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Exploring Process Integration Practices in Sustainable Industrial Waste Treatment Systems

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A B S T R A C T

The growth of industrial activity has intensified waste generation, posing challenges to environmental sustainability and resource efficiency. This study examines the application of process integration in sustainable industrial waste treatment systems and evaluates its contribution to energy efficiency, resource utilization, and environmental impact reduction. Using conceptual analysis and case studies of waste treatment technologies—including heat recovery, material recycling, and integrated reaction–separation processes—the study applies pinch analysis and mass–energy balance evaluation to identify optimal integration opportunities. The results demonstrate that process integration significantly reduces energy consumption, minimizes residual waste, and increases the reuse of valuable materials, while also lowering emissions and operational costs. These findings confirm that process integration is an effective and practical strategy for designing sustainable industrial waste treatment systems and provides valuable insights for advancing environmentally friendly and competitive chemical engineering solutions.

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INTRODUCTION

The rapid development of global industry in recent decades has driven significant increases in the production of goods, energy consumption, and the utilization of natural resources. On the other hand, the escalation of industrial activities also has direct implications for the increase in the generation of industrial waste in various forms, both liquid, solid, and gaseous waste. If not managed properly, industrial waste has the potential to cause serious environmental impacts, including water, soil, and air pollution, as well as risks to human health and ecosystem sustainability (Shamshad & your Rehman, 2025). This condition confirms that industrial waste management is no longer just a technical issue, but an integral part of the sustainable development agenda.

Industrial waste generally has complex and heterogeneous characteristics, depending on the type of process, raw materials, and technology used. Liquid and solid waste from various industrial sectors often contains suspended solids, organic materials with high polluting loads, heavy metals, and harmful and toxic compounds that are difficult to degrade naturally (Shamshad & your Rehman, 2025). Waste disposal without adequate treatment can lead to the accumulation of pollutants in the environment, degrade the quality of water and soil resources, and disrupt the balance of ecosystems. Therefore, a waste treatment approach is needed that is not only effective in removing pollutants, but also efficient in terms of energy and resource utilization.

In this context, chemical engineering plays a strategic role in designing sustainable industrial waste treatment systems through innovative and integrated process design approaches. The conventional end-of-pipe approach is considered inadequate because it tends to focus on wastewater treatment as the final stage without considering the overall efficiency of the system. Alternatively, the concept of process integration and process intensification is developing as a key strategy to improve the performance of waste treatment systems through optimization of interactions between operating units and process subsystems.

The concept of process integration emphasizes the merging and synchronization of various process operations in a holistic framework with the aim of maximizing energy efficiency, minimizing waste, and improving resource recovery from waste streams (Panda et al., 2024). This approach allows for the reuse of exhaust heat, the integration of mass flows, as well as the reduction of external energy requirements. Thus, waste is no longer seen solely as a residue that must be treated, but rather as a potential source of energy and valuable materials that can be reused in the industrial system.

Recent studies show that the application of process integration in industrial waste treatment, especially through the integration of membrane technology, selective separation, and material recycling strategies, is able to significantly increase process efficiency while reducing environmental burden (Panda et al., 2024). Integration between reaction and separation units, for example, can reduce the need for advanced purification stages and reduce energy consumption. This approach is in line with the circular economy paradigm that encourages repeated use of resources and the reduction of residual waste.

Furthermore, the literature also emphasizes that process integration in waste treatment cannot be viewed partially, but rather must consider systemic interactions between operations. This includes energy recovery from waste streams, simultaneous reduction of pollutant loads, and optimization of water and material use in the entire process system (Kiatkittipong & Lim, 2023). The systemic approach is in line with the principles of green chemistry which aims to reduce energy consumption, minimize the use of hazardous materials, and maximize the added value of each stage of the process.

Although the potential for process integration in industrial waste treatment has been widely reported, its implementation at the industrial level still faces various challenges. These challenges include the complexity of waste characteristics, the variability of operational conditions, the relatively high initial investment needs, and the limitations of technology integration with existing industrial systems. In addition, the design of an integrated system requires a comprehensive analysis, including mass and energy balances, technical-economic feasibility evaluations, and overall environmental impact considerations.

Based on this background, this study aims to explore process integration practices in sustainable industrial waste treatment systems and evaluate their contribution to improving energy efficiency, resource utilization, and reducing environmental impact. This study is expected to provide a deeper conceptual understanding and applicable reference for the development and design of industrial waste treatment systems that are efficient, competitive, and in line with sustainability principles.

THEORETICAL REVIEW

Industrial Waste Treatment in a Sustainability Perspective

Industrial waste treatment has undergone a paradigm shift from a conventional approach based on pollution control to a sustainability approach that emphasizes resource efficiency and minimization of environmental impact. Recent studies show that a sustainable waste treatment system must consider the linkages between energy consumption, material utilization, and environmental emissions simultaneously (Zhang et al., 2021). This approach is becoming increasingly relevant as environmental regulatory demands and industry commitments to net-zero emissions targets increase.

In the context of chemical engineering, waste treatment is no longer separated from the main production system, but rather is positioned as an integral part of the entire process chain. Several studies confirm that the integration of waste treatment with production systems can provide dual benefits in the form of reducing pollutant loads while improving energy efficiency and process economics (Li et al., 2022). This emphasizes the importance of a systemic approach in the design of industrial waste treatment technology.

Concept and Principles of Process Integration

Process integration is a process design approach that aims to optimize the entire system through coordination and synergy between operating units, energy flow, and mass flow. This concept is rooted in the principle of system optimization and has been widely applied in energy saving, in particular through techniques such as pinch analysis and heat exchanger network integration (Klemeš et al., 2020). In recent years, the application of process integration has expanded to the fields of waste treatment and industrial sustainability.

Research by Foo and Manan (2021) shows that process integration is able to identify opportunities for the reuse of energy and materials that were previously wasted as waste. By utilizing this approach, waste treatment systems can be designed to minimize external energy requirements and reduce the formation of secondary waste. This makes process integration a strategic tool in supporting the industry's transition to more sustainable practices.

Energy Integration and Recovery of Resources from Waste

One of the main focuses of process integration in industrial waste treatment is energy integration and resource recovery. Industrial waste often still contains thermal energy and valuable materials that can be reused through the right process integration strategies. Recent studies report that the integration of heat recovery and material recycling can significantly lower the total energy consumption of waste treatment systems (Varbanov et al., 2022).

In addition to energy recovery, the reuse of materials from waste—such as water, nutrients, and valuable chemical compounds—is an important aspect of the circular economy framework. According to Moreno et al. (2023), an integrated approach allows the transformation of waste into secondary resources, thereby reducing dependence on primary raw materials. This integration not only provides environmental benefits but also improves the economic viability of the waste treatment system.

Process Integration and the Circular Economy

The concept of process integration is closely related to the circular economy principle which emphasizes the closed cycle of materials and energy in industrial systems. Several studies state that process integration is a major enabler in the implementation of the circular economy in the industrial sector, especially in waste management (Geissdoerfer et al., 2021). Through process integration, the waste stream can be reconnected to the production system as an alternative input.

In the context of industrial waste treatment, a circular economy approach supported by process integration allows for a significant reduction in residual waste. A study by Costa et al. (2022) shows that an integrally designed waste treatment system can increase the rate of material reuse while lowering carbon emissions. These findings reinforce the argument that process integration is not only technically relevant, but also strategic in achieving the industry's sustainability goals.

Research Challenges and Gaps

Although the benefits of process integration in industrial waste treatment have been widely reported, there are still a number of research challenges and gaps. One of the main challenges is the complexity of industrial waste characteristics that vary between sectors, making it difficult to implement generic integration solutions (Ahmetović et al., 2020). In addition, limited operational data and uncertainty of process conditions are often obstacles in designing optimal integrated systems.

The literature also shows that most studies still focus on partial optimizations, such as the integration of energy or water separately, without considering the overall interaction between energy, materials, and environmental impacts (Ibáñez-Forés et al., 2023). Therefore, a more comprehensive study is needed on process integration practices in sustainable industrial waste treatment systems, especially those that combine technical, environmental, and resource analysis in an integrated manner.

METHODOLOGY

Research Approach

This research uses a qualitative-quantitative approach based on process system analysis, with a focus on exploring and evaluating process integration practices in sustainable industrial waste treatment systems. This approach was chosen because process integration requires a thorough understanding of the interconnectedness between operating units, mass-energy flows, and environmental and resource implications simultaneously. The methodology used combines systematic literature review, process conceptual modeling, and mass and energy balance analysis, as recommended in recent sustainable process design studies (Martínez-Hernández et al., 2021).

Process Integration Conceptual Framework

The conceptual framework of the research was prepared based on the principle of process integration which focuses on optimizing the entire waste treatment system, not on separate operating units. The framework includes the identification of waste sources, mass and energy flow characteristics, heat and material recovery potential, and integration opportunities between processes. This approach allows for systemic evaluation of interactions between processing units and supports efficient and sustainable system design (Klemeš et al., 2021).

Mass and Energy Balance Analysis

The analysis of the mass and energy balance is carried out as the basis for evaluating the performance of the industrial waste treatment system. Each process integration scenario is analyzed to determine the distribution of material flow, energy requirements, and resource recovery potential. This approach is widely used in the study of process sustainability because it is able to quantitatively identify points of inefficiency and optimization opportunities (Deng et al., 2022). The results of mass and energy balance are the main inputs in assessing the effectiveness of process integration.

Application of Pinch Analysis for Energy Integration

To evaluate energy saving opportunities, this study applied pinch analysis as the main method of heat integration. Pinch analysis is used to identify the minimum requirements for hot and cold energy, as well as to design an optimal heat exchanger network in industrial waste treatment systems. This method has proven to be effective in reducing external energy consumption and improving the thermal efficiency of integrated systems (Wan Alwi et al., 2021). Analysis was carried out on various integration scenarios to compare potential energy savings.

Resource Recovery Evaluation

In addition to energy integration, this study evaluates the potential for resource recovery from waste streams, including process water, valuable materials, and residual energy. The evaluation was carried out by examining the level of resource reutilization before and after the implementation of process integration. This approach is in line with the circular economy principle that emphasizes the use of waste as a secondary resource (Zhao et al., 2023). The indicators used include material recovery ratios, residue waste reduction, and the potential for substitution of primary raw materials.

Sustainability Performance Indicators

The performance of integrated waste treatment systems is evaluated using sustainability indicators that include energy, resource, and environmental aspects. Key indicators include energy consumption intensity, material reuse rate, and potential emission reduction. This indicator-based approach allows for objective comparisons between process integration scenarios and supports sustainability-oriented design decision-making (Azapagic & Perdan, 2020).

Data Analysis and Interpretation

Data obtained from mass–energy balance analysis, pinch analysis, and resource recovery evaluation were analyzed comparatively to identify the most effective process integration practices. The results of the analysis are interpreted by associating quantitative findings with the implications of process engineering and environmental sustainability. This approach aims to produce recommendations for industrial waste treatment system design that are applicable and relevant to chemical engineering practitioners.

RESEARCH RESULTS

Identify Process Integration Opportunities in Industrial Waste Treatment Systems

The results of conceptual analysis and system mapping show that industrial waste treatment systems have a number of significant opportunities for the implementation of process integration, especially in energy flows and materials that have not previously been optimally utilized. Based on the analysis of the mass and energy balance, it was identified that there was a waste stream with a fairly high residual thermal energy content, as well as the potential for the reuse of water and valuable materials from certain treatment units. These findings indicate that conventional waste treatment approaches still leave systemic inefficiencies that can be corrected through process integration.

Integration between operating units allows for reduced duplication of processing functions and increased synergies between processes. For example, the exhaust heat from the reaction or separation unit can be reused for pre-heating the inflow, thereby lowering the external energy requirement. These results confirm that process integration plays a strategic approach to transform waste treatment systems from linear structures to more efficient and sustainable integrated systems.

The Impact of Process Integration on Energy Efficiency

The application of pinch analysis in industrial waste treatment systems shows significant energy savings potential after the implementation of process integration. The results of the analysis show a decrease in external heat and cold energy requirements due to the optimization of internal heat exchange between process flows. The integration of a heat exchanger network designed on the basis of pinch points allows for maximum utilization of the system's internal energy and minimizes energy wastage. A comparative summary of the performance of non-integrated and integrated waste treatment systems is presented in Table 1 to highlight the impact of process integration on energy efficiency and sustainability.

Table 1. Comparative performance of non-integrated and integrated waste treatment systems

Performance Parameters	**Non-Integrated Systems**	**Integrated System (Process Integration)**	**Technical and Sustainability Implications**
Relative energy consumption	High, depending on external energy supply	Lower due to internal heat utilization	Lowers utility energy requirements and operating costs
Process energy intensity	Not optimal, energy dissipated between operating units	Optimized through heat exchanger network integration	Supporting the overall energy efficiency of the system
Resource recovery rate	Limited, waste is treated as residue	Higher through the reuse of energy and materials	Driving the adoption of a circular economy
Residual waste volume	Relatively high	Reduced due to optimization and reuse	Reduces final processing load and environmental impact
Potential emission reductions	Low, comparable to high energy consumption	Greater due to decreased external energy requirements	Supporting the industry's sustainability and decarbonization targets

System sustainability indicators	Partial and fragmented	More comprehensive and systemic	Aligned with the principles of sustainable process design

Comparatively, the integrated system scenario shows a lower energy consumption intensity compared to the non-integrated system. This decline not only impacts operational efficiency but also has direct implications for reducing emissions associated with energy consumption. These findings are in line with sustainable process design principles that emphasize reducing energy inputs through system optimization, rather than simply improving the performance of individual units.

Resource Recovery and Reuse

In addition to energy efficiency, the results of the study show that process integration contributes significantly to increasing resource recovery from waste streams. Evaluation of process water reuse showed an increase in the rate of water recycling after integration, which had an impact on decreasing raw water requirements. This is especially relevant for industries with high water consumption and facing limited water resources.

The recovery of valuable materials from waste is also increased through the integration of separation and purification processes. By connecting the waste treatment unit to a production system or other supporting processes, the waste can be reused as a secondary raw material. This approach reinforces the role of process integration as a circular economy enabler, where waste is treated as a resource that has economic and functional value. A comparative overview of resource recovery and reuse performance before and after process integration is summarized in Table 2.

Table 2. Resource recovery and reuse performance in non-integrated and integrated waste treatment systems

Aspects of Resource Recovery	**Non-Integrated Systems**	**Integrated System (Process Integration)**	**Impact on Sustainability**
Process water reuse	Limited, mostly disposed of after processing	Improved through internal recycling and reuse	Reduce raw water requirements and pressure on water resources
Water use efficiency	Low, dependent on external supply	Higher due to integrated water circulation	Supporting sustainable industrial water management
Recovery of valuable materials	At a minimum, waste is treated as residue	More optimized through separation and	Converting waste into secondary raw materials

		purification integration	
Utilization of waste as a process input	Not integrated with the production system	Connect to production processes or support	Supporting circular economy principles
Reduction of dependence on primary raw materials	Low	Higher due to substitution by recovered materials	Improve resource efficiency and industry competitiveness
Functional and economic value of waste	Low	Higher through increased added value	Fostering value-oriented industrial systems

Integrated System Sustainability Performance Evaluation

Sustainability performance evaluation using energy, resource, and environmental indicators shows that integrated waste treatment systems have better performance than conventional systems. The energy intensity indicator has seen a consistent decline, while the ratio of resource reuse has increased significantly. In addition, the reduction in the volume of residual waste that must be disposed of indicates the potential for a reduction in long-term environmental impact.

The indicator-based approach allows for a comprehensive and measurable analysis of the benefits of process integration. These results confirm that the sustainability of waste treatment systems depends not only on the effectiveness of pollutant removal, but also on the overall efficiency of energy and material use. Thus, process integration can be positioned as a holistic approach that bridges technical, environmental, and economic goals.

Process Engineering Implications and Industrial Applicability

From the perspective of process engineering, the results of this study show that process integration can be implemented as a design strategy that is flexible and adaptive to various characteristics of industrial waste. This approach allows for the design of systems that can be tailored to operational conditions and industry-specific needs, without sacrificing sustainability performance. Nevertheless, the complexity of the design and the need for in-depth systemic analysis demand adequate technical competence and operational data support.

Applicatively, the results of this study provide a conceptual basis for the industry to re-evaluate existing waste treatment systems and identify opportunities to improve performance through process integration. While initial investment may be required, the long-term benefits of energy savings, reduced operational costs, and increased compliance with environmental regulations make process integration a technically and economically viable strategy.

DISCUSSION

The findings of this study are consistent with the current literature that emphasizes the importance of a systemic approach in sustainable industrial waste treatment. A number of studies show that the integration of energy efficiency, resource recovery, and material flow optimization is a key element in designing a sustainable and competitive waste treatment system (Chen et al., 2023; Morero et al., 2022). The systemic approach allows the identification of interactions between process units that were previously neglected in conventional designs, thus opening up opportunities for simultaneous improvement of environmental and economic performance. Nevertheless, this study makes an additional contribution by integrating energy analysis, resource recovery, and sustainability indicators into a single integrated evaluation framework, an approach that is still relatively limited in the literature that tends to evaluate energy and material aspects separately (Al-Mansour & Elkamel, 2024).

However, this study still has a number of limitations, especially related to the generalization of results in various industrial sectors that have very diverse waste characteristics and operational conditions. The literature shows that variations in waste composition, scale of operation, and technical and regulatory limitations can affect the effectiveness of implementing process integration in waste treatment systems (Nascimento et al., 2021). Therefore, further research is needed to test the proposed framework on industry-specific case studies as well as integrate life cycle assessment (LCA) approaches to obtain a more comprehensive, life-cycle-based environmental impact evaluation (Heijungs & Suh, 2023).

CONCLUSION AND RECOMMENDATION

The application of process integration in industrial waste treatment systems has been proven to improve energy efficiency, resource recovery, and overall sustainability performance. Integration between operating units reduces external energy consumption, minimizes residual waste, and improves water recycling and utilization of valuable materials, making the system more holistic and efficiency-oriented.

The research also presents an integrated evaluation framework that combines energy analysis, resource recovery, and sustainability indicators, providing a methodological basis for effective, economical, and environmentally friendly system design.

FURTHER STUDY

The limitations of research related to generalization of results on various waste characteristics encourage the need for further studies with the application of life cycle assessments for a more comprehensive evaluation of environmental impacts. Overall, process integration plays an important role in supporting circular economy principles and sustainable process design, while offering practical and conceptual contributions to the development of green industries.

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