org/https://doi.org/10.1016/j.jenvman.2015.08.013

Yong, Z., Gang, X., Guanxing, W., Tao, Z., & Dawei, J. (2009). Medical waste management in China: A case study of Nanjing. *Waste Management*, *29*(4), 1376–1382. https://doi.org/https://doi.org/10.1016/j.wasman.2008.10.023

Zhang, X., Yin, Z., Xiang, S., Yan, H., & Tian, H. (2024). Degradation of Polymer Materials in the Environment and Its Impact on the Health of Experimental Animals: A Review. *Polymers*, *16*(19). https://doi.org/10.3390/polym16192807