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Plastic waste collection route optimization: Bulgan province

Enkhbaatar Dembereldash[1], Uyanga Batbaatar[2], Sanchirgarav Batzorig[3], Enkhdul Tuuguu[2,*]

[1] *Erdenet Institute of Technology, Erdenet, Mongolia*
[2] *School of Engineering and Technology, National University of Mongolia, Ulaanbaatar, Mongolia*
[3] *Sustainable Plastic Recycling in Mongolia, EU SWITCH-ASIA project, Caritas Czech Republic in Mongolia, Ulaanbaatar, Mongolia*

***CORRESPONDING AUTHOR**
Enkhdul Tuuguu
enkhdult@num.edu.mn
ORCID
0000-0001-6147-2130

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ABSTRACT

Efficient plastic waste collection in rural Mongolia is critical to reducing environmental pollution and improving recycling outcomes. This study optimizes plastic waste transport routes in Bulgan province using the travelling salesman problem (TSP), and vehicle routing problem (VRP) algorithms and open-source GIS tools. By analyzing population data, waste generation rates, and vehicle capacity, ten optimal routes were identified for 15-ton load serving 19 key locations. Results show large disparities in route efficiency, with urban centers generating more waste per kilometer than sparsely populated areas. Recommendations include dynamic routing, vehicle load capacity, and investing in local waste compacting equipment. The findings offer practical solutions for cost-effective, sustainable rural waste management.

KEYWORDS

Waste generation rate, Solid waste management, TSP, VRP, MILP

1. INTRODUCTION

Plastic waste is defined as "any plastic material discarded after use, whether from households, industries, agriculture, or commerce." It is especially problematic due to its persistence in the environment, leading to soil, air, and marine pollution [1]. In 2000, global plastic production was 234 million tons per year, but by 2019, this amount had almost doubled to 460 million tons. The amount of plastic waste generated annually also doubled, increasing from 156 million tons in 2000 to 353 million tons in 2019. Of this waste, only 9% is recycled, 19% is incinerated, and 50% is landfilled. The remaining 22% is either openly dumped or burned, causing environmental pollution [2].

Although plastic production decreased by 2.2% during the COVID-19 lockdown period, the use of single-use protective gear and disposable plastic products increased, leading to a significant rise in plastic waste. In 2019, 22 million tons of plastic ended up in the environment, of which 88% was in the form of macroplastics, microplastics (less than 5 mm), and polymers also spread widely [2, 3]. Therefore, without implementing proper plastic waste management systems—including collection, transportation, and appropriate treatment technologies—it is impossible to prevent pollution of the environment.

Due to economic growth and increased consumption of goods and products, the volume and variety of waste have significantly increased, becoming one of the pressing issues of modern society. Optimizing waste collection and proper disposal methods is a costly but critical process in waste management, with substantial social and economic implications. Among all waste types, the collection and transportation of plastic waste to recycling facilities is a complex process. The main goal of plastic waste management is to ensure safe, efficient, and low-cost collection, transportation, and processing now and in the future. Mongolia has 24 plastic recycling facilities [4], but their operations have stagnated due to post-COVID economic challenges and raw material supply issues. In Ulaanbaatar's municipal waste composition, plastic bottles account for 3.6%, plastic bags for 3.0%, and hard plastic waste for 1.7%. On average, one person generates 432 grams of daily waste [4]. In other words, plastic waste accounts for 8.3% of total household waste. A study of household waste in Khashaat soum, Bulgan province, showed that plastic waste makes up 11% of the total household waste [5].

In both urban and rural areas, some households separate plastic waste at the source and deliver it to recycling collection centers or hand it over to workers from sanitation companies (TÜK) or some homeowners' associations (HOA), who collect and sell it to recycling plants. However, this is not a common practice. In rural areas, even if waste is separated, the lack of nearby recycling facilities and remote locations often results in plastic waste being openly dumped into the environment.

Route optimization plays a critical role in the development of effective waste management systems, especially for remote and low-density areas. By identifying the most efficient paths for collection vehicles, municipalities can reduce fuel consumption, lower operational costs, and improve service coverage [2]. For policymakers and infrastructure planners, route optimization provides essential data to support targeted investments in recycling facilities, compacting equipment, and transportation logistics. It enables evidence-based decision-making for designing scalable and economically viable waste systems across rural Mongolia.

This study addresses the logistical challenges of rural plastic waste collection by developing optimized transport routes in Bulgan province. By applying route optimization models, we aim to design efficient, cost-effective systems to support future waste management infrastructure. This is the first study applying vehicle routing models to rural waste logistics in Mongolia, filling a critical gap in the literature and offering practical solutions for regional waste management planning.

2. RESEARCH METHODS

In municipal waste, 8% is considered as mixed plastic waste both at the soum and city level, thus it can be considered as national data [4, 5].

Table 1. Constants for optimization

No.	Parameters	Indicator	Reference
1	Waste generation	400 g/person-day	The Asia Foundation, 2019 [4]
2	Proportion of mixed plastic waste	8%	The Asia Foundation, 2019 [4]
3	Mixed plastic waste per person	32 g/person-day	Calculation based on The Asia Foundation, 2019 [4] data
4	Uncompacted mixed plastic density	26 kg/m³	Material bulk density [7]

5	Bale (pressed block) dimensions	60 x 90 x 100 cm	Summary of online sources
6	Bale volume	0.54 m³	Calculation is based on dimention
7	Bale press machine compaction ratio	10:1	Summary of online sources [6]
8	Bale weight	~150 kg	Calculation is based on the density and compaction ratio
9	Long-distance transport truck dimensions and capacity	9 x 2 x 3 m 15 tons	Vehicle standard information [7]
10	Population of Bulgan province	-	1212.mn
11	Collection and interest points	Coordinates of waste sites	Observed from Google Maps

Open-source tools such as the Google Maps, Maps.me, and OpenStreetMap were used to perform route optimization calculations. Depending on the objective, different methodologies were applied to route planning tasks. In our research, we used Open Source Routing Machine (OSRM) algorithm on Google Maps and OpenStreetMap to retrieve distance matrix of interest points, the MILP algorithm implemented to simulate the TSP and the VRP to obtaine optimal routes. In Table 2 represnt input data for optimization including interest points, population and distance matrix of interest points.

Table 2. Input data for optimization

Collection site coordinate	Population	Bulgan province distance matrix	Bulgan	Bayan-Agt	Bayannuur	Bugat	Buregkhangai	Gurvanbulag	Dashinchilen	Mogod	Orkhon	Rashaant	Saikhan	Selenge	Teshig	Khangal	Khishig-Undur	Khutag-Undur	Khyalganat	Unit	Erdenet
48.790031, 103.570253	12810	Bulgan	0	152	163	52.9	81.9	188	135	146	24.2	214	97.9	126	228	102	73.3	144	123	93.4	74.2
49.041861, 102.060740	3364	Bayan-Agt	152	0	331	194	228	326	302	292	171	400	70.6	267	245	243	220	161	264	110	216
47.794984, 104.466385	1858	Bayannuur	163	331	0	228	82.6	77.5	32.1	137	156	178	231	301	403	277	106	319	297	268	249
49.077236, 103.669127	2202	Bugat	52.9	194	228	0	129	245	182	193	71.3	261	140	97.2	270	73.3	120	180	94.1	135	45.6
48.243742, 103.882160	2927	Buregkhangai	81.9	228	82.6	129	0	88.6	54.1	141	57.6	133	174	202	304	178	80.3	220	199	169	150
47.747123, 103.507642	3286	Gurvanbulag	188	326	77.5	245	88.6	0	48.9	132	164	74	227	308	410	284	127	326	304	275	256
47.830387, 104.065927	3049	Dashinchilen	135	302	32.1	182	54.1	48.9	0	108	128	81	203	272	374	248	77.3	290	269	240	220
48.277676, 103.000552	2681	Mogod	146	292	137	193	141	132	108	0	121	206	212	266	368	242	75.4	284	262	233	214
48.632442, 103.563920	3385	Orkhon	24.2	171	156	71.3	57.6	164	128	121	0	189	116	144	247	120	49.1	162	141	112	92.6
47.379452, 103.975374	3202	Rashaant	214	400	178	261	133	73.6	80.8	206	189	0	300	351	453	327	201	369	348	318	299
48.663702, 102.642830	3587	Saikhan	97.9	70.6	231	140	174	227	203	212	116	300	0	213	212	189	166	127	210	76.8	161
49.429961, 103.944374	3330	Selenge	126	267	301	97.2	202	308	272	266	144	351	213	0	343	84.1	193	259	105	208	51.5
49.944563, 102.695926	3621	Teshig	228	245	403	270	304	410	374	368	247	453	212	343	0	319	296	92.4	340	135	292
49.305935, 104.397287	1568	Khangal	102	243	277	73.3	178	284	248	242	120	327	189	84.1	319	0	169	235	20.7	184	32.4
48.294412, 103.450315	3056	Khishig-Undur	73.3	220	106	120	80.3	127	77.3	75.4	49.1	201	166	193	296	169	0	211	190	161	142
49.388185, 102.666031	5046	Khutag-Undur	144	161	319	186	220	326	290	284	162	369	127	259	92	235	211	0	255	50.4	207
49.471458, 104.344691	2975	Khyalganat	123	264	297	94.1	199	304	269	262	141	348	210	105	340	20.7	190	255	0	205	53.1
49.143308, 102.814919	993	Unit	93.4	110	268	135	169	275	240	233	112	318	76.8	208	135	184	161	50.4	205	0	157
49.091508, 104.171801	102634	Erdenet	74.2	216	249	45.6	150	256	220	214	92.6	299	161	51.5	292	32.4	142	207	53.1	157	0

TSP is one of the most widely used methods for solving route optimization problems. It involves determining the shortest possible route for a salesman to visit each customer located at different sites exactly once and return to the starting location. In other words, it optimizes the shortest round-trip route that passes through all points of interest once. However, as the number of points increases, the complexity of the computation also grows. Using the TSP method, we performed calculations under the following conditions. The route begins and ends at Bulgan soum, passing through all the interest points shown on Table 3. A single vehicle must visit each point exactly once, and the objective is to determine the shortest possible route that completes the loop.

VRP is a method used to determine the optimal routing of multiple vehicles through points of interest. It aims to minimize the total distance traveled by all vehicles. The following assumptions and data were used for optimization. The route starts from various points of interest and ends at designated collection points. Multiple vehicles are used, each with a maximum capacity of 15 tons, a compaction ratio of 10:1 and time factor was added.

The MILP simulation of routing ran for about 10 minutes on ASUS ZenBook UX501J and evaluated between 10,000 possible routes and defined shortest travel routes.

3. RESULTS AND DISCUSSION

3.1. TSP Calculation Result: Route passing through all points of interest

The shortest possible route that starts from Bulgan soum, passes through all other interest points and returns to Bulgan soum was calculated using the TSP method, it covers a total distance of 1,634 km.

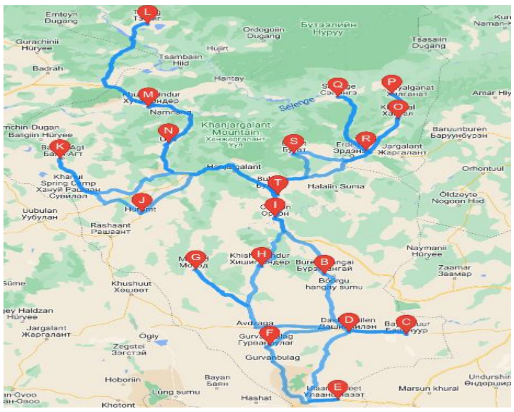

Figure 1. The loop that begins and ends at Bulgan soum

From Figure 2, considering the road condition, urbanization and infrastructure, Bulgan soum, Erdenet city, and Bayannuur soum are identified as designated collection points of VRP to minimize the travel distance of all collection trucks and are fully capacitated.

3.2. VRP calculation results

Optimizing the logistics of plastic waste collection and transportation is critical in developing regions with varying population densities and geographical constraints. This requires innovative approaches to address the challenge of managing plastic waste effectively. [7, 9].

In Bulgan province, plastic waste collection routes were optimized using the VRP method, assuming uniform 15-ton capacity trucks and pre-compacted waste at a 10:1 compression ratio [7]. The study aimed to find the shortest total distances while ensuring each truck's load is fully utilized without exceeding its capacity. Each truck services different numbers of soums, covers various distances, and takes differing numbers of days to fill its 15-ton capacity (Table 3, Figure 2).

This results in imbalances in workload and operational efficiency. Areas like Khyalganat and Erdenet contribute significantly more waste relative to others, aligning with urbanized population centers. Lower-density rural areas like Teshig and Unt have lower waste but still require long-distance coverage.

Table 3. Identified waste collection route

Route		Distance (km)	Population	Plastic Waste (kg/day)	Days to Fill 15 tons	Waste per km (kg/km)
Route 2	Bugat → Erdenet	45	2,202	70.5	212.9	333.33
Route 3	Selenge → Erdenet	51	3,330	106.6	140.8	294.12
Route 4	Khyalganat → Khangal → Erdenet	52	4,543	145.4	103.2	288.46
Route 8	Khishig-Undur → Orkhon → Bulgan soum	73	6,441	206.1	72.8	205.48
Route 6	Gurvanbulag → Dashinchilen → Bayannuur	80	6,335	202.72	73.9	187.50
Route 9	Buregkhangai → Bulgan soum	81	2,927	93.7	160.2	185.19
Route 5	Mogod → Bayannuur	137	2,681	85.8	174.8	109.49
Route 1	Bayan-Agt → Saikhan → Bulgan soum	168	6,942	222.1	67.5	89.29
Route 7	Rashaant → Bayannuur	178	3,202	102.5	146.4	84.27
Route 0	Teshig → Khutag-Undur → Unt → Bulgan soum	236	9,660	309.1	48.5	63.56

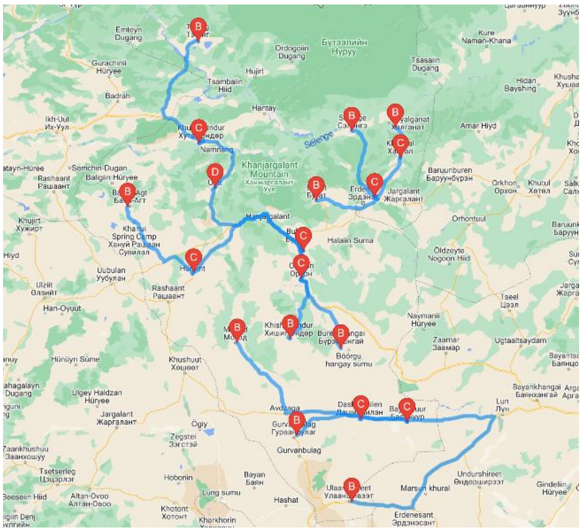

Figure 2. 10 routes, through the soums of Bulgan province, 3 centralized collection points

Results show that Route 2 is most efficient while Route 0 is less efficient. Route 0 covers 236 km but reaches full capacity only after 309 days, showing very low waste generation along that route. In contrast, Route 2 travels just 45 km but fills up in 213 days, suggesting a high population density and greater waste output. This implies a strong correlation between waste volume and population concentration.

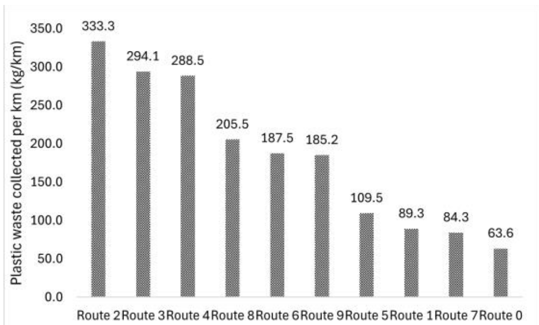

Figure 3. Plastic waste collection efficiency (kg/km)

The data reveals clearly that some routes are more efficient than others. For instance, in Figure 3, Routes 2, 3, and 4 are the most loaded per kilometer, while routes 0, 7, 1, and 5 are less loaded but travel much further. This highlights the need to dig deeper into waste generation patterns and create adaptable routing strategies.

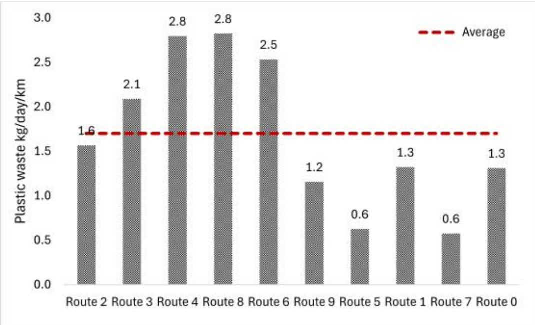

Figure 4. Daily plastic waste per kilometer

Figure 4 shows that Routes 3, 4, 8, and 6 are the most loaded trucks per km, while Routes 2, 9, 5, 1, 7, and 0 are less loaded but travel further than the previous four routes.

To improve efficiency, it's worth exploring options like rebalancing workloads across routes or reassigning service areas. In areas with fewer residents or less waste, using smaller trucks could cut down on fuel consumption, costs, and emissions.

Lastly, since the current model is based on present population and waste data, it's important to develop a dynamic model that also considers future population growth, changing consumption patterns, and improved sorting practices. Additionally, if some localities lack compacting presses, the actual load volume will increase, requiring recalculation of vehicle capacities. Therefore, it's important to confirm waste density and compaction conditions when planning. Adjusting the collection frequency dynamically (e.g., once a week or twice a month) can also be more efficient than fixed schedules.

Based on the route optimization results, policy improvements should focus on flexible route planning that reflects actual waste generation rates, especially in sparsely populated areas. Supporting localized waste composition studies, investing in regional baling facilities, and enabling dynamic vehicle allocation can reduce transport costs and increase efficiency [9, 10]. Encouraging waste sorting on-site and implementing performance-based incentives will further enhance the sustainability of rural plastic waste management.

Our method relies on current population and waste data, so it's important to develop a dynamic approach. This updated method should take into account future population growth, changing consumption habits, and advancements in waste sorting and management.

4. CONCLUSION

The optimal route for collecting plastic waste was determined using the TSP and VRP methodologies, with 10 routes to 3 collection points. The efficiency of waste collection routes depends on population density and geographical distribution. To determine the efficiency of collection more effectively, it is necessary to conduct a study on the quantity and structure of waste emissions. The results of this study are important for the efficient logistics of not only plastic waste, but also other secondary resources, at low cost, and reducing the impact on the environment.

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