

Model Optimization and Sensitivity Analysis of Transportation Network for Agricultural Waste Vermicomposting

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Abstract

Substantial quantities of organic waste from agricultural production are generated and pose a significant challenge for decision-makers in rural countries like the Philippines. Current practices, such as on-site burning and unregulated disposal, contribute to environmental pollution. Among the different valorization technologies for agricultural waste pathways, vermicomposting has emerged as the most easily adopted technology because of its practicality and scalability, suited for agricultural and rural areas. However, the successful adoption of this technology is hindered by challenges like the collection and transportation of agricultural waste to the processing center. This study proposes a Minimum Cost Network Flow (MCNF) framework to optimize the transportation network of the above valorization technology. The model seeks to find optimal routing of waste from farms to the vermicomposting center, and from the vermicomposting center to the compost market, with the least cost. Moreover, this novel MCNF model incorporates waste characteristics into the logistic problem and satisfies the circular economy concept. The efficiency of the proposed model is validated and evaluated on a case study in Bohol Province, Philippines, under different scenarios.

Keywords: OR in agriculture, vermicomposting, optimization, mathematical programming, routing problem

1. Introduction

Agriculture is one of the key contributors to the Philippine economy and accounts for approximately 22.2% of the country's gross domestic product. In 2023, the value of agricultural production was about US\$8.4 billion, an increase of 0.7 % in the previous year PSA (2024). The primary producers are crop production, livestock, and poultry industries and have seen a steady growth of 3.4% over the last decade (Mappa, 2023). However, the consequences of this development are waste generated from agricultural production, approximately 2.29 million tons of dry rice straw, 4.49 million tons of sugarcane trash, and 4.49 million tons of corn stover, with a potential of generating as much as 11 million tons of waste from these crops annually (Go et al., 2019). Additionally, nitrogenous waste from the livestock and poultry industry produced about 13 million tons/year of waste (Calub, 2016). Current practices such as on-site burning and unregulated disposal cause air, soil, and water pollution in rural areas.

Agricultural waste management is a critical issue faced by many countries due to the increasing production of both nitrogenous and carbonaceous wastes. Several policies have been enacted in the Philippines to regulate and mitigate agricultural waste. In 2000, Republic Act (RA) 9003, or "the Philippine Ecological Solid Waste Management Act," stated the use of environmentally sound methods that maximize the utilization of resources and encourage resource conservation and recovery. Specifically, the law emphasized composting, recycling, and source reduction as a means to reduce the amount of solid waste being disposed in local government unit jurisdiction. In addition, RA 10068, or the Organic Agriculture Act of 2010, was enacted to promote and develop organic agriculture and encourage the establishment of facilities and equipment for processing agricultural waste into organic fertilizer.

Although vermicomposting is a sustainable approach to agricultural waste management, collecting and transporting agricultural waste from the field and into vermicomposting facilities are also important problems to consider. Composting centers must have a continuous supply of farm waste from the field and deliver the processed compost to the end-user or the farmer. A complicated challenge in waste management includes careful consideration of the location of the composting site, logistics and scheduling of waste material into the network, and transport of processed compost to the market or farm. In addition, the quality of compost produced from agricultural waste must come from various types of waste sources with different characteristics. Effectively managing and transporting agricultural waste to vermicomposting units pose significant challenges. The transport network must be optimized to ensure cost efficiency, minimize environmental impact, and maintain the quality of vermicompost.

2. Literature Review

2.1 Vermicomposting as a Sustainable Waste Management Approach

Vermicomposting is the practice of utilizing earthworms to decompose organic waste and produce nutrient-rich compost and a promising technology for potentially achieving agricultural sustainability (Lim et al., 2015). This practice facilitates the diversion of organic waste from landfills and avoids farm residues being burned, thus minimizing greenhouse gas emissions and contributing to sustainable waste management (Vuković et al., 2021). Moreover, the resulting by-products or vermicompost have a higher concentration of nutrients compared to conventional compost, possess a natural growth stimulant and soil conditioner (Rupani et al., 2023; Shafique et al., 2021). Worldwide, vermicomposting is utilized for waste treatment from wastewater sludge (Domínguez et al., 2021; Rusanescu et al., 2022), food waste

pretreatment (Muruga et al., 2021), composting organic fractions from solid waste (Arfelli et al., 2023), and recycling farm residues (Liu et al., 2021; Rao et al., 2024).

The quality of vermicompost depends on the substrates' carbon (C) and nitrogen (N). It is critical to account for the appropriate carbon-nitrogen ratio (C:N) of the different substrates before vermicomposting for optimal earthworm digestion. A good C:N ratio for optimal microbial action after vermicomposting is within the range of 25 to 30 (Ndegwa & Thompson, 2000). For instance, in the Philippines, a mixture of 25 % carbon source biomass (rice straw, leaf trimmings, etc.) is combined with 75% animal manure to result in a suitable C:N of 30 (Guerrero, 2010). Similarly, treatments with 50% cow manure and 50% of corn silage residues provided improved vermicompost and earthworm by-products (Edwiges et al., 2022). Some combination of agricultural waste and cow dung with a 1:1 ratio and 1:2 mixed crop residues with sheep manure also provided better quality vermicompost product (Suthar, 2007). Therefore, it is imperative to associate decomposition and earthworm production strongly with the quality of the substrate, especially in terms of their chemical and biological composition.

The crucial role of vermicomposting in agricultural waste management and agricultural sustainability is gaining support worldwide. Agricultural waste collection and transport network analysis from farm fields to vermicomposting facilities is also a significant problem that ensures the success of this approach. This literature review presented the integration of vermicomposting with the logistic problem in agricultural waste management.

2.2 Collection and transport network problem in agricultural waste

Numerous studies have investigated facility location and vehicle routing problem (LRP), often modeled separately for optimization. A study of the interdependency of these two optimization problems started in 1989 (Salhi & Rand, 1989), and since then, continuous research on the integrated approach to LRP problems has been done. A literature review was conducted by Tadaros and Migdalis (2022) on the cases and classifications of locations and routing problems. Activities like collection and transportation, storage, transfer, and processing are incorporated for papers in waste management applications. While these models are present in most location-routing problems, most of these works are still deterministic and static; the author, as concluded by Drexl and Schneider (2015), suggested several aspects for further study, like dynamic and stochastic problems and integrated problems in logistics. This literature review presents the different studies on the characteristics of LRP in agriculture waste management.

There are several applications of LRP in agriculture using the network flow problem approach. Tran et al. (2024) recently presented a Mixed-Integer Nonlinear Programming (MINLP) model for collecting and transporting agricultural waste. The model is a location-assignment-routing problem (LRP) that optimally locates waste storage and determines an optimal set of routes for vehicles to collect and transport from agricultural field storage to bio-organic processing facilities. The overall objective is to minimize storage costs and transport waste from storage to processing facilities. A linearized solution technique was derived from the nonlinearized model, and a novel parallel water flow algorithm was utilized to solve the large-scale instances. It outperforms the general optimization solver and tabu search algorithm in a reasonable amount of time. Another example is the sustainable Close-Loop Supply Chain Network (CLSCN) design in the olive industry (Seydanlou et al., 2022). For small instances, the model is solved using the epsilon-constraint method, while for high complexity, a new hybrid optimization algorithm combining Virus Colony Search Algorithm (VCS), Simulated Annealing (SA), Electromagnetism-like Algorithm (EMA) and Genetic Algorithm (GA) are proposed for the first time. Gracia (2014) and Farrokhi-asl (2017) both address the location

routing problem in agricultural waste management, with Gracia focusing on biomass transportation and Farrokhi-asl on waste collection. Gracia's work applies a hybrid approach of genetic algorithms and local search methods to improve operational efficiency, while Farrokhi-asl presents a mathematical model for waste collection and proposes the use of multi-objective evolutionary algorithms. Zhi-wei (2005) extends the discussion to the municipal solid waste logistics system, introducing a two-phase Tabu search algorithm to minimize system operation costs.

Table 1. Summary of the different literature of LRP in agricultural waste management

Application	Objective	Decision*				Solution Approach**	Validation Approach	Reference
		L	R	V	I			
Solid waste collection site	Singe	x				IP, Heuristic approach	Case Study	Ghiani et al. (2012)
Biomass from orchard	Single			x		IP, HGA	Case Study	Gracia et al. (2014)
Solid Waste Management	Multiple	x	x			GIS-MOMIP, Conversion to one objective	Case Study	Asefi and Lim (2017)
Waste collection	Multiple	x	x	x		MOLP, NGSa and MOPSO	Case Study	Farrokhi-Asl et al. (2017)
Urban waste	Single	x				GIS Resource Dynamo	Case Study	Wielemaker et al. (2020)
Lignocellulose waste	Single	x				GIS	Case Study	Patel et al. (2021)
Olive waste recycling	Multiple	x	x		x	MILP, Hybrid Optimization Algorithm	Case Study	Seydanlou et al. (2022)
Paddy rice waste collection	Single	x				GIS	Case Study	E.-S. G. Khater et al. (2022)
Decentralized solid waste composting	Multiple	x				GIS-MCDA	Case Study	Yeo et al. (2022)
Agricultural biomass	Single	x	x	x		MINLP, Parallel Water Flow Algorithm	Case Study	Tran et al. (2024)
This paper	Multiple	x	x			GIS, MOLP	Case Study	

* Note that L= Location, R= Routing, V = Vehicle Allocation, I= Inventory

** Note that IP= Integer programming, HGA = Hybrid Genetic Algorithm, GIS = Geographic Information Systems, MOMIP = Multi Objective Mixed Integer Programming, MINLP = Mixed Integer Nonlinear Programming, MILP = Mixed Integer Linear Programming, MOLP = Multi Objective Linear Programming, NGSa = Non-dominated Sorting Genetic Algorithm, MOPSO = Multi Objective Particle Swarm Optimization and MCDA = Multi-Criteria Decision Analysis

Several studies combine Geographic Information Systems (GIS) and mathematical modeling to design LRP in agricultural biomass transport networks. In municipal solid waste (MSW) management, a GIS and Multi-Objective Mixed-Integer Programming (MOMIP) is formulated in the collection, composting, recycling, and disposal in the growing challenge of MSW with a simulated annealing algorithm solved in General Algebraic Modeling System (GAMS) software and was able to solve large-sized instances (Asefi & Lim, 2017). Similarly,

GIS combined with a multi-criteria decision analysis (MCDA) approach offered a practical and efficient method in determining the suitable site for collecting agricultural residues and decentralized organic composting plant site (E. S. G. Khater et al., 2022; Yeo et al., 2022).

Other studies separately handle location and routing problems. For example, a GIS framework was also utilized for the optimal location of lignocellulosic biomass and municipal solid waste (MSW) potential and waste-to-conversion facility in Alberta, Canada (Patel et al., 2021). The first stage of the location and assignment of the facility is similar to the capacitated facility location problem (CFLP) using integer programming modeling (Ghiani, 2012) in which the minimization of the total cost of the facility location problem. Another example of GIS in modeling is the geospatial distance between the nutrient supply of buildings in cities and the demand sites of nearby agricultural lands (Wielemaker et al., 2020). The GIS model “Resource Dynamo” prioritized the supply sites with higher concentrations of nutrients (hotspots) and matched the nearby agricultural fields as demand. Furthermore, the model delineates optimum transport routes between these nutrient supply sites and the agricultural demand site.

It can be seen from previous papers that LRP in agricultural waste and solid waste management has not been fully investigated. Particularly on integrating characteristics of waste material into the mathematical modeling. Hence, this paper aims to contribute to the application of the network optimization approach to perform the following:

- GIS-assisted transportation network design involving types of agricultural waste, particularly lignocellulose/biomass waste (carbon source) and livestock waste (nitrogenous waste);
- Integrate characteristics of waste (carbon to nitrogen ratio) into the closed-loop transportation network optimization problem and
- Applying the model to solve a real case of vermicomposting transportation network in Bohol Province, Philippines.

3. Model formulation

Figure 1 provides an example of the vermicomposting location and routing problem for this study. Each cluster of farms producing carbonaceous waste and nitrogen-rich waste is assigned to one vermicomposting facility. The assignment of a vermicomposting facility is dependent on the distance between the cluster fields, the vermicomposting facility capacity, and the demand. The above problem is similar to an MCNF, which seeks the minimum cost of transportation and production of vermicompost. The solution consists of optimal routes of transporting waste from cluster farms to vermicomposting facilities and delivery of vermicompost to compost markets.

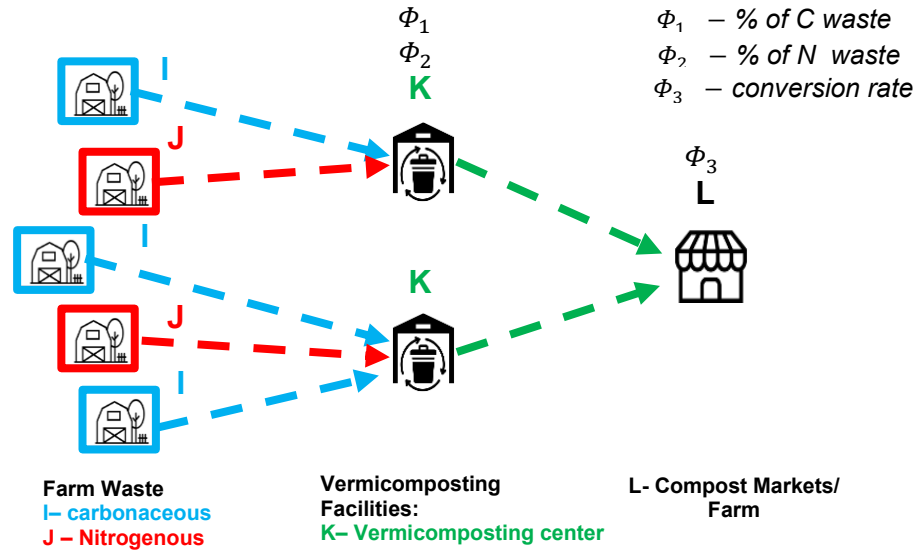


Figure 1. Example of location routing problem for vermicompost production

Agricultural waste comes from carbonaceous waste, typically from rice fields and other biomass, and nitrogen-rich waste from livestock is being considered in this routing problem. Farm waste I and livestock waste J are being transported to vermicomposting facility K. From vermicomposting facility K, the processed vermicompost is delivered to the compost market represented by demand node L. This transport network design followed a well-known minimum cost network flow (MCNF) problem in transportation. Moreover, the model extends its network to satisfy demand at the compost market/organic farm, which facilitates a circular bioeconomy.

In this paper, the proper carbon-nitrogen (C:N) ratio was considered, integrating the suggested percentage of carbonaceous waste with nitrogen-rich waste during vermicomposting, as represented by variables ϕ_1 , ϕ_2 , respectively, will provide a quality end product. Moreover, a conversion rate represented by ϕ_3 provides consideration of the processing efficiency of farm waste into vermicompost. Decision variables $x_{1,i,k}$ and $x_{2,j,k}$ represent the quantity of waste material transported between nodes I and nodes K, and between nodes J and nodes K, respectively. On the other hand, $x_{3,k,l}$ represents the quantity of processed vermicompost from facility K to demand node L.

A mathematical model is formulated for transporting farm waste into the vermicomposting site and delivery of vermicompost to the compost market.

$$\min = \sum_{i,j} (COST1_{i,k} * x_{1,i,k}) + \sum_{j,k} (COST2_{j,k} * x_{2,j,k}) + \sum_k (COST3_k * CAP_k) + \sum_{k,l} (COST4_{k,l} * x_{3,k,l}) \quad (1)$$

s.t.:

$$\sum_k (x_{1,i,k}) \leq SUPPLY_i \quad \forall i \quad (2)$$

$$\sum_k (x_{2,j,k}) \leq SUPPLY_j \quad \forall j \quad (3)$$

$$\sum_i x_{1,i,k} \geq (\phi_1) (\sum_l x_{k,l}) \quad \forall k \quad (4)$$

$$\sum_j x_{2,j,k} \geq (\Phi_2) (\sum_l x_{k,l}) \quad \forall k \quad (5)$$

$$\sum_l x_{3,k,l} \leq CAP_k \quad \forall j \quad (6)$$

$$\Phi_3 * \sum_k (x_{3,k,l}) \geq DEMAND_l \quad \forall l \quad (7)$$

$$x_{1,i,k}, x_{2,j,k}, x_{3,k,l} \geq 0 \quad \forall i, j, k \quad (8)$$

In this MCNF model, the objective function (1) aims to minimize the total cost, including the transportation cost $COST1_{i,k}$, $COST2_{j,k}$, and $COST4_{k,l}$ as well as the vermicomposting cost $COST3_k$. The transportation cost is proportional to the distance between each node multiplied by the unit transportation cost (\$/kg-km). Constraints (2) and (3), or supply constraints, ensure that the quantity of farm waste from I and J must not exceed the total supply. Constraints (4) and (5), or mass balance equation, ensure that the proper waste ratio is being observed at vermicomposting facility K. Constraint (6) ensures that the quantity transported to the vermicomposting facility is less than or equal to the processing capacity at K. Constraint (7) ensure that the quantity of vermicompost being delivered from facility K must not exceed the total demand at L. Constraint (8) or the non-negativity decision variable ensured that the flow of material is irreversible.

4. Numerical Experiments

This section illustrates the application of the mathematical model using a case study in the Province of Bohol, Philippines, as a numerical example. Data regarding rice straw was obtained from the Philippine Rice Research Institute rice production for the first cropping season in 2024. Estimating rice residue was obtained using the framework of Htoo et al. (2022) and Patel et al. (2021). On the other hand, manure production was estimated with a duration of 6 months, coinciding with the cropping calendar for the first season of the study area. Transportation cost was computed following the guidelines of Chiu et al. (2016) and considering the average diesel cost from June to December of 2024. The details and parameters are listed in Table 2 below.

Table 2. Parameters in the mathematical model

Parameter	Value	Unit
UTC (Unit Transportation Cost)	1.27	US\$/ton-km
φ_1	30	Percentage
φ_2	70	Percentage
φ_3	70	Percentage
Ck (Processing cost at center)	0.025	US\$/ton
I1-I9 (supply of C waste from I)	20.18,109.57,6.40, 81.72,73.05111.85, 151.50,340.95, 100.62	Ton
J1-J5 (Supply of N waste from J)	175.50,169.92, 6.20, 63.72, 116.82	Ton
K1-K11 (Capacity at K)	400, 300, 250, 400, 300, 300, 300, 300, 400, 400, 400	Ton
L1-L4 (Demand at L)	150, 125, 150, 200	Ton

Distances of collection points for rice straw residues, livestock farms, vermicomposting facilities, and organic farms are demonstrated in Table 3, Table 4, and Table 5, respectively, below.

Table 3. Distance (km) of rice collection center (I) to vermicomposting center (K)

I	Vermicomposting Center (K)										
	1	2	3	4	5	6	7	8	9	10	11
1	59.9	3.4	55.8	49.0	79.9	84.6	73.8	61.8	63.9	56.6	61.1
2	66.0	64.5	48.2	33.4	37.0	28.6	16.5	6.2	44.3	51.1	47.1
3	81.3	54.3	17.6	48.7	32.3	36.9	35.8	47.3	59.6	18.4	22.6
4	66.6	65.1	44.8	34.0	33.7	25.2	13.1	3.9	45.0	47.8	43.8
5	55.2	3.6	60.5	49.9	84.6	86.8	74.7	62.8	61.0	61.3	65.8
6	47.3	10.5	67.4	48.6	91.6	90.8	78.7	66.8	53.1	68.2	72.7
7	67.2	48.5	33.7	34.7	43.9	47.1	35.0	35.0	45.6	34.5	38.6
8	11.3	50.7	90.2	27.9	86.5	81.1	69.0	57.0	16.4	91.1	90.3
9	39.5	36.2	63.3	15.1	59.5	54.1	42.0	30.1	30.0	64.1	63.4

Table 4. Distance (km) of livestock farm (J) to vermicomposting center (K)

J	Vermicomposting Center (K)										
	1	2	3	4	5	6	7	8	9	10	11
1	70.5	43.2	36.0	37.9	46.2	50.3	38.2	38.3	48.9	36.8	40.9
2	10.4	52.1	91.0	28.7	87.2	81.8	69.7	57.8	17.1	91.8	91.1
3	61.4	3.6	55.2	47.7	79.3	83.9	72.5	60.5	62.6	56.0	60.5
4	32.4	83.1	91.3	41.8	75.7	67.9	60.8	56.9	30.3	94.2	90.2
5	17.9	66.8	87.9	25.5	84.1	77.6	66.6	54.7	14.0	88.7	88.0

Table 5. Distance (km) of vermicomposting facility (K) to organic farm/compost market (L)

K	Compost Market/Organic Farm (L)			
	1	2	3	4
1	25.0	76.1	33.1	32.5
2	65.6	81.1	45.0	73.5
3	77.6	85.7	57.1	1.0
4	89.7	5.3	62.5	12.6
5	95.1	7.0	66.4	14.2
6	99.0	25.5	67.1	24.0
7	99.7	32.2	1.0	30.8
8	57.7	33.2	14.2	34.8
9	62.2	43.6	21.0	68.0
10	63.6	77.2	21.5	1.5
11	64.1	14.9	25.1	11.9

4.1 Results and Discussion

The test problem was solved using GAMS software on a personal computer with a 64-bit OS, 11th Gen Intel R (2.40GHz) processor, and 8.00 GB RAM. For scenario 1, a typical 30% C and 70% N waste ratio was utilized in the model, which yielded around US\$32,514.968.

However, a smaller transportation cost would be achieved if the waste ratio were adjusted to a 50% C: 50% N in Scenario 2, with a value of US\$30,097.47. The optimal route, as well as the transported waste and compost, are shown in Table 5 below. The model tries to meet all the demand under different carbon-to-nitrogen waste ratios. As shown in the table below, different scenario of waste ratios requires different collection sources for both C and N waste. Also, it is seen in the result that several collections for rice straw and livestock farms were not included in the optimal solution. These bottlenecks can provide insight for future vermicomposting facility expansion to include these waste sources.

Table 5. The results of the optimization model for the case problem

Scenario	Objective Function Z (US\$)	Decision Variable					
		I→K	x1(ton)	J→K	x2(ton)	K→L	x3(ton)
Demand with 30C: 70N waste ratio	32,514.968	I2- K8	79.39	J1- K3	175.50	K1- L1	150.0
		I3- K3	6.40	J2- K1	169.92	K2- L3	74.34
		I4- K7	81.72	J3- K2	106.20	K3- L4	127.33
		I8- K1	44.36	J4- K4	11.91	K4- L2	125.0
		I9- K4	100.62	J5- K4	116.82	K4- L4	35.55
						K7- L3	57.20
						K8- L3	18.45
				K8- L4	37.12		
Demand with 50 C: 50N waste ratio	30,097.47	I2- K8	109.57	J1- K3	115.04	K1- L1	150.0
		I3- K3	6.40	J2- K1	169.92	K1- L4	103.87
		I4- K7	81.72	J5- K4	93.82	K3- L4	85.01
		I8- K1	192.76	J5- K9	22.99	K4- L2	125
		I9- K4	100.62			K4- L4	11.11
						K7- L3	57.20
						K8- L3	76.69
				K9- L3	16.09		

5. Conclusion and Future Work

In this paper, a transportation network was formulated and optimized for vermicomposting. This model incorporated the proper waste ratio of source materials, particularly carbonaceous (C) waste and nitrogenous waste (N) from livestock. This ensures the quality of compost production. An MCNF model is constructed to minimize the transportation cost of waste source to the vermicomposting facility and the vermicomposting facility to the demand market. A numerical experiment on the case study in Bohol, Philippines, and the model obtained an optimal solution under different waste ratios.

The mathematical model does not consider uncertainty in the supply farms and demands, respectively. In order to satisfy uncertainty, the model can be extended to include facility location for farm waste and opening new markets to meet the supply and demand uncertainty. Furthermore, the model can be utilized to determine the optimal number of vehicles and solve various aging timing issues in the waste material.

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