Industrial Symbiosis as a Strategy for Efficient Hazardous Waste Management: An Optimization Approach

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ABSTRACT
By contaminating soil, air, and water resources, hazardous waste has a detrimental effect on the environment, disrupting ecosystems and reducing biodiversity. An analytical framework to improve the industrial symbiosis in waste management is identified in this study. Resource efficiency is assessed by reallocating landfill waste into recycling and improving utilization streams through the development of a district-level data-driven hazardous waste optimization approach. A genetic algorithm (GA) was incorporated into a mathematical model to estimate the best landfill diversion strategy for each district in order to optimize the system. The model allows for dynamic waste redistribution while taking into account current recycling and utilization capacities by combining waste flow concepts with heuristic optimization. With a best objective value of 31.9989, the results of this suggested approach show an overall improvement in system efficiency. This district-level analysis shows how, initially, the less efficient regions improved more after optimization, while the more efficient regions maintained their peak performance. Policymakers and planners can create region-specific industrial symbiosis strategies. This study advances sustainable waste management techniques and facilitates the shift to circular economy systems by fusing evolutionary optimization.

Keywords: Hazardous waste, Industrial Symbiosis, Circular Economy, Waste recycling, Landfill.

Introduction

Hazardous waste (HW) is any undesirable material that poses a risk to the environment when disposed of, such as explosive, combustible, oxidative, toxic and carcinogenic, abrasive, and/or toxic/ecotoxic [1]. For many years, waste management which encompasses the collection, transportation, medication, recycling, and disposal of waste has been a significant environmental issue. Urbanization, industrialization, and growing society have all been linked to an increase in waste production. Both hazardous and non-hazardous waste are considered in the waste management plan. Non-hazardous waste does not present a risk to the environment or public health, but HW does. A significant amount of hazardous waste is produced as a result of the industrial sector's constant growth. Therefore, care must be taken during the storage, segregation, transportation, and disposal of hazardous waste to minimize environmental risks because hazardous waste cannot be disposed of in the environment directly.

Industrial symbiosis (IS) is a transformative strategy that enables various sectors to engage in mutually beneficial exchanges of resources, energy, and byproducts. IS greatly reduces waste and environmental impact while improving economic performance by converting waste streams from one industry into useful inputs for another by imitating the efficiency of natural resources [2]. To guarantee HW efficient management, it must be identified and categorized. Additionally, different countries have different identification procedures. A clean, safe, and environmentally friendly environment requires sustainable HWM. Policies and environmentally friendly tactics can be used to accomplish this Recycling, composting, incineration; gasification and pyrolysis [3-8] are a few popular approaches for sustainable waste management [9]. Nevertheless, these methods often work alone and primarily address waste after it is produced. Industrial symbiosis, on the other hand, provides a more integrated approach that boosts overall system efficiency and converts waste into useful resources by permitting the exchange of waste materials between processes. This will guarantee social security, health, safety, a green economy, and environmental preservation.

The circular economy (CE) refers to the production and use of goods in an environmentally friendly manner. It adheres to the idea that nothing is wasted and every product is used repeatedly. The CE places equal weight on social and personal well-being, environmental sustainability, and economic prosperity [10]. The concept of a CE is interpreted differently by various sectors and stakeholders. Countries differ in how much waste is produced from various sources. Municipal solid waste (MSW) is currently produced at a rate of 2.01 billion Mt annually worldwide, and it is projected to rise by 2.59 billion Mt annually and 3.40 billion Mt annually by 2030 and 2050, respectively [11]. Depending on the region and degree of development, the daily production of MSW can range from 0.11 to 4.54 kg. Asia produces one-third of the world's waste, with India contributing significantly with 0.50–0.9 kg/capita/day. Metals (1.1–2.2%), polyethylene (2.8–4.3%), glass (0.5–1.1%), and rubber (0.1–1.4%) are examples of hazardous waste found in a typical MSW. Food waste (68.3–81.1%), paper (7.2–10.7%), textiles (1.3–2.2%), and others (4.5–10.4%) are the remaining non-hazardous fractions in MSW [12].

The management of HW can be done in a number of ways. By maximizing efficiency or avoiding needless use in manufacturing processes, the first stage of the HWM hierarchy motivates stakeholders (industries and communities) to minimize the use of raw materials. The second-best tactics in the HW hierarchy are reuse and recycling. In addition to saving energy and resources needed to produce the new product, this step enables the stakeholders to avoid spending money on the new material. The most popular method of disposal is landfilling[13].

MATHEMATICAL MODEL

Notations

L_i : The amount of delivered waste to district I from landfill

L_i^* : Landfill waste after diversion

R_i : Quantity of district I's recycled waste

R_i^* : Recycled waste after diversion

U_i : Co- processing / energy recovery waste utilization amount in district 1

I_i : Incinerated waste in district i

W_i : Total amount of waste generated in district i

x_i : decision variable representing the proportion of landfill waste diverted to recycling in district i

SEI_i : Symbiosis efficiency Index

SEI_i^* : Symbiosis efficiency Index after optimization

θ : System constrain parameter known as maximum allowable diversion fraction

Total waste

$$W_i = L_i + R_i + U_i + I_i$$

Baseline symbiosis efficiency

The Symbiosis Efficiency Index (SEI) is defined to quantify the efficiency of waste utilization:

$$SEI_i = \frac{R_i + U_i + I_i}{W_i}$$

This index represents the proportion of waste effectively recovered from the total generated.

Waste Flow Transformation

A part of landfill waste is diverted into recycling streams in order to integrate industrial symbiosis. The definition of the transformed waste flows is:

$$R_i^* = R_i + x_i L_i$$

$$L_i^* = L_i(1 - x_i)$$

Optimized Symbiosis Efficiency

The updated efficiency index after optimization is given by:

$$SEI_i^* = \frac{R_i^* + U_i + I_i}{W_i}$$

Objective Function

The goal of the model is to maximize the total symbiosis efficiency across all districts:

$$\max Z = \sum_{i=1}^{n} SEI_i^*$$

System Constraints

The optimization is subject to the following constraints:

Mass Balance Constraint:

$$W_i = L_i^* + R_i^* + U_i + I_i$$

This guarantees the conservation of total waste, demonstrating how industrial symbiosis redistributes waste flows without changing total generation.

Diversion constraint: $0 \le x_i \le \theta$

This restricts the amount of waste that can be diverted from landfills while taking infrastructure and technology viability into consideration.

Non-negativity of flows: $R_i^* \ge 0, \quad L_i^* \ge 0$

Key Assumption

The optimization framework only concentrates on redistributing waste flows rather than reducing waste generation, and the overall amount of waste produced in each district stays constant.

PROBLEM DESCRIPTION

The production of hazardous waste has significantly increased as a result of rapid industrialization, endangering the environment. Even though many areas have facilities for recycling, utilization, and recovery, a significant amount of waste is still disposed of in landfills, indicating inefficiencies in the allocation and recovery of this waste. A systematic framework is needed to determine the best waste redistribution while taking actual word constraints into account. Industrial symbiosis improves waste transfer to a useful resource of another being a sustainable solution. Specifically, the amount of landfill waste that will be recycled should be measured without compromising the overall equilibrium of the system. This study models a waste management system at the district level. The objective is to improve circularity and resource efficiency through optimal waste flow redistribution. The problem is formulated as a constrained optimization model, treating landfill waste as a recoverable resource.

Result And Discussion

Using Julia programming language for the suggested optimization framework, an industrial symbiosis was carried out on a district-level hazardous waste data set by methodically redistributing the waste flow. An uneven adoption of resource recovery management and practice is revealed by the baseline Symbiosis Efficiency Index (SEI). While Karur and Namakkal regions, with an SEI of 0.99, showed near-optimal performance, indicating well-established recycling and utilization pathways, districts like Nagapattinam and Tiruchirappalli, each with an SEI of 0.21, showed low efficiency due to a greater reliance on landfill disposal. The model's best objective value of 31.9989 was attained by incorporating genetic algorithm-based optimization, and improvements were consistently seen in the majority of districts. Few areas have an improved SEI, demonstrating how landfill diversion can improve recovery efficiency without changing the overall amount of waste generated.

Larger x_i diversion fraction values are assigned to the areas with greater inefficiencies. Recycling flows R_i^* have significantly improved in districts like Cuddalore and Nagapattinam, which have x values of 0.48 and 0.47, respectively, indicating higher diversion allocations. Districts like that, on the other hand, are doing well with SEI scores of 0.983 and 0.996, indicating little improvement because their system is already operating at maximum efficiency. This demonstrates that the model adapts to the conditions of each district rather than applying the same modifications everywhere. The findings also demonstrate that landfill waste can be viewed as a valuable resource and that recycling it enhances the flow of materials between processes and increases system efficiency.

This finding focuses on how districts with low efficiency provide the greatest gains. Efficiency is greatly increased when even a tiny amount of waste is diverted from landfills to recycling facilities. Each district requires a different approach to managing various waste types and industries due to their unique characteristics. Additionally, decision-makers can plan more effective waste exchange systems by combining flow-based modeling with optimization techniques like genetic algorithms. Overall, the study demonstrates that in order to support a circular economy approach to hazardous waste management, landfills should be viewed as potential resources rather than just places to dump waste.

Conclusion

This study demonstrates how industrial symbiosis can be enhanced by appropriately managing the flow of waste between various processes. Waste can be reused and redirected to create value that benefits other industries rather than being thrown away. Particularly in areas where current waste management practices are inadequate, minor adjustments to waste handling can result in a significant improvement. The system becomes more effective, lessens its impact on the environment, and makes better use of the resources available by rerouting the waste from landfills to recycling. Using industrial symbiosis as a tool for sustainable waste management, this study highlights the need for industries and regions to collaborate so that the results of one process can be used as inputs for another, promoting resource conservation and advancing the objectives of the circular economy.Overall, the study offers a straightforward and adaptable framework that can assist planners and legislators in spotting chances for improved waste utilization and creating more effective and long-lasting waste management systems.

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