

Transesterification and Densification in Solid Waste Treatment Systems: A Narrative Conceptual Review of Physicochemical Methods

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Abstract

The increasing generation of organic solid waste due to population growth, urbanization, and industrial activities requires management systems that not only reduce waste volume but also promote sustainable resource and energy recovery. This article presents a conceptual review of the integration of transesterification and densification as physicochemical methods in solid waste treatment. The study uses a narrative conceptual review approach based on scientific literature published between 2020 and 2025, focusing on process principles, reaction mechanisms, feedstock characteristics, and integration potential within a waste-to-energy framework. The findings indicate that transesterification converts the lipid fraction of waste into biodiesel as liquid energy, while densification improves solid residues into biomass fuel with higher energy density and stability. The integration of these processes can enhance energy recovery efficiency, reduce waste volume, and lower greenhouse gas emissions. However, implementation still faces challenges, including waste heterogeneity, the need for pre-treatment, and optimization of material and energy flows. Conceptually, the integration of transesterification and densification shows strong potential as an innovative approach to sustainable solid waste management, supporting circular economy strategies and the transition toward low-carbon waste-to-energy systems.

Keywords: Transesterification, Densification, Solid Waste, Physicochemical Methods, Waste-To-Energy.

Abstrak

Peningkatan produksi limbah padat organik akibat pertumbuhan penduduk, urbanisasi, dan aktivitas industri menuntut sistem pengolahan yang tidak hanya berfokus pada reduksi volume, tetapi juga pada pemulihan sumber daya dan energi secara berkelanjutan. Artikel ini menyajikan tinjauan konseptual mengenai integrasi transesterifikasi dan densifikasi sebagai metode fisika-kimia dalam pengolahan limbah padat. Kajian dilakukan menggunakan pendekatan

narrative conceptual review terhadap literatur ilmiah periode 2020-2025 yang mencakup prinsip proses, mekanisme reaksi, karakteristik bahan baku, serta potensi integrasi dalam kerangka waste-to-energy. Hasil kajian menunjukkan bahwa transesterifikasi mengonversi fraksi lipid limbah menjadi biodiesel sebagai energi cair, sedangkan densifikasi meningkatkan kualitas residu padat menjadi bahan bakar biomassa dengan densitas energi dan stabilitas yang lebih tinggi. Integrasi kedua proses ini berpotensi meningkatkan efisiensi pemulihan energi, mengurangi volume limbah, serta menurunkan emisi gas rumah kaca. Namun demikian, implementasinya masih menghadapi tantangan seperti heterogenitas limbah, kebutuhan pra-perlakuan, serta optimasi aliran material dan energi. Secara konseptual, integrasi transesterifikasi dan densifikasi memiliki prospek kuat sebagai pendekatan inovatif dalam pengelolaan limbah padat berkelanjutan yang mendukung ekonomi sirkular dan transisi menuju sistem energi rendah karbon.

Keywords: Transesterifikasi, Densifikasi, Limbah Padat, Metode Fisika-Kimia, Waste-To-Energy.

1. Introduction

The increase in industrial activities, population growth, and urbanization has accelerated the accumulation of organic solid waste, particularly in large cities. Ineffective management has the potential to contaminate the environment and increase greenhouse gas emissions due to uncontrolled decomposition [1]. This condition requires waste treatment approaches that not only reduce volume but also recover material and energy value sustainably through the reuse of waste as a resource [2].

Conventional methods such as landfilling and open burning are increasingly unsustainable due to limited land availability, the risk of secondary pollution, and their contribution to climate change [3], [4]. As an alternative, physicochemical approaches have developed because they are capable of transforming waste properties into more stable and valuable forms. The implementation of these technologies has been shown to support resource recovery, extend material life cycles, and reduce environmental burdens when integrated holistically into waste management systems [5].

Transesterification is one of the physicochemical methods widely developed to convert the lipid fraction of organic solid waste, such as food waste, used cooking oil, and agro-industrial residues, into biodiesel as a renewable energy source [6], [7]. This process involves a reaction between triglycerides and alcohol in the presence of a catalyst, producing alkyl esters as the main product and glycerol as a by-product [8], [9]. The utilization of waste as a feedstock for transesterification not only reduces environmental pressure caused by waste disposal but also improves resource utilization efficiency and supports the development of waste-based renewable energy [10], [11].

Densification is a physical method that increases the energy density of solid waste through mechanical compaction into biomass briquettes or pellets, thereby improving physical stability, storage and transportation efficiency, and calorific value per unit volume [12], [13]. In biomass energy systems, densification plays an important role in enhancing the technical and economic feasibility of utilizing solid waste as an alternative fuel, particularly at decentralized scales [14], [15].

The integration of transesterification and densification offers a more comprehensive solid waste treatment approach compared to single-method applications. Transesterification utilizes the lipid fraction as liquid energy, while densification converts solid residues and non-lipid fractions into solid fuels with high energy value [16]. This integrated approach aligns with circular economy principles by maximizing energy recovery and minimizing final residues [17], [18].

Despite the considerable potential of integrating transesterification and densification, its implementation still faces several challenges, including the heterogeneity of waste composition, the need for intensive pre-treatment, process energy consumption, and the limited number of conceptual studies that integrate both methods systemically. Most existing studies still focus on evaluating the processes separately, resulting in limited understanding of the synergy between the two methods within an integrated solid waste treatment system.

Based on this background, this article aims to present a conceptual review of transesterification and densification as physicochemical methods in solid waste treatment systems. This study discusses the fundamental principles of each process, their potential integration within a treatment system, and the benefits and challenges of their implementation from a sustainability perspective. This review is expected to provide a conceptual foundation for the development of more efficient, sustainable, and energy-recovery-oriented solid waste treatment technologies.

2. Method

This section describes the research stages and the rationale for method selection using a *narrative conceptual review* approach. This approach is applied to comprehensively examine the literature and support conceptual analysis relevant to the standards of sustainable energy review articles. In addition, it outlines the strategies for identifying, selecting, and analyzing literature related to physicochemical based solid waste treatment, particularly through transesterification and densification processes [19], [20].

2.1 Research Parameters and Data Acquisition

To obtain a comprehensive review, the literature was collected in a structured manner using reputable scientific databases, namely Scopus, Web of Science, and Google Scholar. The keywords used in the search included combinations of “transesterification” “biodiesel production” “solid waste” “organic waste” “densification” “briquetting” “pelletization” “physicochemical treatment” “waste-to-energy” and “circular economy” with the assistance of Boolean operators. The time range of the literature was limited to the period 2020-2025 to represent recent developments in the fields of waste treatment and sustainable energy.

The initial search yielded 168 documents, which were then rigorously screened through evaluation of titles, abstracts, and full texts. The results of this systematic filtering process produced 28 articles that were the most relevant and representative for further analysis in accordance with the focus of the study (Figure 1). The quality of the included studies was ensured by restricting the review to peer-reviewed publications in reputable journals. Furthermore, a qualitative risk-of-bias assessment was conducted by examining methodological rigor, clarity of research design, data transparency, and the consistency of the reported evidence, thereby enhancing the credibility and reliability of the synthesized findings.

2.2 Inclusion and Exclusion Criteria

The inclusion criteria comprise peer-reviewed journal articles discussing transesterification and/or densification of solid waste, focusing on physicochemical aspects or process engineering and their relevance to energy recovery, waste reduction, or the circular economy. Exclusion criteria include non-scientific publications, non-peer-reviewed reports, studies focusing only on feedstock without treatment processes, and articles not available in full text. These criteria ensure the quality and relevance of the analyzed literature.

2.3 Analytical Approach

Within the framework of this study, the analysis was conducted using a qualitative–thematic approach to identify patterns, relationships, and developments in existing studies. The review covers the mechanisms of transesterification and densification, case studies and applications, their integration within waste-to-energy systems, and the contribution of these technologies to energy efficiency, waste reduction, and the circular economy. This approach provides a comprehensive understanding of the interconnections and development potential of these technologies.

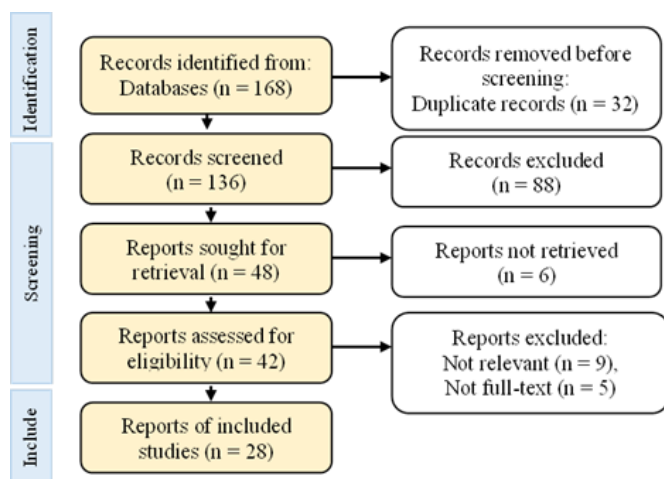


Figure 1. Literature Selection Flow

2.4 Methodological Limitations

This study employs a narrative conceptual review approach and therefore does not produce quantitative synthesis or aggregate statistical analysis. While this approach may

introduce subjectivity in the selection and interpretation of the literature, it remains relevant for developing a conceptual framework, identifying research gaps, and formulating future directions for physicochemical based solid waste treatment technologies.

3. Result and Discussion

3.1 The Role of Transesterification in Physicochemical-Based Solid Waste Treatment

Transesterification plays a strategic role in the treatment of lipid-fraction organic solid waste for energy recovery and environmental impact reduction [21]. This process converts triglycerides and free fatty acids into biodiesel, a renewable fuel with high energy density and lower emissions compared to fossil fuels [8], [9]. The utilization of solid waste as a feedstock for transesterification directly reduces the pollution potential of fatty wastes that are difficult to degrade and may generate greenhouse gas emissions if decomposed uncontrollably [1], [22].

Food waste, agro-industrial residues, and oily sludge have high potential as feedstocks for transesterification due to their triglyceride and free fatty acid contents [6], [21]. With appropriate pretreatment, fatty wastes can be converted into biodiesel without complex purification and without competing with food resources, thereby supporting renewable energy production based on secondary resources [8], [10]. The transesterification results confirm selective energy recovery from non-food waste as biodiesel with liquid fuel characteristics.

In the context of waste-to-energy systems, transesterification serves as a selective mechanism that converts the lipid fraction often a problematic component in solid waste management into liquid energy products that can be directly utilized [23]. This approach improves overall energy recovery efficiency because the lipid fraction has a higher calorific value compared to lignocellulosic or inorganic fractions commonly found in solid waste [6].

The performance of transesterification of organic solid waste is strongly influenced by advances in catalyst technology, particularly heterogeneous catalysts, which improve reaction stability, increase conversion rates, and simplify biodiesel glycerol separation while reducing secondary waste and enabling catalyst reuse [24], [25]. In physicochemical waste treatment systems, transesterification also serves as part of an integrated process that allows non-lipid residues to be further utilized through densification or thermochemical conversion, thereby enhancing energy recovery and waste valorization [13], [17].

Thus, transesterification can be viewed as a strategic instrument in physicochemical-based solid waste management oriented toward resource recovery, environmental impact reduction, and improved energy efficiency. This role positions transesterification as a key component in the development of sustainable energy systems aligned with the principles of the circular economy and the transition toward low-carbon development.

3.2 Densification as a Strategy for Improving the Energy Efficiency of Solid Waste

Densification is a physical method aimed at increasing the energy density of solid waste through mechanical compaction into biomass briquettes or pellets, resulting in more uniform, stable, and easily handled fuel characteristics within energy utilization systems [13], [15]. This process is widely applied to lignocellulosic wastes such as agricultural residues, sawdust, and urban biomass waste as part of a circular economy based waste-to-energy strategy [17].

Various studies show that densification can significantly increase the bulk density of biomass, from about 80-200 kg/m³ in loose biomass to 600-1,200 kg/m³ in the form of briquettes or pellets, depending on the type of feedstock, moisture content, and compaction pressure and temperature conditions [12], [14], [26]. This increase also raises the volumetric energy density from less than 4,000 MJ/m³ to more than 9,000-20,000 MJ/m³ without a significant reduction in the specific calorific value per unit mass, thereby improving the efficiency of biomass storage and transportation [12], [26].

In addition to increasing density, densification has also been shown to improve the physical properties of biomass, including particle size homogeneity, mechanical stability, and the compressive strength of the product. Experimental studies indicate that the durability index of densified biomass briquettes or pellets generally ranges from 90-98%, reflecting high resistance to mechanical degradation during handling, storage, and distribution [26], [27]. These characteristics make densified biomass more suitable as an alternative solid fuel compared to loose biomass, particularly for small to medium-scale energy applications.

The increase in energy density through densification also has a direct impact on energy utilization efficiency. The literature reports that the calorific value of densified biomass generally ranges from 15-20 MJ/kg, depending on the type of waste and its initial moisture content, with improvements in volumetric energy utilization efficiency reaching 4-6 times compared to non-densified biomass [4], [12], [13]. This condition enables solid waste to be used more efficiently as an alternative fuel in the domestic sector, small and medium industries, and decentralized energy systems.

Furthermore, densification plays an important role in reducing energy losses along the biomass supply chain. Non-densified biomass is prone to physical degradation, increased moisture content, and logistical inefficiencies due to its low bulk density. By increasing volumetric energy density, densification can reduce transportation volume requirements by approximately 50-70%, thereby significantly lowering logistics energy consumption and distribution costs [2], [12], [17].

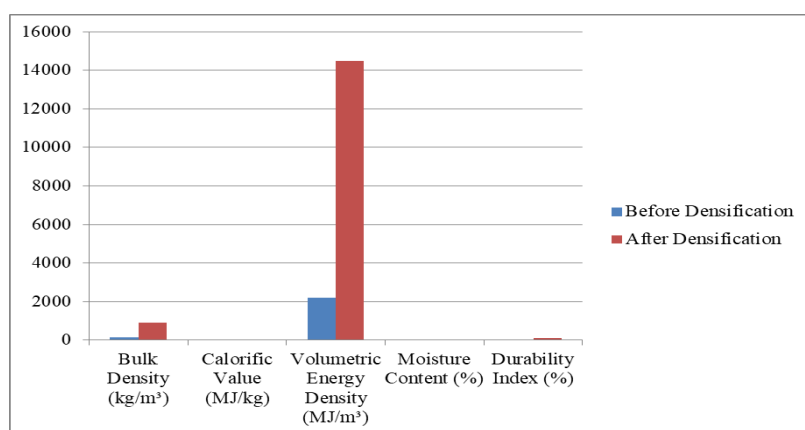


Figure 2. Energy Densification of Solid Waste

Figure 2 is based on a synthesis of literature from various studies on biomass and solid waste densification processes published between 2020 and 2025, and therefore the values

presented are representative. The figure shows that the densification process significantly improves the technical and energy characteristics of biomass. The most notable increase occurs in bulk density, indicating that the biomass becomes more compact, thereby enhancing the efficiency of storage, transportation, and energy distribution. The calorific value also shows a moderate increase due to material homogenization and reduced moisture content, resulting in improved combustion stability.

In addition, densification increases volumetric energy density, reduces moisture content, and enhances combustion efficiency and storage stability. The improvement in the durability index also strengthens the mechanical resistance of briquettes or pellets, minimizing mass loss during handling and transportation. Overall, this process enhances the energy quality of biomass while improving supply chain efficiency and its compatibility with waste-to-energy and co-firing systems.

3.3 The Concept of Integrating Transesterification and Densification in Solid Waste Treatment Systems

The integration of transesterification and densification enables the optimal utilization of solid waste through the simultaneous conversion of lipid fractions and solid fractions within a single integrated physicochemical treatment system [28]. This approach aligns with the advanced waste-to-energy paradigm, which views waste as a source of valuable energy and materials through a combination of complementary processes [2], [3]. In this system, transesterification converts the lipid fraction of non-food waste into biodiesel with high energy value, supported by heterogeneous catalysts and reaction intensification to improve efficiency and facilitate product separation [8], [29].

Biomass-based catalysts contribute to improving the sustainability of biodiesel production, particularly through the utilization of renewable resources and the reduction of dependence on conventional catalysts [30]. In addition, the development of more efficient and stable catalysts can optimize the performance of the transesterification process in terms of both conversion efficiency and operational stability [25]. Solid residues remaining after transesterification, which are still rich in lignocellulose and bound carbon, can subsequently be densified into solid fuels with stable calorific values, thereby supporting a layered energy recovery strategy within integrated waste treatment systems [12], [13].

Densification functions to increase volumetric energy density, mechanical stability, and the ease of handling solid residues after transesterification. Its primary objective is not to increase the specific calorific value but to optimize the balance between mass yield, combustion quality, product strength, and logistical efficiency within the biomass energy supply chain [15], [26], thereby strengthening the technical and operational feasibility of waste-based energy utilization [12].

The integration of transesterification and densification forms a multi-product energy recovery system that produces biodiesel and solid fuel from a single waste stream, thereby improving material efficiency, reducing final residues, and supporting an energy-based circular economy [5], [18]. System optimization through the combination of anaerobic digestion and

gasification can further enhance conversion efficiency by utilizing organic fractions that remain unprocessed [31]. Thus, this integrated system is more adaptive and sustainable than single-process approaches because it can accommodate waste heterogeneity while maximizing energy and resource recovery.

The concept of integrating transesterification and densification represents an innovative approach to organic solid waste management that optimizes the utilization of all waste fractions through targeted processing. The lipid fraction is converted into biodiesel through transesterification, while the non-lipid fraction and solid residues are processed into solid fuels through densification [7], [23], [29]. This approach enables the production of multi-form energy (liquid and solid), enhances the flexibility of energy utilization, and reduces environmental impacts through the reduction of waste volume and greenhouse gas emissions [5], [11]. In addition to improving waste management efficiency, this concept also supports sustainable energy systems based on resource recovery and the circular economy [2], [17].

Table 1. Integration of Transesterification and Densification in Solid Waste Processing Systems

System Stage	Waste Fraction Processed	Main Process	Main Output	Energy Efficiency / Performance	References
Pre-treatment	Heterogeneous organic solid waste	Sorting, drying, and size reduction	Improved feedstock homogeneity	Reduced energy demand for downstream processing	[3], [4], [5]
Fraction Separation	Organic waste after pre-treatment	Lipid–non-lipid fraction separation	Lipid fraction ready for transesterification	Improved energy conversion efficiency	[2], [28]
Transesterification	Waste cooking oil and waste lipids	Catalytic transesterification	High-quality biodiesel	Biodiesel yield of 85-98%	[8], [30]
Transesterification	Sludge, mixed oils, and microbial lipids	Waste-based transesterification	Biodiesel from unconventional feedstocks	High conversion efficiency using low-value feedstocks	[10], [21], [24]
Biodiesel Process Intensification	Waste cooking oil	Microbubble-assisted transesterification	Accelerated reaction rate	Significant reduction in reaction time	[23], [29]
Biodiesel Process Intensification	Waste lipids	Machine learning-based optimization	Optimized operating conditions	Reduced energy-intensive trial-and-error experiments	[22]
Product Separation	Biodiesel–glycerol mixture	Phase separation and purification	Purified biodiesel	Reduced product losses	[6], [25]
Residue Utilization	Solid biomass residues	Drying and further conversion	Feedstock for densification	Increased residual energy value	[11], [17]
Biomass Densification	Sawdust and agricultural residues	Briquetting and pelletizing	Energy-dense briquettes and pellets	Energy density increased by >20%	[13], [15], [26]
Biomass Densification	Biomass residues	Pelletization and torrefaction	Stable solid biofuel	Improved transportation efficiency	[12], [16]
System Output	Integrated waste management system	Multi-pathway waste-to-energy conversion	Biodiesel, briquettes, and biochar	High resource utilization efficiency	[18], [31]
Sustainability Implications	Modern waste management systems	Circular economy and waste valorization	Reduced waste generation and emissions	Improved overall system efficiency	[7], [14]

System Stage	Waste Fraction Processed	Main Process	Main Output	Energy Efficiency / Performance	References
Sustainability Assessment Stage	Entire system flow	LCA and TEA	Environmental and economic indicators	Integrated sustainability optimization	[32], [33]

Table 1 shows that the integration of transesterification and densification forms a multi-product solid waste treatment system that optimizes energy recovery. Pre-treatment improves waste compatibility, transesterification converts the lipid fraction into biodiesel, and densification utilizes the remaining residues to produce high-energy solid fuel. This combination reduces final residues, improves material utilization efficiency, and strengthens the implementation of circular economy-based waste-to-energy systems.

The integration of transesterification and densification creates a complementary system for treating organic solid waste based on fraction characteristics. Lipid fractions are converted into biodiesel, while non-lipid fractions and residues are densified into high-energy biomass fuel, enhancing energy recovery, reducing waste volume and emissions, and optimizing material flow within an integrated system (Figure 3).

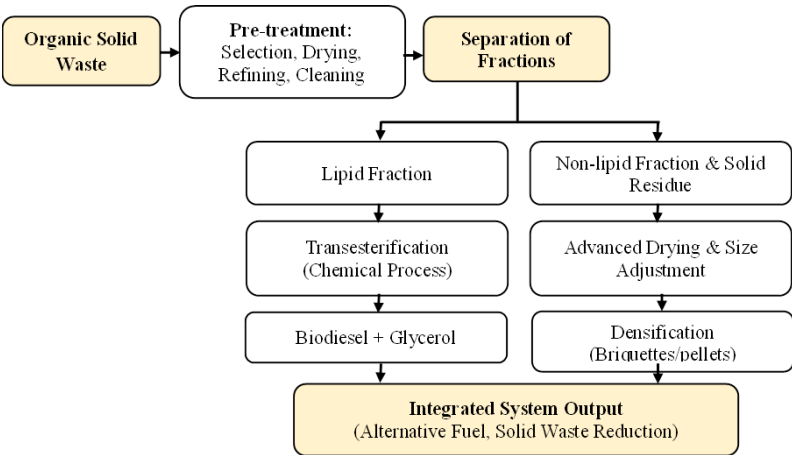


Figure 3. Conceptual Framework of Transesterification and Densification as Physicochemical Methods

Figure 3 shows that the integrated transesterification-densification system operates through the separation of organic solid waste fractions, where the lipid fraction is converted into biodiesel via transesterification, while the non-lipid fraction and solid residues are utilized through densification to produce solid fuel. This flow illustrates that each waste fraction is processed through different yet interconnected conversion pathways, resulting in multi-product energy recovery while reducing final residues. The framework demonstrates how a physicochemical approach can optimize material utilization and improve the efficiency of waste-to-energy systems.

3.4 Life Cycle Assessment and Techno-Economic Assessment

The successful implementation of integrated transesterification–densification systems depends not only on technical performance but also on environmental sustainability and

economic feasibility. Therefore, life cycle assessment (LCA) and techno-economic assessment (TEA) provide complementary approaches for the comprehensive evaluation of waste-to-energy systems. LCA assesses the environmental impacts across the entire life cycle of the process, whereas TEA evaluates economic performance through analyses of capital investment, operating costs, energy consumption, and potential profitability [32], [33].

The literature synthesis indicates that utilizing waste as a feedstock for biodiesel production and biomass densification can substantially reduce greenhouse gas emissions while improving resource efficiency by converting solid residues into high-energy-density fuels. However, pre-treatment requirements, energy demand, catalyst consumption, and downstream purification remain the primary factors influencing the economic viability of the integrated system [3], [4]. Consequently, thermal integration, process intensification, and the utilization of process residues as internal energy sources have emerged as key strategies for enhancing overall efficiency and reducing production costs.

Integrating LCA and TEA within a unified evaluation framework is essential for simultaneously optimizing the technical, economic, and environmental performance of transesterification-densification systems. Such an integrated approach provides a robust basis for industrial-scale implementation, supporting the development of sustainable waste-to-energy technologies and accelerating the transition toward a circular economy and low-carbon energy systems.

3.5 Research Gap and Future Directions

Although integrating transesterification and densification has shown potential to improve energy recovery and resource utilization from organic solid waste, most studies optimize these processes separately and remain limited to laboratory-scale applications. Industrial implementation is still hindered by feedstock heterogeneity, high pre-treatment and energy requirements, material flow management, and the lack of integrated technical, economic, energy, and environmental assessments.

Future research should focus on developing adaptive pre-treatment technologies, more efficient and contaminant-tolerant catalysts, and enhanced energy efficiency through thermal integration and process intensification. In addition, integrated TEA, LCA, and carbon footprint analysis are needed to evaluate economic viability, environmental performance, and overall sustainability. Such integrated system modeling will support the large-scale deployment of transesterification-densification technologies in integrated waste management facilities and urban waste-to-energy systems, contributing to the transition toward a circular economy and low-carbon energy systems.

4. Conclusion

This review highlights that transesterification and densification, as physicochemical methods, play complementary roles in solid waste treatment systems. Transesterification converts lipid fractions into biodiesel as liquid energy, while densification utilizes solid residues as biomass fuel. The integration of these processes enables more efficient utilization of waste

fractions, enhances energy recovery, and contributes to reducing waste volume and greenhouse gas emissions.

Despite their potential to support waste-to-energy strategies and circular economy principles, several challenges remain, including feedstock heterogeneity, pretreatment requirements, and process efficiency limitations. Therefore, future research should focus on technological innovation, process optimization, and techno-economic assessment and life cycle assessment. Such efforts will be essential to support the development of efficient and sustainable solid waste treatment systems oriented toward energy recovery.

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