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Agent-Based Modelling Analysis on the Potential Economic Benefits of Mud Cake Waste to Wealth

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Production of refined sugar generates a significant amount of mud cake waste which has traditionally been managed through disposal in landfills. Such practice is not sustainable and can have negative environmental impacts. While previous research has primarily focused on evaluating the environmental and economic impacts of bagasse, less attention has been given to mud cake waste. By applying the waste-to-wealth concept and promoting a circular economy, this study aims to evaluate the potential economic benefits of using mud cake waste as an alternative raw material in cement production. To assess the potential economic benefits, the study employs an agent-based modelling analysis that simulates the actions and interactions of multiple agents. The results of the analysis demonstrate the potential economic benefits of mud cake waste exchange for both sugar producers and cement manufacturers. The concept of a win-win scenario is emphasized, where both parties share an equal amount of exchange costs and reap mutual benefits in cost savings, improved resource efficiency, and reduced environmental impacts by reducing the amount of waste being disposed of to the landfill.

1. Introduction

Mud cake waste is a solid waste produced during the filtration process of sugarcane juice in the sugar refinery industry. Approximately 0.03 t of mud cake is generated for every 1 t of raw sugar processed (Gupta et al., 2011). As the demand for sugar production increases, so does the generation of mud cake waste. Sugar refineries employ a carbonation process for purification that utilizes lime-based solutions, resulting in mud cake waste that may contain a significant amount of lime. Disposing of this waste into landfills has a negative environmental impact due to its insoluble and imbalanced nutrient composition. It decomposes slowly and emits intense heat and foul odors (Sen and Chandra, 2007). To address this issue, the concept of waste-to-wealth in industrial symbiosis, which involves one company's waste being used as raw material by another company presents a potential solution (Chertow, 2000). Cement manufacturers could be potential consumers of mud cake waste, given the similarity in composition between the waste and the raw materials used in cement production, such as calcium oxide (lime) CaO, silica SiO_2, alumina Al_2O_3, and iron oxide Fe_2O_3. Evaluating the potential economic benefits, specifically in terms of cost reduction, for both mud cake producers and cement manufacturers is crucial for promoting this waste-to-wealth activity. This study employs agent-based mod eling analysis to simulate scenarios between mud cake producers and cement manufacturers as potential partners in an industrial symbiosis relationship. The analysis aims to evaluate the potential economic benefits by considering the percentage of mud cake exchange and the cost factor coefficient, which translate into different scenarios. Through this analysis, the study demonstrates the effect of mud cake waste utilization on cost reduction for both the waste producers and potential consumers, specifically in the context of cement production.

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2. Literature background

The production of refined sugar from raw sugar involves a purification and boiling process, which includes affination, carbonation, and filtration. These processes require additional chemical substances to remove impurities from the raw sugar, resulting in the generation of waste containing the impurities and excess chemicals. For example, the addition of lime during carbonation contributes to the properties of mud cake, which contains calcium carbonate or lime constituent. Subsequently, this mud cake or press mud waste is generated through filter press process. Several literature reviews have examined this waste management issue and the associated challenges, providing valuable insights into waste management practices (Raza et al., 2021) and potential solutions (Meghana and Shastri, 2020) in the sugar industry. Previous studies also have investigated the properties of this mud cake waste and explored its potential applications in energy production (Rajaeifar et al., 2019) and agriculture (Abera et al., 2020). The mud cake contains significant amounts of calcium, silica, and other compounds, making it suitable for reuse as a construction material (Gautam et al., 2021), fertilizer (Chattha et al., 2019), and in biogas production (Nimbalkar et al., 2017).

Cement, as a widely used construction material worldwide, undergoes a production process involving raw material blending, burning to produce clinker, clinker grinding, and packaging. The raw materials for cement production include limestone, clay, sand, and corrective materials such as iron ore and gypsum, which provide lime, alumina, silica, and iron sources (Harrisson, 2019). Research has shown interest in incorporating mud cake into Portland cement production (Li et al., 2014), with a study demonstrating that up to 20 % mud cake can be added as a raw material without significantly deteriorating the properties of cement. Another recent study suggested that adding 10-15 % of mud cake could potentially contribute to eco-friendly cement production (Radwan et al., 2021). It's worth noting that these studies were conducted on an experimental scale, and the generation of mud cake waste occurs at an industrial level, necessitating the development and implementation of proposed solutions on an industrial scale. Industrial symbiosis is defined as the reutilization of one company’s waste or byproduct to be an alternative resource for another company (Neves et al., 2019). This concept of waste-to-wealth allows entities and companies that are traditionally separated, to cooperate among themselves in the sharing of resources, contributing to the increase of sustainability with environmental, economic, and social benefits (Neves et al., 2020). For example, the industrial symbiosis case study involved cement manufacturing, steelmaking plant and zinc smelting plant (Sellitto and Murakami, 2018). A review of industrial symbiosis between the sugar, construction, and energy industries, however, their focuses primarily on bagasse waste, with only a small portion discussing mud cake waste (Gopinath et al., 2018). A successful industrial symbiosis case with the incorporation of cement production by Nanning Sugar Co., Ltd. to address the excess lime sludge in their paper-pulp industrial chains (Yang and Feng, 2008) and by Guitang Group (Zhu et al., 2007) has shown the practicality of the concept.

However, in the context of a developing country like Malaysia, the understanding and implementation of this industrial symbiosis concept are still limited (Zailan, 2020). The economic viability and potential benefits of incorporating mud cake waste into cement production are yet to be comprehensively explored and understood. Economic viability is crucial in fostering industrial symbiosis as it ensures that the utilization of mud cake waste as an alternative resource in cement production is financially advantageous for both the sugar industry and the cement industry. Understanding the economic viability of this symbiotic relationship can incentivize companies to actively engage in waste exchange and resource sharing, leading to improved resource efficiency, cost reduction, and enhanced competitiveness for both industries involved. To address this gap, this study aims to demonstrate the impact of mud cake waste utilization on cost reduction for both waste producers and potential consumers based on the percentage of mud cake exchange and the cost factor coefficient. This study utilizes agent-based modeling analysis (Yazan and Fraccascia, 2020) to simulate scenarios between mud cake producers and cement manufacturers, considering them as potential partners in an industrial symbiosis relationship.

3. Model and method

In this work, two possible industrial symbiosis scenarios are simulated. In Scenario A, no industrial symbiosis forms between Agent I, mud cake waste producer, and Agent J, cement manufacturer. In Scenario B, the exchange of mud cake waste takes place between the agents. The evaluation of the cost borne by both agents depends on the mud cake exchange percentage Q, which varies from 25 % to 100 %, and the cost factor coefficient due to exchange activities denoted by L_m. Three potential cases are considered: case B1, where $L_m = 0$, the exchange cost is paid by Agent J; case B2, where $L_m = 0.5$, both agents share the exchange cost equally; and case B3, where $L_m = 1$, the exchange cost is paid by Agent I (Fraccascia and Yazan, 2018). In this context, the exchange cost here refers to the transportation cost involved in transferring the mud cake waste from Agent I's company to Agent J's company, taking into account the distance d_{ij}. All calculations were performed using commercial statistical software, Microsoft Excel.

Table 1: Simulation parameters

Parameter	Symbol	Value	Unit	Reference
Mud cake quantity	W	10,000	Mt/month	
Distance Agent I to landfill	d_i	10	km	
Limestone quantity	m_1	50,000	Mt/month	
Distance Agent J to limestone supplier	d_j	10	km	
Distance Agent I and Agent J	d_{ij}	10	km	
Unit disposal cost	u_{dc}	45	RM/Mt	(Sabeen et al., 2016)
Unit waste transportation cost	u_{twc}	50	RM/km.Mt	(Sabeen et al., 2016)
Unit purchasing cost of limestone	u_{rc}	250	RM/Mt	
Unit transportation cost of limestone	u_{trc}	50	RM/km.Mt	

The quantity of mud cake generated by Agent I depends on the production capacity of refined sugar. Let W represent the amount of mud cake generated, and Q denotes the percentage of mud cake exchange. In this study, the mud cake exchange amount, SW, is assumed to be equal to the limestone replacement amount. Only the cost of purchasing limestone is considered, while the cost of other raw materials for Agent J remains constant throughout the simulation and is omitted from the analysis.

$$SW = Q \times W \quad (1)$$

In Scenario A, the cost involves for Agent I are waste management costs including waste disposal costs and the transportation cost of mud cake waste to landfill is given by,

$$Tc\_i_o = f(d_i, W, u_{dc}, u_{tw}) \quad (2a)$$

which depends on the distance between Agent I and landfill, d_i, and the amount of mud cake that needs to be disposed of W with the assumption the amount of mud cake generated is equal to the amount of mud cake that needs to be disposed of. Concerning Agent J, the cost would be the purchasing cost of limestone and transportation cost of it which also depends on the distance, d_j, and amount of limestone, m_1 is given by,

$$Tc\_j_o = f(d_j, m_1, u_{rc}, u_{trc}) \quad (2b)$$

In Scenario B, with the assumption of the mud cake is given for free, the additional cost from the industrial symbiosis relationship which covers the transportation of mud cake from Agent I to Agent J and it depends on the exchange amount, SW, the distance between them, d_{ij}, and cost factor coefficient L_m for both agents are given by,

$$Tcxw\_i = f(SW, d_{ij}, L_m, u_{twc}) \quad (3a)$$

$$Tcxw\_j = f(SW, d_{ij}, (1-L_m), u_{twc}) \quad (3b)$$

The remaining cost after waste exchange need to be paid by Agent I and Agent J are the cost for the excess mud cake, W_f need to be disposed of and the cost balance limestone, m_{1f} needs to be purchased are given by,

$$Tc\_i_f = f(d_i, W_f, u_{dc}, u_{twc}) \quad (4a)$$

$$Tc\_j_{new} = f(d_j, m_{1f}, u_{rc}, u_{trc}) \quad (4b)$$

The evaluation of the net cost for both Scenario A and B considering reduction and additional due to industrial symbiosis relationship and mud cake exchange are given by,

$$dTc_i = Tc\_i_o - Tc\_i_f - Tc_{xw}\_i \quad (5a)$$

$$dTc_j = Tc\_j_o - Tc\_j_{new} - Tc_{xw}\_j \quad (5b)$$

4. Result and discussion

The evaluation of cost for Agent I and Agent J for both Scenario A and Scenario B is presented. In Scenario A, no waste exchange occurred. Agent I disposed of all the mud cake generated at the landfill, while Agent J used the original raw material, limestone, to produce cement products. In Scenario B, there was an exchange of mud cake waste between Agent I and Agent J with a percentage of exchange denoted as Q and different cases based on the cost factor coefficient, L_m.

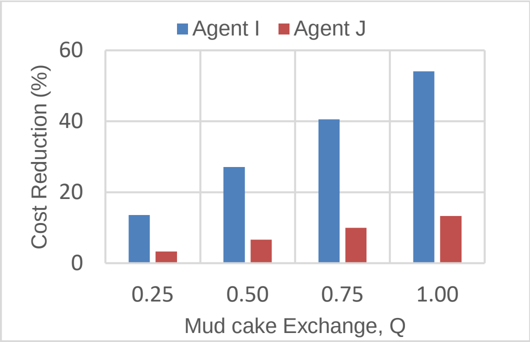

Figure 1: Cost reduction percentage based on exchange percentage

Figure 1 shows the percentage reduction in costs for both agents based on the exchange percentage of mud cake, Q. The percentage of cost reduction increases as the percentage of mud cake exchange increases for both agents, and this trend is consistent across all B1, B2, and B3 cases. It is important to note that Agent J has a lower percentage of cost reduction than Agent I due to the higher cost of purchasing the raw material, limestone, compared to the cost of waste disposal by Agent I. Additionally, previous research (Li et al., 2014) indicates that only a maximum of about 20 % of limestone can be replaced with mud cake. Considering that the simulation accounts for the amount of mud cake generated based on sugar production capacity, and annual sugar production is significantly less than annual cement production, the cost reduction appears equitable for both parties. Moreover, in terms of environmental impact, a higher percentage of mud cake exchange results in a lower quantity of waste being disposed of in landfills, thus making a positive contribution to environmental sustainability.

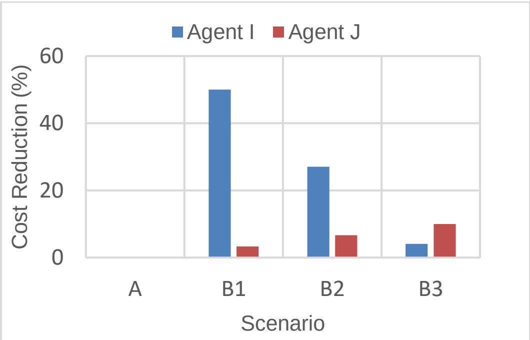

Figure 2: Cost reduction percentage based on the scenario

The percentage of cost reduction for both Agent I and Agent J based on the scenarios are presented in Figure 2. In Scenario A, there is no exchange of mud cake between the agents, resulting in no cost reduction. Agent I, the sugar producer, incurs the cost of disposing of its mud cake at the landfill, while Agent J purchases the original main raw material, limestone. However, in Scenario B with a mud cake exchange percentage of Q equal to 50 %, a trend of cost reduction can be observed. In case B1, where Agent I provides its mud cake to Agent J for free and incurs no transportation cost, Agent I achieves the maximum cost reduction of 50 %. Conversely, in case B3, where Agent I pays for the transportation cost of the mud cake, a significantly lower cost reduction of only 4 % is observed. For Agent J, the minimum cost reduction of approximately 3 % is observed in case B1, as the agent bears the transportation cost of the mud cake. In contrast, case B3 shows a higher cost reduction of up to 10 % for Agent J. In case B2, where both agents share the transportation cost equally, Agent I achieves approximately 27 % cost reduction, while Agent J achieves slightly over 6 % cost reduction. Comparing the percentage of cost reduction for both agents based on the scenarios, case B2 offers the best conditions, as both agents experience a fair percentage of cost reduction.

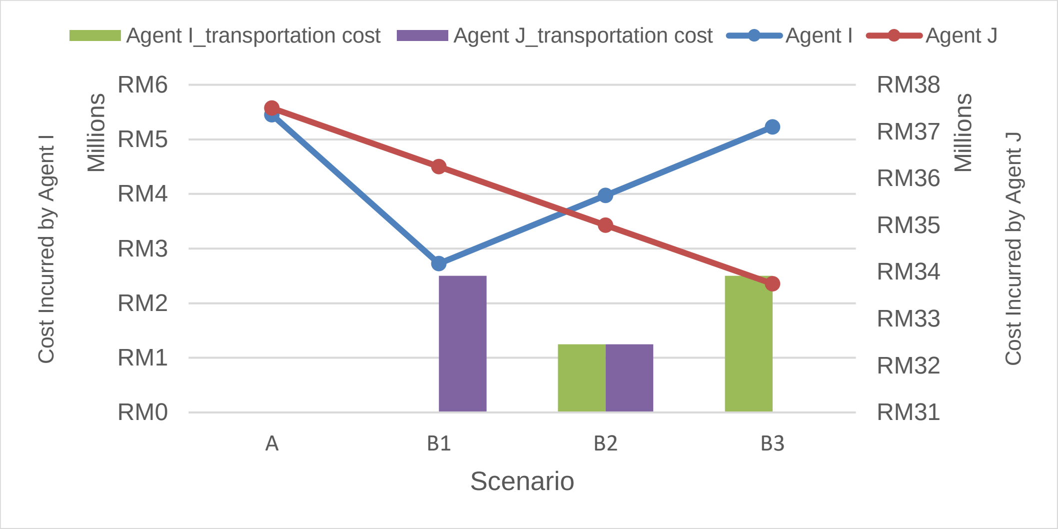

Figure 3: Cost by Agents based on the scenario

When considering the costs incurred by both Agent I and Agent J based on the scenarios depicted in Figure 3, it is evident that the highest costs are observed in Scenario A. For Agent J, the costs steadily decrease from Scenario A to Scenario B3. However, a distinct trend is observed for Agent I. The transition from no waste exchange in Scenario A to waste exchange in Case B1 proves to be the most favourable condition for Agent I, resulting in a significant reduction in waste disposal costs by simply giving their waste to Agent J. However, moving from case B1 to B3, the costs for Agent I increase as the agent now have to bear the transportation costs instead of disposal costs. The costs incurred by Agent I in case B3 are almost equivalent to the costs of waste disposal in Scenario A, rendering the potential benefits from the waste exchange between the agents insignificant. Conversely, the costs incurred in case B1 to case B3 for Agent J show a decreasing trend. Although costs continue to decrease for both Agent I and Agent J across cases B1 to B3, it is crucial to emphasise the maximum benefits for both agents. To promote waste exchange with maximum economic benefits for both agents, a win-win scenario must be established. Based on the scope of this simulation, case B2 emerges as the most favourable scenario for both Agent I and Agent J, as they share the transportation costs for waste exchange, making moderate cost reduction achievable for both parties. Note that for better illustrations of the transportation cost, the left y-axis is used.

5. Conclusions

A simple cost evaluation analysis conducted on the exchange of mud cake waste between the producer and potential consumer highlights the potential cost benefits of implementing an industrial symbiosis relationship. The study shows that the more the waste is shared or replaced as an alternative raw material, the greater the cost reduction is achieved and the lower the quantity of waste being disposed of to the landfill. It is important to note that the maximum economic potential resulting from the waste exchange can only be realised in a win-win scenario where both Agent I (the producer) and Agent J (the potential consumer) share the same cost for the exchange, including transportation costs as considered in this study. The analysis focuses on the basic costs incurred by both agents, assuming that the mud cake is provided for free. Future work may yield different findings if the selling price of mud cake is included in the analysis. Additional investigation is necessary to ensure that the utilization of mud cake as a raw material in cement production does not compromise the quality of the cement produced. It is also crucial to determine the optimal amount of mud cake that can replace limestone while maintaining the desired quality control parameters such as the lime saturation factor, silica ratio, and alumina ratio. This aspect should be explored in future research.

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