SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2026
ORGANIZATION AND MANAGEMENT SERIES NO. 249

CLASSIFICATION AND REDUCTION OF INDUSTRIAL WASTE AS PILLARS OF SUSTAINABLE DEVELOPMENT

Anna HORZELA-MIŚ[1], Jakub SEMRAU[2]

[1] Silesian University of Technology, Faculty of Organization and Management; anna.horzela-mis@polsl.pl,
ORCID: 0000-0003-2345-9861
[2] Silesian University of Technology, Faculty of Organization and Management; jakub.semrau@polsl.pl,
ORCID: 0000-0002-4894-7792
*Correspondence author

Purpose: The aim of the article is to compare selected traditional and circular economy based methods of industrial waste classification and assess their usefulness for supporting sustainable development oriented industrial waste management. The study also explores how modern classification frameworks can contribute to the implementation of circular economy principles by facilitating waste reduction, resource recovery, and improved environmental protection.

Design/methodology/approach: The research is based on a structured narrative literature review using comparative thematic analysis. The study examines traditional classification approaches, including classification by source, chemical composition, and environmental impact, and compares them with contemporary circular economy based approaches such as the 10R hierarchy, material value assessment, and industrial symbiosis potential.

Findings: The analysis indicates that effective waste classification significantly improves the efficiency of industrial waste management systems. Traditional classification methods support risk identification and regulatory compliance, while circular economy oriented classification frameworks enable the identification of waste streams with high recovery potential. Integrating these approaches helps reduce landfill use, improve resource efficiency, and facilitate cooperation between industries through industrial symbiosis.

Originality/value: The article provides a comprehensive overview of industrial waste classification methods and highlights their strategic importance in the transition toward sustainable and circular industrial systems. By integrating traditional classification approaches with circular economy frameworks, the study offers a broader perspective on how waste can be transformed into valuable secondary resources.

Keywords: industrial waste, waste classification, sustainable development, circular economy, waste management, industrial symbiosis.

Category of the paper: Literature review.

http://dx.doi.org/10.29119/1641-3466.2026.249.7

1. Introduction

The rapid growth of industrial sectors worldwide has led to an unprecedented increase in the generation of industrial waste, posing serious environmental, economic, and regulatory challenges. Efficient and sustainable management of these waste streams has become a critical priority in contemporary environmental policy and industrial practice. Industrial waste, due to its complexity and often hazardous nature, requires a multifaceted approach encompassing accurate classification, proactive reduction at the source, and advanced treatment methods. This paper presents a theoretical exploration of the classification, minimization, and processing strategies for industrial waste, with a strong emphasis on integrating sustainable development principles. By examining current methodologies and innovative technological solutions, this study contributes to a deeper understanding of how interdisciplinary and data-driven waste management frameworks can support circular economy transitions and mitigate the environmental impact of industrial activity.

Rapid industrial development and the intensification of global production processes have significantly increased the volume and diversity of waste generated worldwide. Industrial sectors are among the largest contributors to total waste streams, producing a wide range of by-products that differ in composition, toxicity, and environmental impact. According to international environmental reports, the growing scale of industrial activity has intensified pressure on natural resources and ecosystems, making effective waste management a critical challenge for modern economies (Kaza et al., 2018). Improperly managed industrial waste may lead to long-term contamination of soil, surface water, groundwater, and air, as well as pose risks to human health and biodiversity.

In response to these challenges, waste management has become an integral component of sustainable development strategies implemented at global, regional, and national levels. The concept of sustainable development assumes that economic growth should occur in a manner that ensures environmental protection and social well-being for present and future generations (United Nations, 2015). Within this framework, the management of waste streams particularly those generated by industrial activities plays a crucial role in reducing environmental pressures and promoting more efficient use of natural resources. Effective waste management systems contribute not only to environmental protection but also to economic efficiency through the recovery of valuable materials and energy (Ghisellini et al., 2016).

A fundamental element of modern waste management systems is the classification of waste, which enables the identification of its origin, composition, and potential environmental risks. Proper classification facilitates the selection of appropriate methods for treatment, recycling, recovery, or disposal. It also supports regulatory compliance, risk assessment, and the development of effective waste management policies. Without accurate classification, it is difficult to design safe handling procedures or implement efficient resource recovery processes (Tchobanoglous, Kreith, 2020).

In recent years, the traditional perception of waste as an unwanted by-product has gradually evolved. Increasing attention is being paid to the potential of waste as a secondary resource that can re-enter the production cycle. This shift is closely related to the development of the circular economy concept, which promotes the transition from linear models of production and consumption toward systems based on resource efficiency, material reuse, and closed-loop processes (Geissdoerfer et al., 2017). In such systems, waste is minimized through strategies such as reuse, recycling, remanufacturing, and energy recovery, thereby reducing the need for primary raw materials.

Within this context, the classification of industrial waste becomes a key tool supporting the implementation of circular economy principles. By identifying the characteristics and recovery potential of different waste streams, industries can develop more efficient strategies for waste reduction and resource management. Moreover, classification systems enable the identification of waste streams that can be reused, recycled, or utilized in industrial symbiosis networks, where by-products from one sector serve as inputs for another.

The aim of this article is to analyze selected methods of industrial waste classification and to examine their role in supporting sustainable development and circular economy practices. The scientific problem addressed in this paper is the lack of an integrated analytical framework for comparing traditional industrial waste classification methods with circular economy oriented approaches in terms of their usefulness for sustainable industrial waste management. Particular attention is given to classification according to the source of waste generation, chemical composition, and environmental impact. Additionally, the study discusses emerging classification approaches derived from the circular economy perspective, including classification based on circular potential, material value, and opportunities for industrial symbiosis.

2. Literature review

Waste management is one of the most prominent and desirable aspects of sustainable development across all sectors of the economy (Rabe, 2020). Waste management must be considered in a broad context, because the way it is handled may stimulate or slow down the pursuit of the idea of sustainable development (Czekała et al., 2013; Biegańska, Ciuła, 2011). Both current legal frameworks and global initiatives aimed at minimizing waste production and harmful emissions—while preserving the natural environment in its existing state—necessitate the creation of systems grounded in three interdependent pillars: social, economic, and environmental development (Biegańska, Ciuła, 2011). Social and economic progress can be evaluated, among other things, by the volume of waste generated, including both municipal and packaging waste. All forms of waste are potential sources of pollution, and when stored, they pose serious risks to soil, water, and air quality. Therefore, it is important to know the methods of waste classification, which in the further process will result in the proper way of its management (Szuma 2012).

When properly prepared, processed, and utilized, waste can serve as a valuable resource for raw materials. The sustainable development of waste management primarily involves minimizing the need for landfilling and maximizing the recovery of usable components. This principle is especially apparent in the handling of industrial waste. Industrial operations are increasingly shaping the waste policies of production companies, moving beyond the traditional role of merely collecting waste. Producers are now placing greater emphasis on ensuring that as much waste as possible is recycled, while waste handlers are actively supporting this objective. Their collaboration focuses on streamlining the entire waste management cycle—from the point of generation, through sorting and logistical coordination, to final disposal or reuse. This cooperative model encourages the development of environmentally friendly methods and systems. Assigning responsibility for waste management to the producer adds an additional layer of oversight, ensuring compliance with environmental regulations. Moreover, it helps reduce unethical behavior among waste handlers, thereby enhancing adherence to environmental protection standards (Rabe, 2020).

3. Methodology

This study adopts a structured narrative literature review approach. The purpose of the review was to identify and compare the main approaches to industrial waste classification discussed in the literature, with particular attention to their relevance for sustainable development and circular economy implementation. The literature selection process was based on publications addressing industrial waste management, waste classification, hazardous waste, circular economy, 10R strategies, material value recovery, and industrial symbiosis. The analysis included peer-reviewed journal articles, academic books, and selected reports from international organizations relevant to the topic. The following inclusion criteria were applied:

1. publications addressing industrial or production-related waste,
2. sources discussing classification criteria, waste management implications, or circular economy applications,
3. publications with clear conceptual, analytical, or practical relevance to sustainable development.

The following exclusion criteria were adopted:

1. publications focused exclusively on municipal waste without industrial relevance,
2. highly technical studies dealing with narrow treatment technologies without reference to classification frameworks,
3. duplicate or marginally relevant sources.

The collected literature was analyzed using comparative thematic analysis. The reviewed studies were grouped into four analytical categories: classification by source, classification by chemical composition, classification by environmental impact, and circular economy based classification approaches. Each category was assessed in terms of classification logic, practical applicability, environmental relevance, and usefulness for supporting waste reduction and resource recovery.

Despite the wide range of classification methods discussed in the literature, there is still a lack of a coherent analytical perspective that would allow for a systematic comparison of these approaches in terms of their practical applicability and contribution to sustainable development. In particular, it remains unclear to what extent traditional classification methods are sufficient in addressing contemporary challenges related to resource efficiency and waste reduction, and whether circular economy based approaches provide a more effective framework for managing industrial waste streams. To address this research gap, the present study is guided by the following research questions:

RQ1: What are the main criteria used in traditional and circular economy based industrial waste classification methods?

RQ2: What are the strengths and limitations of these classification approaches in the context of sustainable development?

RQ3: Which classification approaches offer the greatest practical value for waste reduction, resource recovery, and industrial symbiosis?

By answering these questions, the study aims to provide a structured comparative analysis of existing classification frameworks and to identify those approaches that offer the greatest potential for supporting sustainable and circular industrial systems.

4. Results

4.1. Classification by source

Industrial waste can be classified according to its source, which means assigning it to specific industrial sectors in which it is generated. Such classification allows for effective adjustment of waste management strategies to the characteristics of technological processes in a given industry and to the properties of the waste materials generated.

Waste from the chemical industry is one of the most demanding categories in terms of environmental management. It is characterized by the presence of hazardous substances, such as organic solvents, acids (e.g. sulfuric, nitric), bases (e.g. sodium hydroxide), as well as by-products of chemical reactions (Tchobanoglous et al., 1993). Depending on the chemical industry – e.g. petrochemistry, plastics production or pharmaceuticals – the composition of this waste can vary significantly. Its toxicity, reactivity and often flammability mean that it requires special supervision, appropriate storage and specialist methods of disposal. Improper handling of this type of waste can contaminate soil and water and pose a threat to human health (Slack et al., 2004).

Waste from the metallurgical industry is characteristic of metal ore processing and metal smelting and processing. They include, among others, metallurgical dust, sludge, slag and waste from galvanic processes and surface treatment. They often contain heavy metals such as lead, cadmium or mercury, which can cause long-term environmental pollution and accumulate in living organisms (Lottermoser, 2010). Due to the large mass and volume of metallurgical waste, their management requires significant logistical outlays. On the other hand, many of these materials can be recycled, e.g. in construction as aggregate or in metal recycling.

Waste from the food industry is characterized by high biodegradability, which results from the high content of organic matter (Gustavsson, 2011). They come from the production, processing and packaging of food and include components such as pomace, sludge from sewage treatment plants, fats, fermentation residues, technological wastewater or product residues. Although they are usually not hazardous, they can cause odor nuisance, rapid spoilage and attract pests. Their management most often focuses on composting, biogas production or use as feed. This waste is also the subject of numerous studies on its potential in the circular economy (Galanakis, 2015).

Waste from the textile industry is generated in the processes of weaving, dyeing, printing and finishing fabrics and during the production of clothes (Ellen MacArthur Foundation, 2017). It contains numerous chemical pollutants, including synthetic dyes, auxiliaries used to fix colours, microplastics and fibre residues. Dyeing wastewater is particularly problematic, as it contains difficult-to-decompose organic compounds and is often highly toxic. An additional threat is posed by microfibres from synthetic fabrics, which enter the aquatic environment and enter the food chain. Sustainable management of this waste requires investment in modern wastewater treatment technologies and the development of textile recycling methods (Kant, 2012).

Waste from the construction industry includes a wide range of materials generated as a result of construction, demolition and renovation works. It mainly consists of mineral waste – concrete rubble, bricks, plasters, but also wood, plastics, insulating materials (e.g. polystyrene, mineral wool) and scrap (Coelho, de Brito, 2010). Although many of these materials are not classified as hazardous, some may contain harmful compounds such as asbestos, PCBs or lead paints. Construction waste accounts for a significant portion of the total waste produced in industrialized countries. Recycling and reusing construction waste is essential for a circular economy, as it reduces the need for new mineral resources (Tam, Tam, 2006).

4.2. Classification by chemical composition

Classification of waste according to chemical composition enables identification of its physicochemical and toxicological properties, which is crucial for selecting appropriate technologies for disposal, recycling or recovery. It also enables assessment of environmental hazards and effective planning of storage and transport of waste materials. There are three main groups of waste: organic, inorganic and mixed.

Organic waste is a group of waste in which the dominant component is carbon compounds (except for some inorganic forms of carbonates). This category includes, among others, waste from the food, textile, petrochemical and pharmaceutical industries (Christensen, 2011). Organic compounds can be natural (e.g. fats, sugars, proteins) or synthetic (e.g. plastics, pesticides, organic solvents). Many of them are easily biodegradable, but some – such as chlorinated hydrocarbons, PCBs or some dyes – can be persistent, toxic and difficult to decompose. Organic waste management includes biological technologies (composting, methane fermentation), thermal (incineration, pyrolysis) and chemical (oxidation, neutralization). Separating biodegradable fractions from non-biodegradable fractions is also particularly important.

Inorganic waste includes waste containing mainly non-carbon chemical elements and compounds, such as metals, oxides, acids, bases, inorganic salts or minerals. This group includes, among others, metallurgical waste, fly ash, sludge from industrial wastewater treatment, slag and sediments from galvanic processes (Wang et al., 2009). Although some of them have high recycling potential (e.g. recovery of metals from catalysts or cells), others - especially those containing heavy metals or toxic substances - must be properly stabilized or stored in special conditions. Processing inorganic waste often requires the use of chemical and physicochemical technologies, such as flocculation, neutralization or incineration.

Mixed waste contains both organic and inorganic components, which makes it the most diverse and difficult to manage group. These can include, for example, sludge, composites, used electronic devices (e-waste), waste from the chemical or pharmaceutical industry, which contains both carbon compounds and heavy metals (Buekens, Yang, 2014). Due to the variety of components, they require comprehensive analysis and complex processing methods - they are often directed to specialist plants, where advanced separation, extraction or thermal neutralization processes are used. Effective management of this type of waste requires strict chemical control and advanced environmental engineering technologies (Pichtel, 2014).

4.3. Classification by environmental impact

A third important method of classifying industrial waste is based on its potential environmental impact. This approach focuses on assessing the degree of risk that a given type of waste may pose to ecosystems, natural resources, and human health. Unlike classification based solely on origin or chemical composition, this method emphasizes the consequences of improper waste handling and its potential long-term effects on the environment.

The assessment of environmental impact is typically based on several key criteria. These include toxicity, persistence in the environment, bioaccumulation potential, flammability and reactivity, as well as the ability of substances to migrate into soil, water, or air. In addition, increasing attention is being paid to the potential of certain waste streams to generate greenhouse gas emissions, particularly in the case of biodegradable waste decomposing under uncontrolled conditions. The consideration of these factors enables a more comprehensive evaluation of environmental risks and supports decision-making in waste management systems.

Based on the environmental impact criterion, industrial waste can be divided into several main categories. Hazardous waste includes materials that exhibit toxic, flammable, reactive, or infectious properties. Examples include chemical solvents, heavy-metal-containing sludge, acid residues, and certain pharmaceutical by-products. These types of waste pose a significant threat to human health and the environment and therefore require strict control, specialized storage conditions, and advanced treatment technologies.

Neutral or inert waste is characterized by low reactivity and minimal environmental impact. This category includes materials that do not undergo significant chemical transformations and do not release harmful substances under standard environmental conditions. Such waste can often be safely stored or used in construction applications, provided that it meets regulatory requirements.

Biodegradable waste consists primarily of organic materials that can be decomposed by microorganisms. Typical examples include waste from the food processing industry or certain types of agricultural and textile residues. Although biodegradable waste is generally considered less hazardous, its improper management may lead to the emission of methane and other greenhouse gases, contributing to climate change. Therefore, controlled treatment processes such as composting or anaerobic digestion are recommended.

Recyclable waste includes materials that can be reprocessed and reintroduced into production cycles. This category is particularly important in the context of resource efficiency and circular economy strategies, as it reduces the demand for primary raw materials. Examples include metal scrap, selected plastics, and certain types of construction waste.

Finally, difficult to manage waste represents a heterogeneous group characterized by complex composition, contamination, or technological barriers to processing. This category often includes composite materials, mixed waste streams, or residues containing both organic and inorganic components. Such waste typically requires advanced treatment technologies and may involve high economic and environmental costs. Table 1 presents the waste category along with its characteristics and potential impact on the environment.

Table 1.
Classifying waste by its potential environmental impact

Waste category	Characteristics	Potential environmental impact
Dangerous	They contain toxins, heavy metals, flammable or reactive substances.	Water, soil, air pollution; threat to human health
Neutral	No chemical reaction, low toxicity	Low environmental impact
Biodegradable	Decompose naturally	Can be used in composting; may generate methane
Recyclable	Suitable for reprocessing	Reduces the use of primary raw materials
Difficult to manage	Complex composition, heterogeneous	Requires expensive processing and special technologies

Source: Own study.

Hazardous wastes include those that are toxic, flammable, reactive or infectious, such as certain chemical or medical wastes (UNEP, 2007). Inert waste, on the other hand, does not exhibit reactive properties and can be safely stored. Biodegradable waste is decomposed by microorganisms, but under uncontrolled conditions can generate methane and other greenhouse gas emissions (Naqvi et al., 2021). Recyclable waste, on the other hand, has the potential to recover secondary raw materials, reducing the consumption of primary resources (Anuar et al., 2025).

From a practical perspective, classification based on environmental impact plays a crucial role in risk assessment and prioritization within waste management systems. It enables the identification of waste streams that require immediate intervention, supports regulatory compliance, and facilitates the selection of appropriate treatment and disposal methods. Moreover, this approach is closely aligned with environmental protection policies and international regulations, which increasingly emphasize the need to minimize the negative impact of industrial activities on ecosystems. At the same time, it should be noted that classification based solely on environmental impact may not fully capture the economic or circular potential of waste streams. For this reason, it is most effective when combined with other classification approaches, particularly those related to material value and circular economy principles. Such integration allows for a more balanced approach that considers both environmental safety and resource efficiency.

4.4. Classification of industrial waste in the context of the circular economy

In recent years, traditional approaches to waste classification have been increasingly complemented by frameworks derived from the concept of the circular economy. The circular economy (CE) promotes the transition from a linear model of production and consumption based on the sequence “take–make–dispose”—to a regenerative system in which resources remain in use for as long as possible (Winans et al., 2017). Within this framework, waste is no longer treated solely as an undesirable by-product of industrial activity but rather as a potential resource that can re-enter the economic cycle through various recovery pathways.

The circular economy perspective emphasizes the preservation of material value, the extension of product life cycles, and the minimization of resource extraction. Consequently, the classification of industrial waste increasingly considers its potential for reintegration into production systems rather than focusing exclusively on its origin or chemical composition (Su et al., 2013). Several classification approaches have been proposed in the literature to support this transition, including classification based on circular potential, material value, and opportunities for industrial symbiosis.

4.5. Classification according to circular potential – the 10R framework

One of the most widely discussed frameworks in circular economy research is the hierarchy of circular strategies known as the 10R model. This concept expands the traditional waste hierarchy and describes multiple strategies for retaining the value of materials and products within the economic system (Reike et al., 2022). The model includes a sequence of strategies that differ in the degree to which they preserve product functionality and material value.

The hierarchy begins with strategies aimed at preventing waste generation, such as refuse (R0), which involves avoiding unnecessary production or consumption. Subsequent strategies include reduce (R1) and reuse (R2), which focus on minimizing resource use and extending the life of products without significant modification. Further strategies, such as repair (R3), refurbish (R4), and remanufacture (R5), involve restoring products or components so they can continue to serve their original function.

When the original functionality of a product can no longer be maintained, materials may still be recovered through repurpose (R6), recycle (R7), and recover (R8 or R9 depending on the classification system), including energy recovery processes. These lower levels of the hierarchy retain less of the original value but still allow resources to remain within the economic cycle instead of being disposed of (Pan et al., 2022).

From the perspective of waste classification, the 10R framework enables the categorization of industrial waste according to the most appropriate circular strategy. For example, high-quality production residues or defective components may be directed toward remanufacturing or reuse processes, whereas complex composite materials may be classified as recyclable or energy-recoverable waste streams.

4.6. Classification based on material value

Another important dimension of waste classification in the circular economy is the material value embedded in waste streams. This approach distinguishes between high-value waste and low-value waste, depending on the economic and technological feasibility of recovering valuable materials. High-value waste typically includes materials with significant recycling potential, such as metals, high-grade polymers, and electronic components. These materials retain considerable economic value even after their initial use and can often be reintroduced into production processes with relatively limited processing. For instance, metallurgical slag or electronic waste may contain valuable metals such as copper, aluminium, or rare earth elements that can be recovered through advanced recycling technologies.

Low-value waste, by contrast, consists of materials that are difficult to recycle due to contamination, complex composition, or low market value. Examples include mixed plastic waste, contaminated construction debris, or composite materials. Such waste streams often require energy recovery or specialized treatment technologies, which may reduce their environmental impact but provide limited economic benefits. Classifying waste according to material value helps industries prioritize recovery processes and allocate resources more efficiently. By identifying high-value waste streams, companies can implement targeted recycling strategies and develop business models that support resource efficiency and circular material flows (Moscati et al., 2023).

4.7. Classification according to industrial symbiosis potential

A further dimension of circular waste classification concerns the potential for industrial symbiosis, which refers to the collaborative exchange of materials, energy, or by-products between different industrial entities. In such systems, waste generated by one company becomes a resource for another, thereby reducing overall resource consumption and waste generation (Holly, Schild, 2025). Industrial symbiosis is a central concept within industrial ecology and is often implemented in industrial clusters where companies operate in close geographical proximity. For example, waste heat from a power plant may be used in nearby manufacturing processes, while by-products from the food industry can serve as raw materials for bioenergy production.

From a classification perspective, waste streams can be categorized according to their compatibility with potential symbiotic applications. Some waste materials are easily transferable between industries due to their consistent composition and predictable supply, while others require additional processing before they can be utilized by external partners. This type of classification encourages the development of integrated industrial networks in which material flows are optimized across multiple sectors. By identifying waste streams with high symbiosis potential, companies and policymakers can facilitate partnerships that enhance resource efficiency and support the broader objectives of sustainable development.

5. Discussion

The results of this study provide a structured overview of industrial waste classification approaches and allow for a comparative assessment of their relevance in the context of sustainable development. The analysis reveals that both traditional and circular economy based classification frameworks play important but distinct roles in industrial waste management systems.

5.1. Comparison of traditional and circular classification approaches

Traditional classification methods based on source, chemical composition, and environmental impact remain essential for ensuring regulatory compliance, risk assessment, and operational safety. These approaches are well-established in the literature and widely implemented in industrial practice, particularly in the context of hazardous waste management and environmental protection (Tchobanoglous, Kreith, 2020). Their strength lies in their clarity, standardization, and direct applicability to existing legal and technical frameworks. However, the analysis indicates that traditional classification systems are primarily focused on identifying risks and ensuring proper disposal rather than maximizing the value of waste as a resource. As a result, they may be insufficient in addressing contemporary challenges related to resource scarcity, circular material flows, and sustainable production systems. This limitation has also been highlighted in previous studies emphasizing the need to move beyond linear waste management models (Ghisellini et al., 2016; Geissdoerfer et al., 2017).

In contrast, classification approaches derived from the circular economy perspective introduce new analytical dimensions, such as material value, circular potential, and industrial symbiosis opportunities. The 10R framework, in particular, provides a hierarchical structure that prioritizes strategies aimed at retaining product functionality and material value within the economic system (Reike et al., 2022). These approaches shift the focus from waste treatment to waste prevention and resource optimization. Nevertheless, circular economy based classification systems also have limitations. Their implementation often requires more detailed data on material composition, production processes, and supply chain interactions. In addition, they depend on the availability of technological solutions and cooperation between industrial actors, which may not always be feasible in all contexts.

5.2. Implications for sustainable development

From the perspective of sustainable development, the findings suggest that no single classification approach is sufficient on its own. Traditional methods provide a strong foundation for environmental protection and regulatory compliance, while circular approaches offer greater potential for improving resource efficiency and reducing waste generation. The integration of these approaches appears to be the most effective strategy. By combining risk-oriented classification (e.g., environmental impact and chemical composition) with value-oriented classification (e.g., circular potential and material value), it is possible to develop more comprehensive waste management systems. Such integrated frameworks can support both environmental safety and economic optimization, aligning with the core principles of sustainable development.

Furthermore, the identification of waste streams with high industrial symbiosis potential highlights the importance of inter-organizational cooperation. As noted in the literature on industrial ecology, the exchange of by-products between industries can significantly reduce resource consumption and environmental impact (Holly, Schild, 2025). This confirms that waste classification should not be treated as an isolated technical activity but as part of a broader system of industrial collaboration.

5.3. Contribution to the literature and research limitations

This study contributes to the existing body of knowledge by proposing a comparative analytical perspective that integrates traditional and circular approaches to industrial waste classification. While previous studies have often focused on specific classification methods or individual aspects of waste management, this paper provides a more holistic framework that highlights the complementarities and trade-offs between different approaches. At the same time, several limitations of the study should be acknowledged. First, the research is based on a literature review and does not include empirical validation of the proposed comparisons. Second, the analysis is primarily qualitative and does not provide quantitative measures of effectiveness for individual classification methods. Third, the applicability of certain circular economy based approaches may vary depending on industrial sector, technological development, and regional conditions.

Future research should therefore focus on empirical case studies that test the practical implementation of integrated classification frameworks in real industrial environments. In addition, further studies could develop quantitative indicators to evaluate the effectiveness of classification methods in terms of environmental impact reduction, resource recovery, and economic performance.

6. Conclusion

Effective classification and reduction of industrial waste constitute fundamental components of sustainable development strategies in modern industrial systems. The findings of this study demonstrate that waste classification should not be treated solely as a technical or regulatory requirement but rather as a strategic instrument supporting environmental protection, resource efficiency, and economic sustainability. The analysis confirms that traditional classification approaches—based on source, chemical composition, and environmental impact—play a crucial role in ensuring safe handling, regulatory compliance, and risk management. At the same time, circular economy based classification frameworks introduce additional dimensions related to material value, circular potential, and industrial symbiosis, which are essential for improving resource recovery and reducing waste generation.

The results indicate that the greatest practical value is achieved through the integration of these approaches. Combining traditional risk-oriented classification with circular, value-oriented perspectives enables the development of more comprehensive and effective waste management systems. Such an integrated framework supports both environmental safety and the transition toward circular industrial models. The study contributes to the literature by providing a structured comparative perspective on industrial waste classification methods and highlighting their complementary roles in sustainable development. It also emphasizes the need to move beyond linear waste management paradigms and to adopt more systemic approaches that recognize waste as a potential resource within industrial ecosystems.

Future research should focus on the development of standardized and integrated classification systems that incorporate environmental, economic, and technological criteria. In addition, empirical studies and quantitative assessments are needed to evaluate the effectiveness of different classification approaches in real industrial settings. The advancement of digital tools for waste tracking and data analysis may further support decision-making processes and accelerate the transition toward a more circular and sustainable industrial economy.

References

1. Anuar, S.Z.K., Nordin, A.H., Husna, S.M.N., Yusoff, A.H., Paiman, S.H., Noor, S.F.M., Nordin, M.L., Ali, S.N., Ismail, Y.M.N.S. (2025). Recent advances in recycling and upcycling of hazardous plastic waste: A review. *Journal of Environmental Management, vol. 380*. https://doi.org/10.1016/j.jenvman.2025.124867
2. Biegańska, J., Ciuła, J. (2011). Zintegrowana gospodarka odpadami komunalnymi w Polsce jako element zrównoważonego rozwoju. *Archiwum Gospodarki Odpadami i Ochrony Środowiska, No. 13(1)*.
3. Buekens, A., Yang, J. (2014). Recycling of WEEE plastics: A review. *Journal of Material Cycles and Waste Management, 16(3)*, DOI: 10.1007/s10163-014-0241-2
4. Christensen, T.H. (Ed.) (2011). *Solid Waste Technology and Management*. Wiley-Blackwell.

5. Coelho A, de Brito J. (2010). Distribution of materials in construction and demolition waste in Portugal. *Waste Management & Research, 29(8),* 843-853. doi:10.1177/0734242X10370240
6. Czekała, W., Lewicki, A., Janczak, D. (2013). Problemy zasad klasyfikacji odpadów organicznych. *Przegląd Prawa Ochrony Środowiska, No. 3*, DOI:10.12775/PPOS.2014.032
7. Ellen MacArthur Foundation (2017). *A New Textiles Economy: Redesigning Fashion's Future*.
8. Galanakis, C.M. (2015). *Food Waste Recovery. Processing Technologies and Industrial Techniques.* Elsevier, https://doi.org/10.1016/C2013-0-16046-1
9. Geissdoerfer, M., Savaget, P., Bocken, N., Hultink, E. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143,* 757-768, https://doi.org/10.1016/j.jclepro.2016.12.048
10. Ghisellini, P., Cialani, C., Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production, 114,* 1132, https://doi.org/10.1016/j.jclepro.2015.09.007
11. Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A. (2011). Global food losses and food waste: Extent, causes and prevention. *Food Agric. Organ*. United Nations.
12. Holly, F., Schild, C. (2025). Concepts, strategies and business models of the circular economy for the manufacturing industry: A Systematic Literature Review. *Procedia CIRP, vol. 135*, https://doi.org/10.1016/j.procir.2024.12.056
13. Ikram, M. (2026). Redesigning the value chain: A net-zero circular economy approach to resource retention. *Business Strategy and the Environment*, https://doi.org/10.1002/bse.70591
14. Kant, R. (2012). Textile dyeing industry: An environmental hazard. *Natural Science, 4(1),* http://dx.doi.org/10.4236/ns.2012.41004
15. Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development*. Washington, DC: World Bank, https://doi.org/10.1596/978-1-4648-1329-0
16. Lottermoser, B.G. (2010). *Mine Wastes: Characterization, Treatment and Environmental Impacts.* Berlin: Springer, https://doi.org/10.1007/978-3-642-12419-8
17. Mansour, F.R., Emara, S., Bedair, A., Hamed, M. (2026). Integration of 10R principles into CIRCLE as an innovative tool for assessing circular economy. *RSC Sustainability, 4,* https://doi.org/10.1039/d5su00806a
18. Moscati, A., Johansson, P., Kebede, R. et al. (2023). Information Exchange between Construction and Manufacturing Industries to Achieve Circular Economy: A Literature Review and Interviews with Swedish Experts. *Buildings, 13(3),* https://doi.org/10.3390/buildings13030633

19. Naqvi, S.R., Beig, B., Naqvi, M. (2021). Circular Economy Approach to Address the Industrial Solid Waste Management. Handbook of Solid Waste Management. *Sustainability through Circular Economy*. https://doi.org/10.1007/978-981-15-7525-9_62-1
20. Pan, X., Wong, C.W.Y., Li, C. (2022). Circular economy practices in the waste electrical and electronic equipment industry: A systematic review and future research agendas. *Journal of Cleaner Production, Vol. 365*, https://doi.org/10.1016/j.jclepro.2022.132671
21. Pichtel, J. (2014). *Waste Management Practices: Municipal, Hazardous, and Industrial, Second Edition (2nd ed.).* CRC Press. https://doi.org/10.1201/b16576
22. Rabe, M. (2020). Wpływ jakości odpadów na zrównoważony modelu gospodarki odpadam. *Ekonomika i Organizacja Logistyki, 5(2),* https://doi.org/10.22630/EIOL.2020.5.2.16
23. Reike, D., Vermeulen, W.J.V., Witjes, S. (2022). Conceptualization of circular economy 3.0: Synthesizing the 10R hierarchy of value retention options. In: A. Alvarez-Risco et al. (eds.), *Towards a Circular Economy, CSR, Sustainability, Ethics & Governance.* Springer Nature Switzerland AG, https://doi.org/10.1007/978-3-030-94293-9_3
24. Slack, R.J., Gronow, J.R., Voulvoulis N. (2004). Hazardous Components of Household Waste, Critical Reviews. *Environmental Science and Technology, Vol. 34, No. 5,* doi:10.1080/10643380490443272
25. Su, B., Heshmati, A., Geng, Y., Yu, X. (2013). A review of the circular economy in China: Moving from rhetoric to implementation. *Journal of Cleaner Production, vol 42,* https://doi.org/10.1016/j.jclepro.2012.11.020
26. Szuma, K. (2012). Z problematyki zbierania i magazynowania odpadów. *Przegląd Prawa Ochrony Środowiska, No. 3*, https://doi.org/10.12775/PPOS.2012.012
27. Tam, V.W.Y., Tam, C.M. (2006). A review on the viable technology for construction waste recycling. *Resources, Conservation and Recycling, 47(3),* https://doi.org/10.1016/j.resconrec.2005.12.002
28. Tchobanoglous, G., Kreith, F. (2020). *Handbook of Solid Waste Management*. Second edition. McGraw-Hill.
29. Tchobanoglous, G., Theisen, H., Vigil, S.A. (1993). *Integrated Solid Waste Management: Engineering Principle and Management Issue.* New York: McGraw Hill Inc.
30. United Nations (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* https://sdgs.un.org/2030agenda, 18.12.2025.
31. United Nations Environment Programme (UNEP) (2007). *Environmental agreements and cleaner production*, https://www.unep.org/resources/report/environmental-agreements-and-cleaner-production: 11.12.2025.
32. Wang, L.K., Chen, J.P., Hung, Y.-T., Shammas, N.K. (Eds.) (2009). *Heavy Metals in the Environment.* CRC Press, https://doi.org/10.1201/9781420073195
33. Winans, K., Kendall, A., Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews, vol. 68*, https://doi.org/10.1016/j.rser.2016.09.123