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RESEARCH ARTICLE

Influence of Industrial Symbiosis on Solid Waste Reuse in Manufacturing Industries in Kisumu County, Kenya

Morelly Kathy Adalla[1,*], Raphael Achola Kapiyo[2], Boniface Oluoch Oindo[2], and Boniface Oure Obong'o[3]

ABSTRACT

Industrial symbiosis (IS) is a practical approach to sustainable economic and environmental management involving exchanging materials, energy, water, and by-products among industries. While IS has been extensively studied in developed countries, its implementation in developing countries still needs to be improved. The purpose of the research was to assess the influence of geographical proximity and symbiotic intensity on the exchange of solid waste materials. This study employed a descriptive, cross-sectional research design and examined 41 manufacturing industries in Kisumu County, Kenya. A combination of quantitative and qualitative data was collected through questionnaires administered to technical officers in the industry. Besides, in-depth interviews with industry experts, county administrators, and industry association representatives were conducted, providing valuable insights and perspectives on the subject matter. The findings established that geographical proximity did not significantly influence types of waste exchanged ($p = 0.298$, $p = 0.327$, and $p = 0.535$) using nutrient-value waste as the reference category. This finding was likely due to high variability in distance between industries in the symbiotic exchanges. In contrast, the symbiotic intensity statistically significantly influenced the amount of solid waste reused in the network (Adjusted $R^2 = 0.113$, $p = 0.039$). Furthermore, it was established that increasing the number of actors in the network ($\beta = 0.324$) can significantly impact solid waste reuse more than increasing the number of types of waste being exchanged ($\beta = 0.243$). This study underscores IS as a sustainable alternative to conventional manufacturing, especially in developing countries, while indicating that factors other than geographical proximity shape symbiosis.

Keywords: Geographical proximity, industrial symbiosis, symbiotic intensity.

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[1] *Environmental Sustainability and Climate Change Research Centre, Industrial & Allied Technology Research Directorate, Kenya Industrial Research and Development Institute (KIRDI), Kenya.*
[2] *Department of Environmental Sciences, School of Agriculture, Food Security and Environmental Sciences, Maseno University, Kenya.*
[3] *Industrial Microbiology and Biotechnology Research Centre, Industrial & Allied Technology Research Directorate, Kenya Industrial Research and Development Institute (KIRDI), Kenya.*

***Corresponding Author:**
e-mail: morellykathy@gmail.com

1. Introduction

Industrial Symbiosis (IS) is an emergent approach focused on the recovery and reuse of wastes (material, water, and energy) from the industry-generating wastes to collocated industry using those wastes as raw materials for industrial processes [1]. It is a strategic practice in an attempt to develop manufacturing systems that are more environmentally sound while drawing economic and social benefits [2]. Globally, the European Commission has openly acknowledged the benefits of adopting the IS approach to enhance resource utilization and production efficiency and has made recommendations for its implementation [3]. Numerous regions worldwide have adopted IS to enhance sustainability within the manufacturing sector [4]–[8].

Industrial symbiosis is practiced over a network of industries where IS relationships are established. The development of these networks can be self-organized, facilitated, or government-planned [5]. [1] argued that geographical proximity plays a crucial role in IS, as it fosters collaboration, facilitates the exchange of waste and by-products, and builds trust and cooperation between companies [9]. However, this may not be a confounder in the case of high-value by-products such as pure Sulphur from sour-gas treatment [10]. Furthermore, geographical proximity is beneficial because it minimizes costs incurred in these waste exchanges [11]. These studies have focused on emphasizing the importance of geographical proximity. However, more needs to be done to quantify this determinant of IS and, more particularly, query its influence on what type of material is exchanged.

The IS networks formed are characterized by their connectedness, also called symbiotic intensity in this field [12]. Chertow [1] introduced a conceptual framework to understand the structure and dynamics of industrial ecosystems, known as the "3-2 heuristic model" of industrial symbiosis. According to this model, for an exchange of at least two distinct resources to occur, it necessitates the involvement of a minimum of three separate entities. Many researchers have measured how networks are connected in their studies using a method by Berkel *et al.* [12]. This method looks at networks through what is known as "symbiotic projects". These projects are counted by the number of companies involved, the number of by-products exchanged, and number of utilities shared. Berkel *et al.* further state that this method is perfect for seeing how one specific network grows. Nevertheless, it is limited when comparing different IS cases or evaluating a network's economic or environmental benefits. This observation by Berkel *et al.* [12] indicates a need to research IS practices by the connectedness of networks as they exist uniquely.

The UNIDO [13] report highlights environmental challenges for African manufacturing: pollution, waste management, and resource use. The environmental performance of Africa's manufacturing industries varies depending on several factors, including the country, the sector, and the specific companies involved. Furthermore, the manufacturing sector faces significant challenges in terms of environmental performance due to limited financial and technical resources, weak regulatory enforcement, and a need for more public awareness about environmental issues [14]. IS, in Africa, has shown promise in addressing environmental challenges in the manufacturing sector. Examples include integrated smallholder agriculture in the West Africa [15], collaboration in the agro-processing sector in the South Africa [16], and emerging networks in the Tanzanian sugar industry [8]. Implementing IS in sub-Saharan Africa faces challenges such as limited financial resources, low awareness of the concept among industries, and lack of institutional and regulatory support [17]. The few cases of the reported IS practice in Africa are self-organized primarily for economic gains. However, there are opportunities to improve resource efficiency and waste management through IS. Research in Africa has highlighted the challenges and barriers to adopting IS. However, more is needed on how the current IS practice is structured regarding geographical proximity, types of material exchanged, the symbiotic intensity of networks, and the amount of solid waste reused in the networks.

In Kenya, IS can be promoted through awareness raising, capacity building, supportive policies, and collaboration platforms between stakeholders, which are crucial for promoting resource efficiency and circular economy practices [18], [19]. Kenya is progressing towards circular practices in crucial sectors, promoting new enterprises focused on redesigning, recycling, and waste management through collaboration between government and the private sector, alongside the introduction of policies like the National Sustainable Solid Waste Management Policy 2021 and Extended Producer Responsibility regulations 2021 [20]. There is a need to examine IS practice quantitatively as it is currently occurring, which will offer substantial information that can shape policy. Kisumu County in Kenya faces significant waste management challenges, leading to pollution and environmental degradation [21], [22]. Studies have highlighted the need for proper solid waste management systems and the potential for value recovery through IS. However, the focus has been on challenges and end-of-pipe solutions [23], [24]. Thus, it is imperative to conduct additional research to assess solutions, such as industrial symbiosis, on solid waste reuse within the County.

2. Methods and Materials

2.1. Study Area

The study was conducted in Kisumu County, an economically important region in Kenya, situated between longitudes 33° 20′ E and 35° 20′ E and latitudes 0° 20′ S and 0° 50′ S (Fig. 1).

Covering approximately 567 km^2 of water and 2086 km^2 of land, the County represents about 0.36% of Kenya's total land area. Kisumu County is the third city in the country. It consists of seven sub-counties: Kisumu East, Kisumu West, Kisumu Central, Muhoroni, Nyando, Seme, and Nyakach, with a population of 1,155.574 according to the 2019 Kenya National Population and Housing Census.

2.2. Characteristics of the Study Area

Kisumu County is home to various industries, some located in the city and others on the outskirts. These industries include agricultural processors, food processors, textiles, leather, molasses, fish processing plants, chemical factories, building and construction, mining, timber, and wood. Smaller backyard industries like tailoring, handicrafts, and boatbuilding are also primarily informal. Kisumu is a significant Northern Corridor hub with well-connected arterial roads and a 217 km narrow gauge rail system for passengers and cargo transport. Water transport through ferry services connects towns on the shores and links the county to Tanzania and Uganda. The county's airport facilitates domestic and international flights to various East African cities. Waste management in the county faces challenges, with approximately 400 tonnes of solid waste generated daily in Kisumu City. Only about 20%–25% of this waste is collected for disposal in an open dump site, with the majority being organic and a significant portion being recyclable. Unfortunately, solid waste is predominantly handled through open burning and dumping practices.

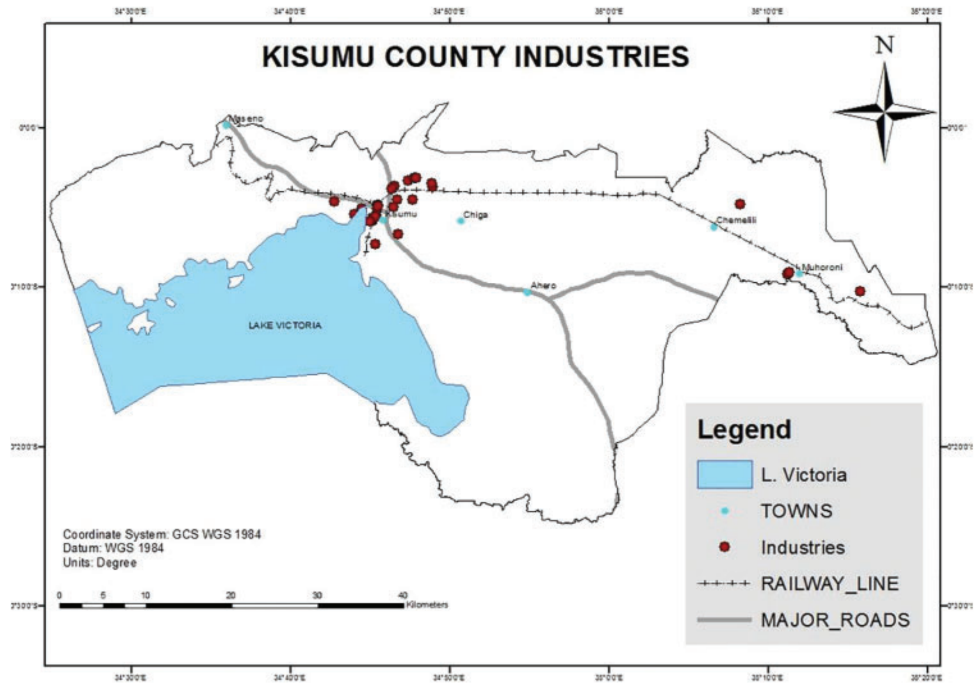

Fig. 1. Kisumu County map showing the location of manufacturing industries and transport infrastructure.

2.3. *Research Design*

The study employed a descriptive cross-sectional study design combining quantitative and qualitative methods. The quantitative component involved collecting and analyzing numerical data to examine the extent of solid waste reuse and to identify any influence of industrial symbiosis on solid waste reuse in the manufacturing industries. The qualitative component involved in-depth interviews to explore key stakeholders' perceptions, experiences, and recommendations regarding industrial symbiosis and solid waste management. The KIs were technical officers from the Kisumu County Government offices in the Department of Water, Environment, Natural Resources, Climate Change, Department of Physical Planning, Lands and Urban Development, Department of Energy and Industrialization, KAM, and finally NEMA.

2.4. *Study Population*

The research population consisted of two primary groups. The first group consisted of manufacturing industries within Kisumu County, encompassing various sizes and sectors. The second group comprised vital stakeholders who have a role in industrial symbiosis practices in the County; this included county government officials from key departments, environmental agencies, and industry associations. A list of 71 industries was obtained from the Ministry of Investments Trade and Industry, Kisumu County.

Inclusion criteria for manufacturing industries:

1. Industries located within Kisumu County, Kenya,
2. Industries from various sectors, such as agro-processing, food and beverage, leather and textiles, chemical and allied,
3. Industries of various sizes, including small, medium, and large enterprises,
4. Industries involved in the reuse of solid waste as part of their operations.

Inclusion criteria for key stakeholders:

1. Government officials and policymakers responsible for environmental regulations and waste management in Kisumu County,
2. Environmental agencies or departments involved in monitoring and overseeing waste management practices,
3. Industry associations and representing the manufacturing sector in Kisumu County.

Exclusion criteria for manufacturing industries:

1. Industries located outside Kisumu County, Kenya,
2. Industries that do not generate solid waste,
3. Industries that do not engage in any form of solid waste reuse either within or with other facilities,
4. Dormant/ shut down industries,
5. Informal sector "jua kali".

Exclusion criteria for key stakeholders:

1. Individuals who do not have specific knowledge or experience related to industrial symbiosis in Kisumu County.

Based on the exclusion criteria, 49 out of the 71 industries formed the population for this study. Hence, saturated sampling was employed in this study. However, only 41 respondents returned the survey. Five key informants were interviewed in this study: Kisumu County administrator for the Department of Environment, Industrialization, Physical Planning, NEMA, and a KAM official.

TABLE I: Multinomial Logistic Regression Results for Element, Energy, Fibre, and Cellulose Value Solid Waste Material, Compared to Distance (Geographical Proximity)

Type of waste		β	Std. error	df	Sig (p).	Exp (β)	95% confidence interval for Exp (B)	
							LB	UB
Element value	Intercept	−0.811	0.321	1	0.012			
	Distance	0.002	0.002	1	0.298	1.002	0.998	1.006
Energy value	Intercept	−0.636	0.303	1	0.036			
	Distance	0.002	0.002	1	0.327	1.002	0.998	1.005
Fibre & cellulose	Intercept	−0.592	0.300	1	0.048			
	Distance	0.001	0.002	1	0.535	1.001	0.997	1.005

Note: a. The reference category is Nutrient value.

2.5. Data Collection

Questionnaires were used to collect primary data from industries. Expert opinion was sought with the help of an interview schedule.

2.6. Data Analysis

A regression analysis examined the relationship between variables and predicted outcomes. With all assumptions met, a multinomial logistic regression was performed to answer the first research question, and a multiple linear regression was performed to answer the second research question.

In the study of 41 industries, 17 different types of solid waste materials were identified. To make the analysis more insightful, these waste types were grouped into four categories based on their reuse value. These categories were:

1. Nutrient value: Waste reused for animal feed.
2. Energy value: Waste reused for biomass briquettes.
3. Element value: Waste materials recycled in plastics, metal, paint, or fertilizers.
4. Fibre and cellulose: Waste materials reused for paper making and leather processing.

3. Results and Discussion

3.1. Influence of Geographical Proximity on the Type of Solid Waste Material Exchanged

The mean distance through which materials are exchanged was 4.5 km. A multinomial logistic regression analysis was performed and parameter estimates for the odds ratio (Exp (β)) were shown in Table I.

The findings indicated that geographical proximity did not significantly influence the exchange of solid waste material types ($p = 0.298$, $p = 0.327$, and $p = 0.535$). Specifically, the odds ratio for locating “element value” or “energy value” solid waste material resources versus “nutrient value” increased by 1.002 per 1 km increase in distance, reflecting a 0.2% increase in the odds ratio. Similarly, for “Fibre and cellulose value” solid waste material resources versus “Nutrient value,” a 1.001 increase in the odds ratio per 1 km increase in distance was observed, corresponding to a 0.1% increase. The model revealed extremely low odds ratios (0.2% and 0.1%). This finding indicates that distance has a very slight effect on the likelihood of finding the “element value” “energy value” of “Fibre and cellulose value” waste material relative to “nutrient value” waste material. While there is an increase in odds, it is a minimal change, indicating that other factors or variables may substantially influence the choice of solid waste material resources. This finding could be explained by the significant variability in how far apart industries were located, indicating a need for more consideration of geographical proximity in exchanges of solid waste material amongst industries in Kisumu.

This finding contradicted that of [25], who established that there were correlations between industrial diversity in geographical terms and the distance materials move, in addition to the number of synergies types. [25] argued that the region’s diversity of industry types is the critical determinant of how far resources go before being repurposed by a company in a different industry. This finding also contrasted with that of [11], who demonstrated that the density of self-organized IS exchanges in the manufacturing cluster across Europe tended to diminish with distance. A possible explanation for this discrepancy in the findings of this study may be that the scope of the study could have been more extensive compared to the other studies that studied symbiosis practice in large regions, such as Jensen *et al*. [25] study in England involving 600 industries. Additionally, the studies were done in developed countries where other factors such as policies, institutions, geospatial planning, infrastructure, technology, and financial resources ease IS practice even in self-organized systems. While this study did not confirm a significant influence of geographical proximity on the type of solid waste material exchanged, it did offer some insight into the need for spatial planning as indicated by the wide variations observed in the data set. Furthermore, industry diversity and input-output matching should be taken into consideration when collocating industries.

3.2. Influence of Symbiotic Intensity on the Amount of Solid Waste Reused

The results of multiple linear regression analysis in Table II show that symbiotic intensity explained 11.3% of the variation in the amount of solid waste reused in the network (Adjusted R square = 0.113), leaving 88.7% of the variation remained unaccounted for by the model in this study. The model explained only 11.3% of the variation, indicating that additional unexamined factors drive symbiotic exchanges.

The model was statistically significant ($F = 3.548$, $p = 0.039$, $\alpha = 0.05$) as determined by the analysis of variance test. This finding was based on the combined effect of the two variables (symbiotic intensity measured

TABLE II: Multiple Linear Regression Results on Symbiotic Intensity (Number of Actors, Number of Types of Solid Waste Material Exchanged) and the Amount of Solid Waste Material Reused

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	Correlations
		B	Std. error	Beta			Part
1	(Constant)	2.009	0.496		4.053	<0.001	
	Number of actors	0.324	0.221	0.308	1.468	0.150	0.219
	Number of types of solid waste material exchanged	0.243	0.448	0.114	0.541	0.591	0.081

Note: Dependent variable: amount of solid waste reused (log_10). Adjusted $R^2 = 0.113$, $F = 3.548$, df (2.38), $p = 0.039$.

as the number of actors and the number of types of solid waste material exchanged). However, when assessed independently, the significance was not statistically significant: "number of actors in a network" ($p = 0.150$) and "number of types of solid waste material exchanged" ($p = 0.591$). The unique contribution of each variable was explored through the semi-partial correlations in the "Part" column. It was observed that the "number of actors in a network" showed a higher unique contribution (0.219) as compared to the "number of types of solid waste material exchanged" (0.081). The model suggests that symbiotic intensity, as represented by the number of actors and types of solid waste material exchanged, had a significant influence ($p = 0.039$) on solid waste reuse in the network despite its accounting for only a modest proportion of the observed variability, with the majority remaining unexplained.

The unstandardized coefficients for the multiple linear regression model show that the constant regression equation was 2.009. The coefficients of the number of actors in the network and the number of types of solid waste material exchanged were 0.324 and 0.243, respectively. The unstandardized coefficients for the multiple linear regression model indicated a constant regression equation of 2.009, with coefficients of 0.324 for the "number of actors in the network" and 0.243 for the "number of types of solid waste material exchanged." This finding infers that increasing the number of actors in a symbiotic network by 1 ton while keeping the number of types of solid waste material exchanged constant leads to a 324-ton increase in solid waste reuse. Conversely, maintaining the number of actors constant and increasing the number of types of material exchanged by 1 ton results in a 243-ton increase in solid waste material reuse. These findings can be attributed to the fact that network clusters with higher intensity exchanged a more considerable amount of waste despite having less representation in the network.

The Beta column (β) of the standardized coefficients demonstrates a comparison of the contribution of each variable to the multiple regression model. The contribution of "Number of actors in a network" (0.308) appeared to be greater than that of "Number of types of solid waste material exchanged" (0.114). This finding revealed that the "number of actors in a network" (0.308) contributed more significantly to the multiple regression model than the "number of types of solid waste material exchanged" (0.114). This observation remained consistent even when one variable was held constant while analyzing the contribution of the other. This finding aligns with prior research cautioning against relying solely on symbiotic intensity to assess the benefits of industrial symbiosis networks. Other factors, such as input cost reduction [26], knowledge, technology [27], and various contextual factors like industry diversity, proximity, facilitating entities, legislation, plans, and policies [28], should also be considered.

The literature offers limited insight into the link between symbiotic intensity and the exchange of solid waste material. It cautions against comparing industrial systems using Symbiotic Intensity, suggesting that it is more suitable for monitoring the growth of specific industrial symbiosis networks rather than comparing different cases [27]. It is encouraging to note that other studies have looked at the amount of waste reused in the network annually and hence diverted from landfills, such as by Boons, Montalvo, Quist and Wagner [27], who established that in Kawasaki, Japan, 14 documented symbioses with key material exchanges divert at approximately 565,000 tons of waste annually from incineration or landfill. Dong *et al*. [29] established that in Liuzhou, China, there were 3 symbiosis activities between industries with an annual waste exchange of more than 2 million tons/year, whereas, in Jinan, China, there were 7 symbiotic links between industries, with a total waste exchange of more than 8 million tons/y. This finding corroborates the ideas of Chertow and Lombardi [30], who suggested that a higher symbiotic intensity can increase resource efficiency as more materials and energy are reused or repurposed within the network, reducing waste and promoting sustainability. This study provides valuable insights into understanding how the symbiotic intensity influences the amount of waste reuse in the network.

4. Conclusion and Recommendation

The study found no significant influence of geographical proximity on the type of waste exchanged, suggesting a lack of solid evidence for a relationship between these two variables. In essence, this finding suggests that geographical proximity may not be the primary driver of decision-making in the context of waste exchange. In contrast, symbiotic intensity significantly influenced the amount of solid waste reused within the network. This research enhances our understanding of industrial symbiosis by shedding light on the role of geographical proximity in waste exchange, particularly within a developing country context. Furthermore, it underscores the importance of symbiotic intensity in the amount of waste reused, highlighting that increasing the number of network industries may have a more substantial impact than diversifying the types of waste exchanged. The study recommends that factors other than geographical proximity in waste exchange be explored in the context of developing countries. Additionally, as an effective waste reduction strategy in the manufacturing sector, efforts should be made to enhance the symbiotic intensity of industries within the Industrial Symbiosis (IS) network.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

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